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Remote sensing applications in archeological research: Tracing prehistoric human impact upon the environment

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REMOTE SENSING APPLICATIONS IN ARCHEOLOGICAL RESEARCH: TRACING PREHISTORIC HUMAN IMPACT UPON THE ENVIRONMENT

by

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Remote Sensing Applications in Archeological Research: Tracing Prehistoric Human Impact Upon the Environment

Thesis directed by Professor Payson D. Sheets

Much of prehistory can be traced by the impacts of human activity upon the environment. The use of remote sensing technology offers the archeologist the opportunity to detect these impacts which are often invisible to the naked-eye. New advances in remote sensing instrumentation, digital image processing, and statistical analyses can be employed in the testing of archeological hypotheses. This thesis applies advanced remote sensing technology to two study areas: Chaco Canyon, New Mexico and Arenal, Costa Rica. Each study area represents diverse environmental and cultural conditions. Prehistoric Anasazi roads have been successfully mapped in Chaco Canyon and a system of prehistoric footpaths has been mapped in Costa Rica using sophisticated remote sensing technology. In both cases these transportation and communication routes have been useful in understanding prehistoric adaptation and social integration.

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INTRODUCTION

Remote sensing technology represents one of the most significant breakthroughs in the history of archeology. It is radically affecting the way archeologists conduct field reconnaissance and excavation. It is also being incorporated into research designs of multidisciplinary projects that are concerned with the study of ancient societies in their environmental context. Archeology was one of the first disciplines to recognize the importance of remote sensing at the turn of the century, yet the potential of this technology has yet to be completely realized.

Remote sensing is the science and art of detecting and recording objects or phenomena from a distance through devices that are sensitive to various bands of the electromagnetic spectrum. This can be achieved at different levels, by instruments mounted on satellites, the space shuttle, aircraft, tethered balloons, or even on the ground. Data collected and recorded by these devices must be verified on the ground or by excavation.

By interpreting the imagery at one place, it is often possible to understand the same phenomena in other areas.

The overall goal of this research investigation was to demonstrate the utility of remote sensing in detecting the activity and impact of prehistoric societies on the environment. The specific objectives in achieving this goal were: 1) to demonstrate how archeological information can be extracted from remotely sensed data; 2) to characterize those remote sensing data sources which hold potential for archeological investigations under different environmental conditions; 3) to isolate the appropriate analytical techniques for computer-implemented analysis of remotely sensed data; and 4) to demonstrate the value of remote sensing in providing information to the archeologist in a rapid, non-destructive, and cost-effective manner.

In order to demonstrate the application of remote sensing technology to archeological research, two study areas were selected which represented diverse environmental, temporal, and cultural conditions. These study areas were used to test several hypotheses that resolve investigative questions through the use of remote sensing. The prehistoric populations, archeological features, and environmental regions examined in this investigation were 1) the Anasazi roadways in the semi-arid region of Chaco Canyon, New Mexico (A.D.1-1350; and, 2) the Arenal peoples prehistoric footpaths and site locations in the tropical rainforest of Costa Rica (500 B.C. - A.D. 1200).

The research discussed in this paper represents a pioneering effort in a field that is expanding rapidly. The untapped potential of photographic and digital remote sensing, combined with developments in computer hardware and software, offer the discipline of archeology an opportunity to discover information and resolve controversies that have remained unanswered. With the commercialization of space, construction of the space station, and competition from foreign nations in satellite technology, remote sensing can become a fundamental component of future archeological research.

BACKGROUND

Much of human history can be traced through the impacts of human actions upon the environment. Research concerning the interaction between cultural and physical systems and knowledge of the regional context has been crucial in understanding man-land relationships by anthropologists for a long time (Adams and Nissen 1972;

Adams 1981; Binford 1962; Butzer 1982; Clarke 1977; Steward 1955; Willey 1953; Wiseman 1978). The archeologist must locate and reconstruct the ancient landscape, the resources available for exploitation, occupational settlements, campsites, manufacturing centers, and other features of cultural activity (e.g. Butzer 1980; Flannery 1976; MacNeish 1975; Redman 1982; Sheets 1983). Traditionally this information has been collected by ground survey, often requiring large field teams and several seasons of activity. The archeological research of large regions could take many decades of endeavor and a fortune in cost (Wiseman 1983). To reduce labor and cost, several sampling strategies were developed that would hopefully attain productive research objectives through accurate statistical techniques (Mueller 1975; Plog, Plog, and Waite 1982). These strategies, however, vary from region to region and have resulted in non-systematic, uncomparable, and non-intensive resource inventories.

To date, a systematic methodological inventory of cultural resources and archeological features has never been accomplished. Each archeological project approaches the problem in a different way. The variation in data acquisition methods, levels of approach, and site definition vary from researcher to researcher. In addition, climatic factors, time of year, and vegetation conditions can contribute to the resultant inventory. Even the most intensive inventories miss archeological phenomena which cannot be seen from ground level. Remote sensing can be used as a methodological procedure for detecting, inventorying, and prioritizing surface and shallow-depth archeological information in a rapid, accurate, and quantified manner. Archeological survey is being radically altered by remote sensing and is now allowing archeologists the opportunity to create research designs with a geographic scope larger than ever before envisioned.

ACCELERATING LAND-USE CHANGES

It is ironic that the use of satellite and airborne remote sensing technology which has such potential for archeological research is also indirectly contributing to the destruction of archeological sites. The commercial use of remote sensing, for instance, has sometimes contributed to the flooding or deforestation of large areas. The ability to quickly map both renewable and non-renewable resources on a large scale has generated industrial competition. In the wake of the search for new mineral deposits, productive forest stands, rich agricultural areas, and recreational lands, archeological sites are being destroyed at a phenomenal rate. These accelerating land use changes, coupled with a rapid rise in the vandalism and looting of cultural resources, have placed traditional archeological survey and feature detection techniques at an enormous disadvantage.

Although cultural resources are protected on public lands in the United States by state and federal regulations (e.g. Executive Order 11593), the enforcement of this legislation is ineffective due to the limited funding levels and complex logistical problems. Even though the laws of foreign countries are generally more protective of cultural resources, they experience even greater detection and enforcement problems than those encountered in the U.S. Even on well-protected sites, the cost of survey and excavation are skyrocketing while the funding levels for archeological research is decreasing. In short, contemporary archeological methodologies are often unable to keep pace with the growing destruction of archeological sites.

An example of archeological destruction can be seen along the Usumacinta River Valley between Mexico and Guatemala (Stuart 1988). Commercial agencies using

Landsat remote sensing technology have located productive stands of forests. As a result these areas have experienced rapid deforestation and burning. The Maya archeological sites within these areas are generally built of limestone. The sites are subsequently destroyed as the heat fragments and pulverizes the limestone blocks while the rains quickly erode them.

THE POTENTIAL OF REMOTE SENSING FOR ARCHEOLOGICAL RESEARCH

A remotely sensed methodology which produces a systematic and intensive approach to survey and feature detection, would contribute to offsetting the problems currently faced in archeological reconnaissance. Investigators would be able to analyze large regions, prioritize areas for research, and select optimum areas for extensive excavation. The ability to achieve these objectives has arrived, for the use of remote sensing has come of age for archeology. In a decade it has grown from an esoteric speciality practiced by a few scientists to a capability that is beginning to be applied by dozens of researchers in archeology throughout the world.

Remote sensing data can be recorded in either an optical or digital format. An example of an optical format is black and white aerial photography. In this format the images are exposed onto film and processed chemically. In the digital format, which originated in the mid 1960's, the images are recorded numerically and are processed electronically using a computer. There are advantages and disadvantages to both techniques, yet the recent trend has seen increasing use of digital methods, as new sensor instrumentation and more advanced computers are developed. The use of black and white photography at the turn of the century, however, opened the door for archeologists to see information which could not be seen from ground level and provided the impetus for adapting the digital imagery of the space age.

CONTEMPORARY HUMAN IMPACTS

One of the major contemporary ecological and environmental concerns is the solution of problems created by the confrontation of people with nature as a result of their technological advancements (Lulla and Mausel 1983). The destruction of wildlands, disappearance of wildlife species, climatic change, world-wide pollution, and degredation in environmental quality have aroused national and international concerns.

To address these issues, the non-destructive techniques of remote sensing are being used to monitor the man-made changes to the atmosphere, oceans, and landscape. The monitoring of the landscape includes urban development, surface strip mines, forest fires, agricultural development, desertification, biological and botanical habitats, industrial development, transportation systems, irrigation, pollution, erosion, and weather (Richason 1983).

Remote sensing has emerged as one of the most useful techniques in addressing contemporary environmental issues. It has established itself as a tool that can provide a major source of data to scientists, managers, legislators, administrators, and decision makers at international levels. The techniques employed in data acquisition and data analysis are well documented. A growing number of international conferences on remote sensing are held each year and sponsored by such agencies as the United Nations Environmental Program (UNEP). As Lavigne (1977) states, "the extent of habitat destruction by man now becomes ignorance by choice."

Archeology has access to the techniques that have been developed by other disciplines that monitor man-land changes. In addition, archeology should play an active role in the growing conservation ethics that are concerned with the preservation of non-renewable resources. The protection and preservation of cultural resources as well as the rural cultural landscape is an important issue for all anthropologists. The analytical remote sensing techniques that have been developed for contemporary man-land relationships can also be employed in identifying human impacts upon prehistoric landscapes.

RESULTS OF PROPOSED RESEARCH

As stated previously, the overall goal of this project was to demonstrate the use of remote sensing in detecting and understanding the impact of prehistoric societies upon their environments. Hypotheses were tested at two environmentally and culturally distinct areas: Chaco Canyon, New Mexico and Arenal, Costa Rica. Remote sensing analysis was incorporated into the respective research designs to locate and map prehistoric archeological features. In order to demonstrate the utility of remote sensing in archeological research, it was necessary to discuss the basic principles of remote sensing (Chapter 3) as well as the basic analytical techniques used in computer analysis. Following this discussion, each study area (Chapters 4 and 5) was investigated using a combination of aerial and color infrared photography, satellite imagery, digital aiborne sensor imagery, and GIS technology.

CHACO CANYON

The interpretation that Chaco Canyon was the center of an extensive and complex roadway system has gradually evolved over the last 20 years. Chaco Canyon achieved its peak during the Anasazi occupation in the Classic Bonito Phase at 1020-1220 AD. Chaco canyon, located in the San Juan Basin of northwest New Mexico, is an erosional formation created by the Chaco Wash and represents an area of extensive chronological development (Ebert and Hitchcock 1975). The Chaco roadway system is generally associated with the Classic Bonito Phase (BLM 1983).

In 1971, archeologists noticed what appeared to be a network of prehistoric roadways in aerial photographs acquired by Charles Lindbergh and A.V. Kidder in 1929. These features were indicated by changes in vegetation. Grazing practices increased in the 1940's, however, and recent aerial photography has not been as successful in recording the roadways. Although it is difficult to locate the roads from ground level, their existence can be verified through their association with stairways, causeways, ramps, roadcuts, and walls (Bureau of Land Management 1983). Through erosion, compaction and occasional vegetational differences, the roadways have survived as faint lines, often invisible to the human eye.

Although they have a widespread distribution, the purpose(s) of the roadways remains a mystery. A major characteristic of the roadways is their linearity which stands in sharp contrast to the meandering courses of modern roadways. The prehistoric roads are generally 9 meters wide and run in straight lines regardless of topographic features and the surrounding terrain. In addition, they tie together a number of similar cultural manifestations called "outlier" sites. Despite all previous research, the extent of the Chacoan roadway system remains unknown. This is due to the limitations in viewing the roadways as well as the expense in conducting traditional ground survey. As a result, the mapping of this roadway system is an important step toward understanding a complex, regionally based cultural development.

The hypotheses that were tested in Chaco Canyon are:

If the prehistoric roads had an economic function then:

1. they took the "path of least resistance" as they traveled from one place to another, resulting in curving or meandering patterns in areas of difficult terrain;

2. they incorporated greater constructional effort in making travel easier at difficult places, i.e. areas of steep slope, than in areas of flat or level relief;

3. they by-passed and avoided areas of high topographic relief;

4. and, they provided linkage to Chaco Canyon for the storage and redistribution of goods.

Conversely, if the prehistoric roads served a religious function, then:

1. they will connect to a major center of ritual activity (Chaco Canyon) where they will be associated with religious features such as shrines, kivas, great houses, and ceremonial ceramic breakage;

2. and, they will incorporate elevated areas of topogaphic relief into their course such as pinnacles, mesa tops, or other observational areas, and they will be associated with ritualistic concepts such as directional symbolism, orientation, and astronomy; i.e., they continue on their predetermined course in spite of topographic obstacles.

In order to test these hypotheses, it was necessary to examine the archeological evidence from Chaco Canyon and to use remote sensing techniques for the mapping of the prehistoric roadways. Locating the roads from ground level is extremely difficult and natural and man-made activities upon the landscape have destroyed many remnants of the roadway system. Many of the roads that were seen in photography in the 1930's are not visible in the photography of the 1980's. In order to understand the function of the Chacoan road network it was first necessary to map the location of the roads. New techniques in remote sensing assisted in this process.

Recent studies have revised many past interpretations regarding the role of Chaco Canyon in Anasazi society. Through survey and excavation of the roadway system as well as the excavation of great houses, trash middens, and great kivas, new information was available regarding the relationships between these features and the prehistoric roadway system. In addition, ethnographic information from Pueblo sources surrounding this area, was examined to gain an insight regarding the purpose for the Anasazi roads.

This investigation combined remote sensing, archeology, and ethnographic research to test hypotheses and subsequently determine the purpose for the prehistoric roads that run across the Chacoan desert. To achieve an understanding of the Chacoan roadway system, it was essential to map the prehistoric roads, to determine their physical characteristics and associations, to establish the dates for their construction and use, and to determine the sites and resources upon the landscape that are connected to the roads. By examining this information an interpretation for the Chacoan roadway system has been established.

ARENAL, COSTA RICA

The history of archeological remote sensing applications has demonstrated success in arid and semi-arid environments, yet the application to tropical rainforests is practically non-existent. The wet climatic conditions, severe cloud cover, burial by volcanic ash layers, and complicated patterns of heavy vegetation are major obstacles for conventional remote sensing analysis. These problems are apparent in data acquisition, data analysis, logistics, and subsequent field verification. This investigation demonstrates, however, that a successful archeological remote sensing study can be completed in the tropics if a combination of remote sensing instrumentation, advanced image analysis, and GIS application is employed in the research strategy and ground verification. Since these techniques proved successful in Costa Rica, it is probable that they can be applied successfully in other relatively unexplored areas such as the Amazon, eastern Peru, west Africa, and southeast Asia.

Arenal Volcano in northwest Costa Rica has erupted explosively at least nine times during the past 3000 years (Melson 1978). In burying archeological features, these numerous explosions have served to establish a chronology of human interaction with the surrounding landscape. The area has proven to be an excellent natural laboratory for the study of prehistoric settlement, adaptation, activity, and resource exploitation. The area is located between two major ecological zones, each of which possesses inherent advantages and disadvantages. Although this volcanically active area contains certain liabilities, the long-term advantages appear to outweigh the short-term risks. The fertile tephra (airfall ash) produced by weathering of Volcan Arenal are conducive to botanical growth while volcanic raw materials can be used in lithic and ceramic technology. Another volcanic material--laja, was used for tomb and wall construction in the cemeteries (Sheets and Sever n.d.). The influence of volcanic activity upon prehistoric adaptation has only recently been intensively studied (Lange 1978; Snarskis 1981; Sheets 1983,1984, n.d.).

Multidisciplinary research has been conducted in the Arenal area under a cooperative agreement between the National Science Foundation (NSF), National Geographic Society (NGS), and the National Aeronautics and Space Administration (NASA). Under the direction of Payson Sheets (University of Colorado), the PROYECTO PREHISTORICO ARENAL has operated under the theoretical framework of paleoecology, as it attempts to determine the relationship of prehistoric cultural sequences with the dynamics of the surrounding landscape. A total of 62 archeological sites have been discovered consisting of village sites, graveyards, and some lithic manufacturing areas. Field excavation and laboratory analysis have been conducted with such data as lithics, ceramics, pollen, raw materials, and traded-materials. The objective was to understand the chronological development of the society's self sufficiency as well as its relationships with neighboring societies. An outcome of the project's research has been the development of a methodology for detecting prehistoric footpaths.

It is proposed that prehistoric footpaths can be used to help understand a culture's religious, economic, political, and social organization. People negotiate the surrounding terrain for a variety of reasons including: transportation, communication, and ritual. In following these footpaths, the researcher can gain an insight into the nature and purpose of prehistoric human activity.

The hypotheses that were tested in the Arenal area are:

1. If the linear patterns in the remotely sensed data are prehistoric footpaths, then they will demonstrate relationships that are of a cultural origin. Specifically, the paths will reveal a linkage system between resources, villages, and other cultural areas. They will connect with each other, with springs, cemeteries, manufacturing areas, storage areas, and natural resources.

   Conversely, if the linear patterns are attributable to natural processes, they will not demonstrate any cultural relationships. Specifically, they will be reflective of the ongoing geological or erosional processes that continue to occur in the area today.

2. If the adaptive strategy to the rainforest environment was similar throughout all phases of occupation,

> then the archeological remains will be similar through time. Specifically, if the ceramic and lithic traditions are similar through time, then the characteristics of site location will be similar through time. These characteristics include elevation, slope, soil, aspect, distance to water, and life zones.
>
> Conversely, if there was a change in the adaptive strategy to the rainforest environment, then there will be a change in the archeological materials. Specifically, if the ceramic and lithic traditions change in order to adjust to a new adaptive strategy (i.e. hunting and gathering to agriculture), then the variables of site location will also change.

The hypotheses were tested using the information that comes from remote sensing analysis, field survey, and excavation. The first hypothesis investigated the location of prehistoric paths using aerial photography and digital airborne sensor data. The projected path locations were verified through survey and excavation. In this regard some of the techniques were similar to those employed at Chaco Canyon. The pathway network was analyzed to determine the mitigating factors responsible for its arrangement.

The testing of the second hypothesis was assisted by the construction of a Geographic Information System (GIS). The GIS combined several layers of ancillary information with satellite data. These ancillary layers consisted of such information as rainfall, site location, distance from water, elevation, slope, aspect, soil type, and life zones. The GIS was queried to determine those factors that the prehistoric sites share in common. The village site locations were compared throughout all phases of occupation to determine if there was a significant variation in site attributes from one phase to another. It was predicted that if a significant difference in site characteristics were determined, then this would be reflected in the ceramic and lithic data.

The available remotely sensed data over the Arenal area included:

1) Four bands of MSS satellite data (April 1984);

2) Seven bands of TM satellite data (April 1985);

3) Hasselblad color aerial photography (October 1984; April 1985).

4. Lidar (laser profiler) data (October 1984);

5. L-band 30 and 10 meter radar data; four polarizations(March 1985);

6. CIR photography (October 1984; March 1984; Feb. 1988);

7. TIMS 5 meter resolution (Feb. 1988).

Also included in the data inventory were digitized 1:50,000 scale topographic maps of ancillary information such as soils, elevation, slope, aspect, precipitation, life zones, etc., which were used as input into a GIS. From this composite database of information, and in conjuction with the field and laboratory results conducted since 1984, a new insight was gained regarding prehistoric adaptation and social integration in a tropical rainforest environment.

DATA ANALYSIS/COMPUTER FACILITIES

Digital image analysis was conducted at the Earth Resources Laboratory located at the Stennis Space Center, SSC, Mississippi. Data analysis was conducted on a Perkin-Elmer 3242 main frame computer using the Earth Resources Laboratory Applications Software (ELAS). ELAS is a FORTRAN-based software system designed for advanced remote sensing analysis. Some of the extensive hardware facilities include: 16 mb of solid state four way interleaved main frame memory, 5.8 gigabytes of random access disc storage, floating point array processor, pulse code modulated (PCM) front end for reading and decommutating aircraft data, two 800/1600 and two 6250 BPI tape drives, 22 terminals, 512 X 512 32 bit Comtal image display processors, four line printers, one Eikonix model 78/99 automated digitizing system and one Versatec model 8222A plotter.

SUMMARY/SIGNIFICANCE OF THE RESEARCH

People have left a permanent record of their actions upon the environment which often can be seen through remote sensing technology. While remote sensing has been used by archeologists since the turn of the century, generally in the form of aerial photography, it is only recently that attempts have been made to use the sophisticated digital airborne/satellite technology of the last two decades. As cultural features are destroyed at an unprecendented pace as we enter the 1990's, the use of remote sensing technology becomes more crucial, and perhaps even mandatory, for the future of anthropological research.

Alteration of the surface environment by cultural activity has been occurring for thousands of years. The degree of this modification is often related to the level of cultural development. The adaptive strategies of hunter-gatherers has less impact upon the environment than the agricultural practices of industrialized nations, yet both cultural impacts are apparent on both landscapes. The spatial dimensions of these changes are also detectable, ranging from surface mining to backyard swimming pools in contemporary societies, or raised-fields systems to individual burial mounds in prehistoric societies. Despite the rapid changes that are taking place upon the earth's surface in the 1980's, the rural landscape is the principal scene registered today on most remotely sensed images and records the contemporary and prehistoric impacts within it. In addition, the repetitive acquisition of remote sensing technology with Landsat satellites since 1972 has created an archive for future investigations.

There is great diversity in the ways past human activities have altered the landscape. The major processes center around the extraction and deposition of materials. The construction of earthworks, stone structures, raised fields, irrigation systems, transportation routes, and cemeteries, as well as agricultural and quarrying activities have often left a physical "fingerprint" which can be detected through remote sensing. No matter which analytical technique is used to detect this change, the nature of the change remains the same: human adaptation to the natural and cultural environment.

Prehistoric alterations may manifest themselves as differences in soil moisture or composition, vegetation, or shadow patterns. They may take the form of straight or curved lines, geometric patterns, or anomalous shapes that contrast with the natural environment. They may be readily apparent in the imagery or require sophisticated computer-implemented analyses. They may be detected in individual regions of the electromagnetic spectrum, (i.e. ultraviolet, visible, infrared, thermal-infrared, and microwave), or they may require multispectral combinations. If an archeologist understands the dynamics and mechanics of remote sensing, he can detect the impact of prehistoric societies upon the ancient landscape.

The rapid acceleration of remote sensing technology and computer hardware/software capability, however, has created some concern about the realistic limits of its anthropological and archeological applications. Using the most advanced remote sensing data available, as well as the most proven mathematical/statistical techniques, this study has demonstrated the potential of remote sensing technology in two diverse, environmental and cultural areas: Chaco Canyon, New Mexico and Arenal, Costa Rica. It is hoped that this generalist approach will provide the necessary fundamentals which can serve as a baseline for other researchers as they incorporate remote sensing technology into more complex and regionally oriented research designs.

CHAPTER 2

HISTORY OF REMOTE SENSING IN ARCHEOLOGICAL RESEARCH

EARLY DEVELOPMENTS

> Some 5000 to 6000 years of history are known through surviving written records, but this represents less than one percent of the time human beings have existed on earth. Knowledge of the greatest part of human heritage can only be obtained by the discovery and careful excavation of sites and ancient cultures. Archeological photographs serve as tools of discovery and as scientific records of the process and product of such investigations.
>
> The Encyclopedia of Photography, 1984

The development of remote sensing in archeology can be traced to the evolution and overlap of three fields: photography, aviation, and archeology. Photography can be traced back to 1839 when Louis J.M. Daguerre, William Talbot, and Nicephore Niepce, invented a process for creating portraits called daguerreotypy. Later in the same year a French physicist, D.F. Arago, lectured to the French Academy in which he discussed the potential applications of this process (Deuel 1969).

While the use of aerial photography was first proposed during the next year in 1840, it was not until 1848 that the first aerial photograph was taken from a balloon above Bievre, France, by Gaspard Felix Tournachon. At this time dageurreotypy had evolved to the art of photography as new lenses and plates of silver chloride were developed. The first aerial photograph in the Americas was taken by James Wallace Black in 1850 from a balloon 1,197 feet above Boston (Avery 1968).

Aviation developed significantly during the American Civil War when Union and Confederate balloon corps were formed to scout military maneuvers. General McClellan is said to have employed balloon photography to record Confederate positions in Virginia (Avery 1968). Contrary to popular belief, however, there is no evidence which demonstrates that either side ever acquired aerial photographs (Newhall 1969). Kite aerial platforms were employed during the 1880's, but were ineffective due to their instability and limitations in weight-bearing. Simultaneously, however, Major Elsdale of the British Royal Engineers Balloon Establishment had developed a successful technique for self-releasing cameras in unmanned balloons to photograph the English countryside (Deuel 1969).

Archeology was developing into a scientific discipline by the turn of the century as emphasis shifted from the prehistoric art objects themselves to the economic and social systems of the people who had created the objects (Willey and Sabloff 1980). During the 1890's, for instance, the English General Pitt-Rivers urged archeologists to become more systematic in their study of ancient cultures and even suggested the use of aerial photographs (Deuel 1969). It is from these simultaneous developments in photography, aviation, and archeology that archeological remote sensing reconnaissance originated.

The first remote sensing application in archeology occurred in 1891 when a British archeologist, Lieutenant C.F. Close, used a camera attached to an unmanned balloon to photograph the ancient ruins near Agra, India (Deuel 1969). The event, however, went unnoticed in the scientific community due to the poor quality of the photography that resulted and the fact that it was not published.

In 1907, a British engineer named J.E. Capper presented two photographs to the British Society of Antiquarians. These photographs were of the ancient megalithic structure of Stonehenge taken from an unmanned balloon. The photographs were published later in the same year in Archaeologia (Capper 1907). The photographs originally had been taken by Lieutenant P.H. Sharpe in 1906 of the English countryside and incidentally included Stonehenge. While the photographs did not reveal any new information that could not be seen from ground level, they created a large amount of excitement due to the perspective they provided (Deuel 1969). For the first time scholars could see all of Stonehenge, which covers over 2 acres, at once. In short, the significance of the event was not in the information that was provided within the photographs, but the realization of the potential of aerial photography for archeology.

The first intentional application of aerial photography to archeological research occurred in 1908. Italian army engineers photographed the ancient Romans ruins of the port of Ostia (Deuel 1969). Sir Henry Wellcome, an amateur English archeologist, used cameras and box kites to photograph and document his excavations in the Anglo-Egyptian Sudan between 1911-1914 (Ebert and Lyons 1983). And finally, Sir Leonard Wooley, T.E. Lawrence, and Captain S.F. Newcombe used an aircraft for archeological reconnaissance during the 1914 Sinai expedition (Garnett 1938; Knightley and Simpson 1971).

The airplane was first used as a camera platform in 1909 when Wilbur Wright, working with Italian Naval Officers, took an aerial motion picture over Italy (Ambrosia and Whiteford 1983). The airplane provided greater stability and control in acquiring photographic information. World War I accelerated the development of sophisticated camera systems, sensitive films, and photographic techniques by the English, French, and Germans (Rowe 1953). Perhaps more significant for archeology, however, was the use of archeologists as pilots, map makers, aerial observers, and photographers. Archeology and remote sensing were developing simultaneously and archeologists, who had used remote sensing to the greatest extent, were the foremost experts in aerial photography. They were also prime candidates for military drafts and reconnaissance positions during World War I (Carstens et al. 1983; Deuel 1969).

Like archeologists, army pilots and military personnel were also an important part of the early development of aerial photography. The interaction between them became more intense during World War I, but exchange between archeologists and military personnel had existed prior to the War. Even Capper's (1907) original article in Archaeologia was entitled, "PHOTOGRAPHS OF STONEHENGE, AS SEEN FROM A WAR BALLOON."

ARCHEOLOGICAL RECONNAISSANCE IN EUROPE

Several documented examples of military-archeological reconnaissance during World War I are known. British Lieutenant-Colonel G.A. Beazeley conducted several flights over the Tigris-Euphrates plain recording military and archeological information. While on a foray into enemy territory during May of 1918, Beazeley was shot down and captured. His experiences were published after the war in the "Geographical Journal" of 1919 and 1920 (Deuel 1969). O.G.S. Crawford, the foremost contributor to aerial archeology, was also shot down by the Germans while photographing military and archeological information. It was during his many months in captivity that Crawford pondered over the many archeological questions that had aroused his interest before and during the war (Deuel 1969). Finally, Oxford archeologist, John L. Myres, directed the bombardment of the house of German archeologist, Theodor Wiegand, at Didyma from a plane. The purpose seems to have been to divert the Allied fire to Wiegand's house rather than the adjacent Apollo temple where excavations were being conducted (Watzinger 1944).

The close association between archeology and aerial photography, which began for military purposes during World War I, continued through World War II and beyond. During World War II, archeologists were again drafted for military photographic interpretation due to their scientific expertise in the area of aerial photography. Regretfully, the suspicions surrounding the true objectives or hidden agendas of archeologists have followed them across the years into the 1980's as they conduct satellite and aircraft remote sensing analysis in foreign nations. While this is a frustrating situation, it is one to which every archeologist should be sensitive when conducting remote sensing research.

Schorr (1974) states that British archeologists working as photointerpreters during World War I noticed a number of unique properties in the aerial photographs that could be used for site discovery and survey. These properties were described as "features of long-obliterated structures in the terrain, soil formations, and vegetative cover...that are either invisible or easily overlooked in surface reconnaissance." They also stated that "some features, invisible to the eye at any angle, may be recorded for study by the use of special combinations of films and light filters, and overlapping photographs produce stereoscopic vision so that even the slightest undulation produced by surface remains may be accurately measured and described."

The end of World War I began the peacetime applications of aerial photography in several disciplines including archeology. It also initiated a debate in archeology as to whether the British, French, or Germans had been first to establish the use of aerial archeology. What can be stated with certainty is that Wiegand, who had been excavating at Miletus, was in charge of a special unit which was tasked to identify historical monuments using aerial photography in the Near East in order to preserve and protect them throughout the War (Wiegand 1920). This conservation activity was the first known use of remote sensing in cultural resource management. Later, British archeologists supplemented and complemented the German research through surface survey and scientific excavation (Beazeley 1919;1920).

O.G.S. CRAWFORD

The principal figure in the early history of aerial archeological research is the English scientist, O.G.S. Crawford (Figure 2-1). Crawford had served as a

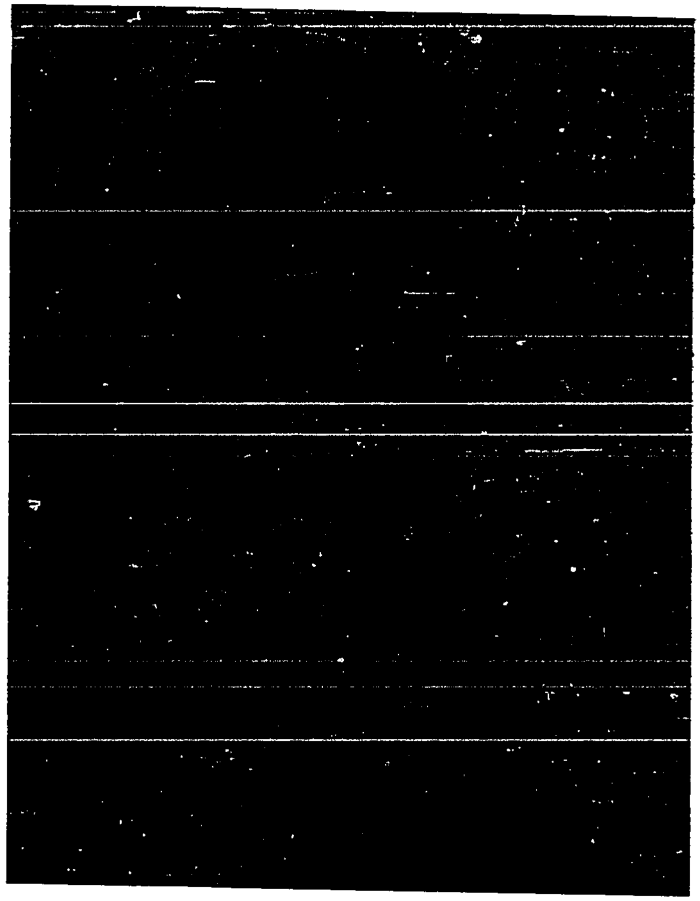


Figure 2-1. Osbert Guy Stanhope Crawford (1886-1957) who laid down the basic principles that govern aerial archeology. From (Deuel 1969:78).

member of the Royal Flying Corps of England in France and Belguim during World War I. Beginning in 1922 Crawford dedicated the remainder of his life toward the application of remote sensing to archeology and cultural resource management. The discipline of archeology, as well as all of aerial photography in general, has been indebted to Crawford's efforts ever since. Crawford established the scientific basis for the interpretation of aerial photography. Educated in geography, archeology, photography, and map making, Crawford discovered that archeological research could be enhanced through understanding the geographic relationships between a culture and the surrounding environment.

While others had recognized that human activity leaves lasting fingerprints upon the earth's surface which can be seen from the air, Crawford was the first to grasp the real importance of the subject. The basis for his aerial archeological interpretation centers around ground signatures which he identifies as shadow marks, crop marks, and soil marks. Crawford also identified the factors which affected aerial photography such as sun angle, lighting, time of day, season, meteorological conditions, atmospheric pressure, camera angle, film type, and skill of the pilot, photographer, and interpreter. In addition he emphasized the need that ground truth information be correlated with aerial photography in order to achieve scientific success (Deuel 1969). These same factors are present even in the most advanced digital satellite technology of the 1980's.

Crawford published the results of his projects extensively in Antiquity, an archeological journal that he founded and edited until his death in 1957. His energetic work demonstrated that aerial reconnaissance could make archeological fieldwork more economical, assist in environmental site reconstructions, and locate cultural features which were not visible from ground level. With assistance from Alexander Keiller, he produced a classic in archeological remote sensing research with his Wessex From The Air (1928). This book emphasized that aerial research should be used to establish scientific techniques for archeological research rather than be used merely to produce visually spectacular results. In this era of high orbital satellite technology and sophisticated computer intelligence it is important that we continue to adhere to Crawford's proven wisdom.

DEVELOPMENTS IN THE U.S.

American interests in aerial archeological reconnaissance lagged behind the dynamic developments in Europe. The first American application of archeological remote sensing research was conducted under the direction of David I. Bushnell (1922) at Cahokia mounds near St. Louis, Missouri, in 1921 by Army pilots H.R. Wells and A.C. McKinley (Rowe 1953). A few months later, this flight was followed by another over Cahokia by Lieutenant George Goddard and Sergeant Ramey (Goddard 1969; Hall 1968) in conjunction with Warren King Moorehead's excavations (1922, 1928) at the site. Unfortunately, however, the published sources at the time indicate that none of the investigators were aware of what the others were doing (Fowler 1977). This lack of communication lessened not only the archeological interpretations but also the development of aerial photographic techniques. In the American Southwest, Army pilots also acquired photography over the Gila and Salt Rivers in the late twenties for the study of prehistoric canals by the Smithsonian Institution (Deuel 1969).

It was Charles Lindbergh who demonstrated the potential use of aerial reconnaissance to American archeologists. While employed by Pan American Airways to establish new air routes in the Caribbean, Lindbergh acquired aerial photographs of Middle American sites such as Tikal, Tulum, and Chichen Itza. These photographs also revealed poorly known sites such as Coba, Rio Bec, and Yaxha as well as a complex of unknown associated features such as mounds, causeways, and temples.

In the summer of 1929, Lindbergh and his wife Anne Morrow acquired photography of certain northern portions of New Mexico and Arizona (Figures 2-2 and 2-3). They flew these photographic missions in conjunction with Harvard archeologist A.V. Kidder who was conducting excavations at Pecos. Lindbergh recorded "hunting for marks of early civilization.... From the air we could see dimly but definitely the square or rectangular lines on the earth that marked where walls had stood..." (Fagan 1985). The oblique photos revealed a number of previously unknown Anasazi pueblos and archeological features such as the cliff houses under the rimrocks of Canyon de Chelley and Canyon del Muerto (Deuel 1969). The Chaco Canyon photos recorded prehistoric roadways which were not noticed in the photography until 1971, and which are the basis for the thermal imaging analysis in Chaco Canyon discussed in Chapter 4. From the archive of over 100 photographs, Kidder was able to recognize the relationship between settlements and topographical

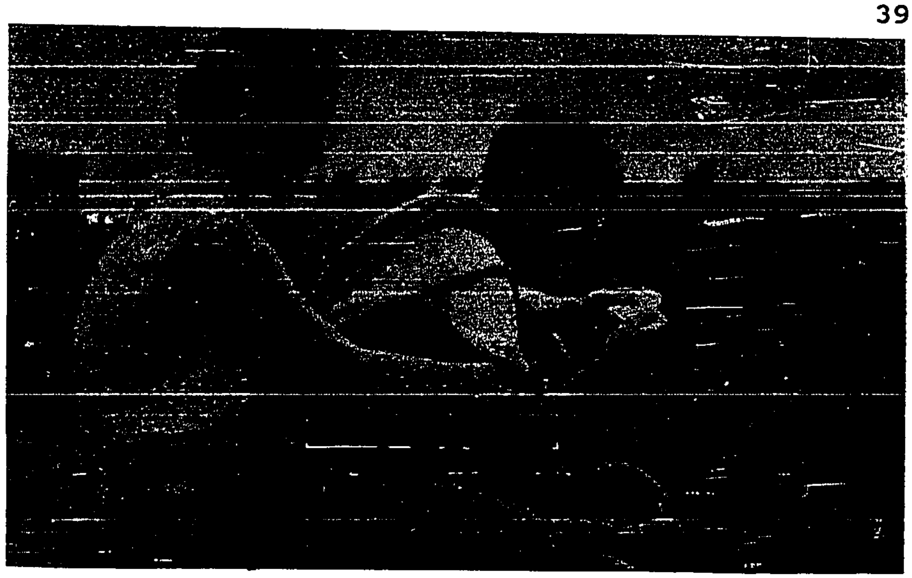


Figure 2-2. Colonel Charles and Anne Morrow Lindbergh examining aerial photographs of a cliff dwelling in the American Southwest in 1929. From (Deuel 1969:238).

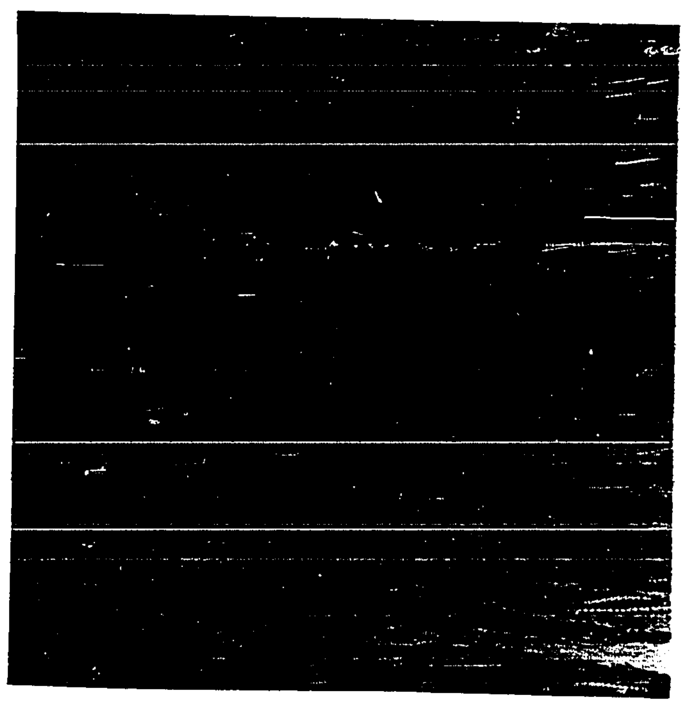


Figure 2-3. Aerial photograph taken by Charles Lindbergh in 1929 showing Pueblo Bonito in the canyon bottom and the North Mesa in the background.

features. Kidder reported:

> Some of the photographs...show clearly the relation that existed in ancient times between water supply, land available for farming, and easily defensible house sites, matters which are of great importance to scientists as they try to picture the conditions under which prehistoric peoples lived (Deuel 1969).

In October of the same year (1929) the Lindberghs teamed up again with Kidder to conduct aerial reconnaissance in Yucatan. They were joined by Dr. Oliver H. Ricketson, an expert on the Peten area. Kidder actually flew with Lindbergh for hundreds of miles recording the location of known and unknown sites in his meticulous notes. Suprisingly, however, very little photography was gathered. The results of this expedition are recorded in "An Archeological Reconnaissance by Air In Central America" (Ricketson and Kidder 1930). Kidder did, however, attain an insight that would have made an important contribution to remote sensing had it been followed up in a scientific manner. Kidder was able to find sites by discriminating different vegetation species. He noticed, for instance, that sapote trees grew in greater profusion near ancient mounds. From the air Kidder could distinguish different trees and brush which were indicators of archeological features. As is discussed later in this chapter, this technique was eventually employed by W. Frank Miller in 1972 and is the basis for much archeological feature detection in digital remote sensing analysis.

The pioneering flights of Lindbergh and Kidder were followed by hundreds of flights. During the 1930's aerial photography was being used by archeologists from universities, museums, and institutions all over the world. Dache M. Reeves, of the U.S. Army Air Service, photographed earth-work sites in the Ohio and Mississippi Valleys, including Marksville, Louisiana, Newark, Ohio, and Cahokia, Illinois (Reeves 1936). These photographs are in the archives of the U.S. National Museum. In one of the first American salvage projects, Smithsonian Institution River Basin Surveys Program photographers recorded sites in the Missouri Basin in response to dam construction which subsequently flooded large tracts of land (Ebert and Lyons 1983).

Aerial photography was especially valuable in areas where ground conditions precluded adequate survey by foot such as the tropical forests and highland deserts. Lt. George R. Johnson recorded many Peruvian archeological sites while working with the Peruvian Naval Service (Johnson and Platt 1930). The Shippee-Johnson expedition (Figure 2-4) that followed shortly thereafter discovered the "Great Wall of Peru" (Figure 2-5) in a

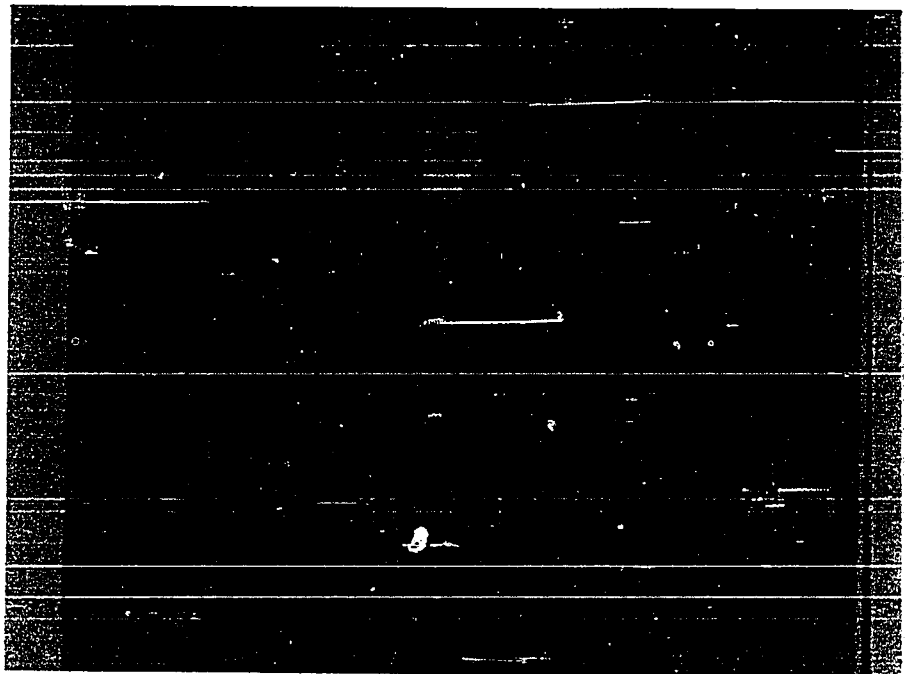


Figure 2-4. Robert Shippee and Lieutenant George Johnson who led an eight-month aerial survey of Peru in 1931. From (Deuel 1969:239).

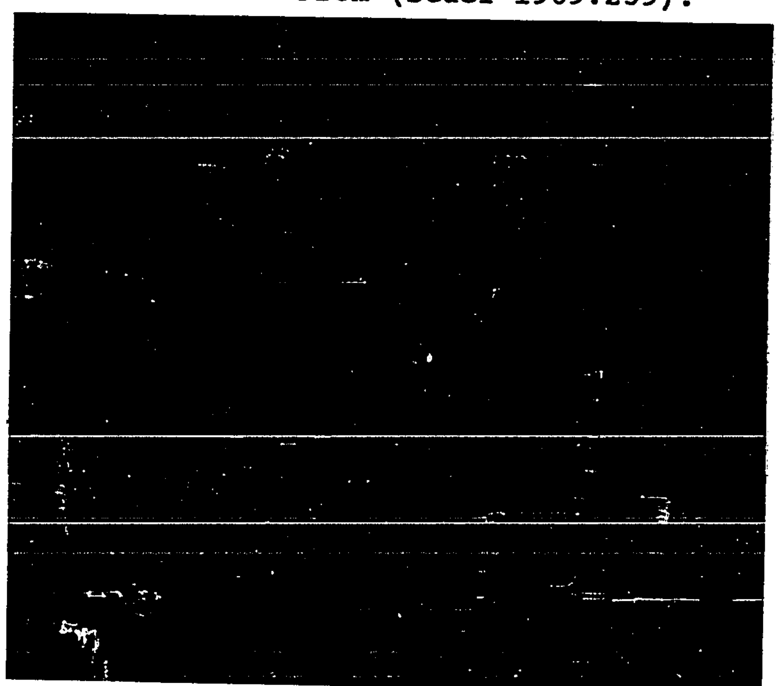


Figure 2-5. A section of the "Great Wall" of Peru which is of pre-Inca origin and runs through the Andean foothills for over 40 miles. From (Deuel 1969:240).

coastal desert environment near Chimbote from the air (Shippee 1933).

DEVELOPMENTS FROM 1939-1972

World War II brought on greater developments in aerial photography. Infrared film was developed to detect camouflaged targets which had been made to look like natural vegetation. This development is significant since it was the first effort to see information slightly beyond the range of human vision. Color infrared film (CIR) was not used in archeological research until the 1950's, when Bernard Ediene demonstrated its capability in Normandy, France to detect buried Roman features that were not discernible on black and white photography (Ediene 1956). Cameron (1958) also demonstrated the advantages of CIR over conventional photography at a number of archeological sites in Nova Scotia. He was able, for instance, to show that a reconstructed wall was incorrectly located (Tartaglia 1977).

After World War II, many countries, particularly the United States, used aerial photography for the topographic photogrammetric mapping of large regions (Ebert and Lyons 1983). The photography was generally acquired in 9" X 9" overlapping sheets that could be used for stereoscopic viewing. The photography was inexpensively available to the general public and archeologists have employed it in their research around the world for years. Even today, this photography can be a valuable low-cost tool for archeological research.

Elmer Harp, who successfully employed both black and white and CIR photography for detecting archeological sites in the Arctic, concluded that while CIR produced higher resolution, contrast, and detail, it did not provide him with any significant new information (Harp 1958; 1968; 1977). This is not surprising since CIR is sensitive to changes in vegetation and seasonality can affect its use. In North Carolina, the use of CIR photography successfully located a former Indian trail, drainage channel, village, and cemetery (Wray 1971), while in Arizona CIR photography located previously unknown prehistoric agricultural fields near Sunset Crater (Schaber and Gumerman 1969; Tartaglia 1977). As will be discussed later, CIR photography acquired in 1984 was essential in the detection of prehistoric footpaths in the tropical regions of Costa Rica (Sheets and Sever n.d.).

An excellent example of the utility of CIR photography is best demonstrated in the Tehuacan Valley. Here, Kent Flannery collected detailed information for reconstructing the microenvironments (Flannery 1968). These zones were mapped in a short period of time by Gumerman and Neely (1972). The research revealed that CIR can be as important in recognizing and mapping ecological zones as in the detection of archeological features; hence encouraging multidisciplinary ecological research.

Since World War II, a broad range of aerial applications in archeology have transpired throughout the world. While it is impractical to list them all I will simply present some of the highlights. A classic application was performed by Gordon Willey (1953) in the Viru Valley of northern coastal Peru. Employing a Peruvian Air Force photographic mosaic, Willey was able to identify many archeological features and reconstruct a story of changing settlement patterns over thousands of years (Willey 1959). Middle Age sites in Europe have also been successfully detected and analyzed (Bowen 1962; Schellart 1962; Chevallier 1962; St. Joseph 1966). Strandberg (1974) demonstrated the application of remote sensing to historical archeology. Numerous studies have addressed the topic of prehistoric roads in Chaco Canyon (Lyons 1976; Lyons and Avery 1977; Lyons and Hitchcock

1977; Lyons and Ebert 1978; Lyons and Mathien 1980; Obenauf 1980; Lister and Lister 1981; and the Bureau of Land Management 1983;1987).

Perhaps the major thrust of archeological remote sensing research during the sixties and seventies was applied to raised field systems. These agricultural features, with their associated causeways, were originally discovered in Bolivia and Colombia (Parsons and Denevan 1967). These features are often difficult to perceive from ground level and can only be appreciated from aerial reconnaissance. Raised field systems have also been detected in Yucatan as well as in Belize (Turner 1974). Similar features have been located in the Valley of Mexico, the Sabana de Bogota in Colombia, and along Lake Titicaca in Peru (Ebert and Lyons 1983). Broadbent (1968) has discussed the striking similarities of the arrangement and design of both the highland and lowland systems.

ARCHEOLOGY ENTERS THE SPACE AGE

The launch of NASA's first Landsat satellite on July 23, 1972, signalled the beginning of a new digital era in archeological remote sensing research. The sensors onboard the satellite provided photographic-like prints in four spectral bands which could also be electronically processed to produce false-color composites. The chemical process of optical photography was now replaced with the computer-generated images of digital data. This digital process was originally created for space and planetary exploration by NASA in the mid 1960's. Even with the launch of Landsat 1, very few people realized the potential of this new technology. In retrospect, it has changed the nature of remote sensing analysis. While the disciplines of geography, geology, forestry, agriculture, soil science, and hydrology have pursued its capability intensively, only a few pioneering works have been attempted in archeology. Nevertheless, it is a tool which is quickly expanding into archeological research designs as better spatial resolution and less expensive computer capability becomes available.

The theoretical framework, regional analyses, and ecological approaches within which the new remote sensing methodology could be applied had been evolving in the discipline of archeology for some time. Certainly the "new archeology" Binford (1964) and the use of statistics (Thomas 1969) opened new doors for archeological research and set the stage for the adoption of remote sensing technology. New concepts in archeology such as "interaction spheres" (Caldwell 1964) and systems theory (Flannery 1968) could take immediate advantage of the new technology if it performed to expectation. The visionary research and new approaches to the study of ancient human interaction with the natural environment could profit from the new technology by conducting analyses in a rapid, accurate, and cost-effective manner. MacNeish's studies in the origin of maize (1958,1975) could take advantage of the same data that Flannery (1968,1973) might use in his studies of systems and the dietary implications of hunting and farming in the Tehuacan Valley. In short, there was an evolution going on in archeology in the recovery, documentation, analysis, and interpretation of data, and archeology was developing new approaches and acquiring additional skills to test hypotheses that initially seemed almost presumptuous in scope.

The potential of satellite technology for archeological and ethnographic research was immediately presented in 1972 (Lyons, Inglis, and Hitchcock). It was forecasted that the new space technology would provide information both on human activities upon the landscape as well as the nature of the environmental background. The authors postulated that "space-derived data held great potential for temporal and regional studies because of their quantitative, synoptic, and repetitive nature" (Lyons and Ebert 1983).

A number of archeological and ethnographic applications of satellite technology were initiated in the 1970's. Many of these projects were not completed; others had varying degrees of success. There were a number of factors which contributed to this situation. First, remote sensing itself was in its infancy. The statistical and computer processes which were being developed for digital analysis under the NASA program were in a basic research mode. Few archeologists or ethnographers had the mathematical background or training to understand the nature of digital analysis. The 80-meter spatial limitations of the satellite were inadequate for archeologists who were making rapid advancements in the application of aerial photography and hand-held photographs taken by astronauts in space. Ethnographers were frustrated by the inability to acquire cloud free data over their study area or acquire funding to perform the necessary large-scale ground truth activities. And the NASA program concentrated its funding toward applications in agriculture, forestry, and geography. In fact, most university remote sensing laboratories today are affiliated with the geography departments. Archeology programs which allocated their limited funds in the new technology saw little return for their investment. The collective effect of these and many more contributing factors resulted in making anthropological researchers skeptical of the new technology. As shall be shown, however, this skepticism is being replaced with a new confidence and enthusiasm as a result of the recent advancements in remote sensing technology as well as a new commitment by the anthropological community.

One of the first successful applications of Landsat technology in anthropological research was the pioneering work of Priscilla Reining (1973; 1974a; 1974b; 1978). Reining demonstrated that Landsat, aerial photography, fieldwork, and sampling strategies could be combined to produce information regarding carrying capacity, population density, land use, resources, crop stress, agricultural potential, and exchange. Her study areas included the agrarian systems of the Niger and Upper Volta as well as the population and migration practices of the Sonrai in West Africa. The same type of research was conducted for the Dogon in Mali during the Sahelian drought by Rosalie Fanale (1974). Cultural and human ecology research that used Landsat was successfuly applied in Kenya by Francis Conant (1976; Conant and Cary

1977). Anthropology will forever be indebted to these researchers for their vision and enthusiasm in the application of digital remote sensing analysis.

Archeology, meanwhile, was encountering major problems in the application of Landsat imagery. Most of the features of interest, ie. prehistoric roads, canals, campsites, structures, and walls, simply were too small to be detected in the Landsat imagery. While airborne sensors were available for overflights, the cost was often prohibitive. Even when airborne imagery was acquired, the limitations of the sensor sensitiviy, computer hardware/software, and data analysis expertise of the investigator precluded successful results. While Landsat data were sufficient for large-scale regional analysis, archeologists, in general, turned back to photography. A notable exception, however, was the Chaco Canyon Remote Sensing Center.

THE CHACO CENTER

The Chaco Center was a joint research project of the National Park Service and the University of New Mexico. For approximately a decade, this center was instrumental in encouraging remote sensing research in both optical and digital formats. Through the integration of many projects which addressed non-destructive methods of archeological exploration, survey, and analysis, a framework was developed for future research. Many of the unheralded accomplishments of this center include: optical-digital comparison, identification of spectral and spatial scanner capabilities, atmospheric correction requirements, photogrammetric mapping, data rectification, ground based instrumentation, and estimates of operational costs. The results of this Center served as a baseline for other remote sensing projects. As will be seen, the thermal analysis of prehistoric roadways in Chaco Canyon by NASA was inspired by the Center's research (Lyons and Avery 1977). The vision of this Center cannot be overlooked, as the researchers there were ahead of their time. Unfortunately, the limitiations of the remote sensing instruments that were available to them did not provide the spectacular results that would have made a dramatic impact on archeology.

AERIAL SURVEY TECHNIQUES

An important approach to archeological remote sensing analysis was conducted by W. Frank Miller. In

1972, Miller developed an aerial survey technique, based on an environmental model inspired by Holdridge (1966), that discriminated Early Woodland/Early Mississippian settlements in humid, forested regions. Thirteen terrain and landform hypotheses, and eleven supplementary soil and vegetative hypotheses served as the basis for this model (Miller 1981). Testing of this model resulted in the prediction and identification of 52 of 62 possible site locations for an accuracy of 84%.

In another study, Miller modified the model to predict the location of three extinct historical towns along the Tombigbee River in Mississippi which were occupied between 1834-1856. These three towns, Barton, Colbert, and Vinton, were successfully detected by noting the effects of human activity upon the environment. The major modifications were found to be the geometric arrangement of old-growth hardwood and cedar trees, linear arrangements indicating roads or house approaches, and the existence of specific ornamentals which were introduced into the environment. Miller demonstrated, for example, that pine and sweetgum, which normally account for 6.8% of the natural stand, changed to 62% of the modified stand, clearly indicating the effects of historic land clearing. Miller was able to identify a number of historic features such as single house locations, roads, fence lines, and historic agricultural fields. Both the prehistoric and historic studies are documented in his "Remote Sensing Techniques in Historical Site Discrimination" (Miller 1981).

Both of Miller's projects called for a combination of photography and digital data. Unfortunately, NASA was unable to gather the digital data and thus Miller's results are based solely on black and white and CIR photography. Nevertheless, Miller was in fact finding archeological sites through "signatures" upon the environment. Digital data would have only served to enhance the results of his research. Miller, a forester, was approaching site discrimination differently than were archeologists who were using Crawford's approach in finding soil marks, crop marks, and shadow marks in the optical and digital data. Miller was employing the same technique first discovered by Kidder in 1930 and, unfortunately, used by looters of sites for many decades, whereby vegetation species (such as Ramon tree concentrations as site indicators) are used as discriminants of archeological features. Eventually, both approaches would be employed in remote sensing analysis. Yet, the importance of Miller's research can be appreciated when compared to the following one conducted in Western Kentucky.

THE JACKSON PURCHASE PROJECT

This project demonstrated an effective method for locating archeological sites in aerial photography using techniques similar to those employed by Crawford. A discussion of the procedure was published in the article, "Using Remote Sensing In A Predictive Archaeological Model: The Jackson Purchase Region, Kentucky" (Carstens et al. 1982). The study showed that aerial photography could improve the accuracy attained through traditional archeological ground survey. While Miller's studies centered upon the identification of geomorphic regions and vegetation patterns, this study addressed site-specific identificaton. As a result of the success of the Kentucky project, I contracted part of my NASA archeological funds to the same research team to conduct similar research over the lower Ohio River and middle Mississippi River valleys of western Kentucky in 1982. Thematic Mapper Simulator (TMS) aircraft data were acquired on April 11, 1982 at 10 and 30 meter resolutions. The primary purpose of the project was to identify spectral signatures in the digital data such as mounds, earthworks, and villages that were distinctly archeological. Although the CIR photography was once again successful, no distinct archeological signatures were developed in the digital data due to the complexity of land cover and land-use patterns (Mid-America Remote Sensing Center 1983). As outlined in the report, several factors in data acquisition and data analysis precluded successful signature detection for archeological features.

AERIAL PHOTOGRAPHY AND DIGITAL IMAGERY

An important application of remote sensing technology is Aulis Lind's (1981) "Applications of Aircraft and Satellite Data for the Study of Archaeology and Environment, Mekong Delta, Vitenam." Using the large volume of aerial photography gathered from the Vietnam conflict, Lind was able to detect ancient canals and settlements. She used Landsat data in conjunction with the aerial photography to understand the pattern of geomorphic changes of the delta environment as they related to archeological features. A similar environmental and lithological approach was used in Egypt by E.M. Shazly (1983). In his "Space Borne Imagery Interpretation of Mega Features Related to Egyptian Archeology", Shazly interpreted 4 bands of Landsat MSS data to isolate drainage systems, water points, playas, plateau surfaces, etc. He used this data to demonstrate that the alternation of pluvial and dry periods was an important factor in both prehistoric and contemporary technological and socio-political development.

Archeologists continued to use aerial photography for site-specific analysis while satellite imagery was relegated to large scale analysis. This can be further documented in the research conducted in France by Carole Crumley and Scott Madry (1983). Archeologists continued to be frustrated by the fact that they could make little progress using satellite imagery alone. Nevertheless, they continued to recognize the "potential" of satellite imagery. E. Barisano and B. Helly (1985) reflect the position of most archeologists conducting satellite research in the conclusion of their "Remote Sensing and Archaeological Research in Thessaly (Greece); New Prospects in 'Archaeological' Landscape". In this paper they end with the statement, "The results obtained, as concerned handling of satellite images and aerial photos...are still incomplete but full of promise."

RADAR DATA

While some archeologists labored with the spectral and spatial limitations of the available satellite data, others investigated the use of airborne radar (microwave) data. The microwave frequencies of radar systems have some unique characteristics when compared to the spectral frequencies of satellite systems. Radar is an active system, i.e., it illuminates the surface with its own energy, and it has a cloud penetration capability. In addition, it has the potential of penetrating vegetation when used at a steep incidence as well as detecting vegetational topographic differences (Henderson and Merchant 1983; Lillesand and Kiefer 1979). These differences are due to variations in soil composition and moisture that can result from buried archeological features. A buried wall, for instance, will often retard surface vegetation growth while a refuse pit will generally accelerate it. The disadvantage of radar imagery is that it is extremely expensive and requires sophisticated analysis when compared to satellite imagery.

An application of NASA radar imagery for archeology was reported in the Science article "Radar Mapping, Archeology, and Ancient Maya Land Use" (Adams, Brown, and Culbert 1981). Using several different radar flights and aerial photography, this study concluded that radar imagery had detected ancient canals that were once used for intensive cultivation and that the Maya had practiced large-scale intensification in swamplands by the Late Classic period. To say the least, this was dramatic news for archeological remote sensing, and the project attained notable publicity. Not only did the project have respected anthropologists in Adams and Culbert, it also had Brown who was a senior radar scientist from the Jet Propulsion Laboratory in Pasadena, California. The project has been referenced in archeological proposals a number of times and facilitated the funding of some of these proposals. There were, however, some immediate disagreements with the Science article which did not surface in the professional literature. I first became aware of them in 1982 when talking with personnel familiar with the project who were not happy with the archeological interpretations. The problem centers around the fact that image analysis is a subjective process and can be heavily biased by the disposition of the interpreter.

Only recently has the Science article been criticized (Dahlin and Pope n.d.). Some of the factors which seem to indicate that the Adams' radar patterns do not represent canals include: 1) none of the patterns have been verified through ground surveys, excavations, or aerial photography, 2) the radar patterns are larger in scale than the verified canals, 3) Dahlin and Pope were unable to duplicate the results using the image enhancement techniques employed by Adams, 4) confirmed canals are found only in freshwater habitats whereas the published maps (Adams et al., 1981) show that they transect many habitats including upland and off-shore habitats, and 5) the spatial resolution of the airborne radar is inadequate to map the small canals that comprise the verified networks (Dahlin and Pope n.d.).

SHUTTLE IMAGING RADAR

A major development for radar applications in archeological analysis occurred as a result of the Shuttle Imaging Radar (SIR) flight on 12 November 1981 at 30 meter resolution (Elachi et al. 1982). This L-band radar system penetrated the sands of the Sudanese desert to reveal subterranean river valleys. Potential habitable zones were detected in the radar imagery and revealed how savanna-like conditions gradually deteriorated toward the current arid situation. Human occupation was dated in this environment to 200,000 ± 100,000 B.C. The SIR experiment aroused a genuine excitement among earth scientists. A second SIR mission was attempted in 1984 but achieved limited success due to technical problems. A 10 meter SIR mission is scheduled for 1991 and will contain several archeological projects funded by NASA. In 1984, I had secured funding to merge Landsat and SIR data together in order to locate geological strata conducive to finding early hominid remains. The unfortunate death of my co-investigator, Dr. Glynn Isaac, however, terminated the project. Although the merge of radar and Landsat data has not been conducted for archeological research to date, it represents an important potential for archeological research and should not be overlooked.

CONFERENCES ON REMOTE SENSING AND ANTHROPOLOGICAL RESEARCH

As a result of several meetings between the archeological community and NASA, a conference was held at the National Space Technology Laboratories, NSTL, Mississippi on March 1 and 2, 1984. This conference was funded by the National Science Foundation (NSF), NASA, and the National Geographic Society (NGS). Twenty-two leading archeologists working in the Old and New World who represented major anthropological institutions, attended the conference to learn of the new advanced remote sensing technology, computer development, and predictive model capability. Participants identified the most immediate applications of the technology as well as noted potential concerns and mis-use of the technology. The results of the conference were published under the title: <u>Remote Sensing And Archaeology: Potential For The Future</u> (Sever and Wiseman 1985). An outcome of the conference was the selection of a project that would utilize the resources of NASA, NSF, and NGS. This project, under the direction of Dr. Payson Sheets, was concerned with human adaptation in the tropical forests of Costa Rica and is the basis for the remote sensing research in the Arenal area discussed below. The importance of the 1984 conference, however, was that the archeological community gathered together to learn of the current capability, as well as the limitations, of the new technology. Having this baseline understanding of the state-of-the-art technology, the archeological community could proceed with a realistic view of remote sensing research.

As a result of the conference, there was a new impteus in the application of remote sensing technology. J. Wilson Myers, a conference participant who had twenty years experience in aerial photography, had success in attaching a multispectral video camera system to a tethered blimp (Myers et al. 1987). Digital data gathered from a NASA learjet was employed in an archeological study along the Red River Valley (Bennett et al. 1986). And the continued optimism of researchers such as Jim Ebert, who was originally involved with the Chaco Canyon Remote Sensing Center, remained evident when 10 meter French satellite (SPOT) data was used for a cultural resource assessment at Bandelier National Monument, New Mexico (Inglis et al. 1984).

Another signficant conference was held in April, 1987 in Boulder, Colorado on the cultural and ecological applications of remote sensing technology. The goal of the conference was to update ecologically-oriented cultural anthropologists on current and future remote sensing capabilities. The conference allowed the participants to exchange information on their respective research projects and plan future research collaboration. The final report of the conference is published under the title Cultural And Ecological Applications Of Remote Sensing (Shankman et al. 1987).

GEOGRAPHIC INFORMATION SYSTEM (GIS)

While satellite data were inadequate in detecting archeological features the data were a perfect compliment to the advances that were taking place in computerized data base development. A database can be defined as a collection of interrelated information, usually stored on magnetic tape or disk. When a database is constructed in reference to a geographic area, it is called a geographic information system (GIS). A GIS database can include data about the position and attributes of geographic, climatic, ecologic, geologic, edaphic, and cultural features that have been coded as points, lines, areas, or grid cells (pixels). Examples of ancillary data that can be input into a GIS include: elevation, slope, aspect, soil type, distance from water, population, geomorphology, life zones, rainfall, wind direction, and surface cover.

The advantage of a GIS is that it is readily accessible (as opposed to a large number of maps) and can be queried to provide information that is not readily apparent in map form. Thus, relationships can be established between such factors as archeological sites, elevation, and soil type. In short, a GIS serves to establish relationships and facilitate analysis in a quick and cost-effective manner. A useful feature of a GIS is its predictive modeling capabilities. In this era of rapid remote sensing development, GIS technology will play a major role in future archeological research.

One of the first attempts to merge satellite imagery with ancillary data in archeological research was performed along the Appoquinimink River in New Castle County, Delaware (Wells et al. 1981). This study demonstrated that the combination of satellite data with digital terrain data could effectively locate areas that had a high probability of containing prehistoric sites. This project was followed by a more advanced study which used a logistic regression model in an environmental database along the Delaware coastal plain. Once again, the model was successful in the prediction of potential site distribution as well as productive in the mapping of large ecological and environmental zones (Eveleigh and Custer 1985).

Berry (n.d.) deals with the ramifications of GIS technology in "Sampling and Predictive Modeling on Federal Lands." He addresses the expanding body of the "gray literature" in archeology, including unrefereed manuscripts and reports, and notes that predictive modeling approaches are seldom submitted for peer review and that innacurate and simplistic models are nevertheless being employed in federal management programs. Berry points out that the indiscriminant use of these models contain certain liabilities the most notable of which is the implementation of "write-off" policies which eliminate or minimize the need for field work.

Michael Hoffman (1982) demonstrated that remote sensing and archeological GIS information can be extended into the contemporary setting by noting that modern archeological research offers a unique temporal dimension that is lacking in modern-day planning models. Perhaps the most advanced and technically sophisticated representation of GIS application developed to date can be found in the paper: "The Archeologists Workbench: Integrating GIS, Remote Sensing, EDA and Database Management (Farley et al. 1988). Kohler and Parker (1986) discuss the background, logic, and nature of predictive models in "Predictive Models for Archaeological Resource Location."

CONCLUSION

A history has been presented of some of the more important research efforts in the development of remote sensing for archeology, but certainly not all of them. A major problem in a discussion of archeological remote sensing is the fact that a number of research projects remain unpublished and undocumented. This paper demonstrates the application of remote sensing in two archeological areas using the most advanced NASA technology available to date. The remote sensing techniques that have been employed in this study will change as remote sensing continues its evolutionary path in becoming simpler, quicker, and more accurate. However, the basic concepts of remote sensing will never change. Remote sensing, despite the glamour and excitement it currently enjoys, is only a tool; a tool from which to generate data and test hypotheses for the continued development of anthropological knowledge.

CHAPTER 3

FUNDAMENTALS OF REMOTE SENSING

Remote sensing in the broadest sense is the measurement or acquisition of information of an object by a recording device that is not in physical contact with it. Data are recorded by devices which are sensitive to various bands of the electromagnetic spectrum. The human eye can be thought of as a remote sensor since the eye allows us to gather information without physical contact. Instruments such as glasses, telescopes, and camera lenses have extended the range of human vision and consequently enhanced our knowledge of our environment. New remote sensing instrumentation now allows us to see and record information that our unaided eyes cannot see. Through the use of detectors this information is recorded in various parts of the electromagnetic spectrum and by the use of computers this information is brought back to visible light (Table 3-1). A glossary of terms used in remote sensing is listed in Appendix A.

All materials in the universe above absolute zero (-273 degrees C) produce electromagnetic radiation in the

TABLE 3-1

CHARACTERISTICS OF REMOTE SENSORS SYSTEMS

Spectral Regions And Sensor Systems	Approximate Wavelength Interval (Micrometers)	Approximate Spatial Resolution Attainable (Milliradians)	Atmospheric Penetration Capability *	Day-Night Capability	Real-Time Capability
Ultraviolet (Optical - mechanical scanners, image orthicons, and cameras with IR film)	0.01 - 0.4	0.01 - 0.1		Day Only	Yes
Visible (Optical-mechanical scanners, conventional cameras with film, and vidicons)	0.4 - 0.7	0.01 - 0.001	H	Day Only	Generally No
Reflectance IR (Conventional cameras, w/IR sensitive film, solid-state detectors in scanners and radiometers)	0.7 - 3.5	0.01 - 0.1	H, Sg	Day Only	Generally No
Thermal IR (Solid-state detectors in scanners and radiometers, quantum detectors)	3.5 - 10-3	1.0	H, S	Day or Night	Yes
Microwave (Scanners and radiometers, antennas and circuits)	103 - 106	10	H,S,F	Day or Night	Yes
Radar (Scanners and scatterometers, antennas and circuits)	8.3 X 103 1.3 X 106	10	H,S,F,R	Day or Night	Potential Exists

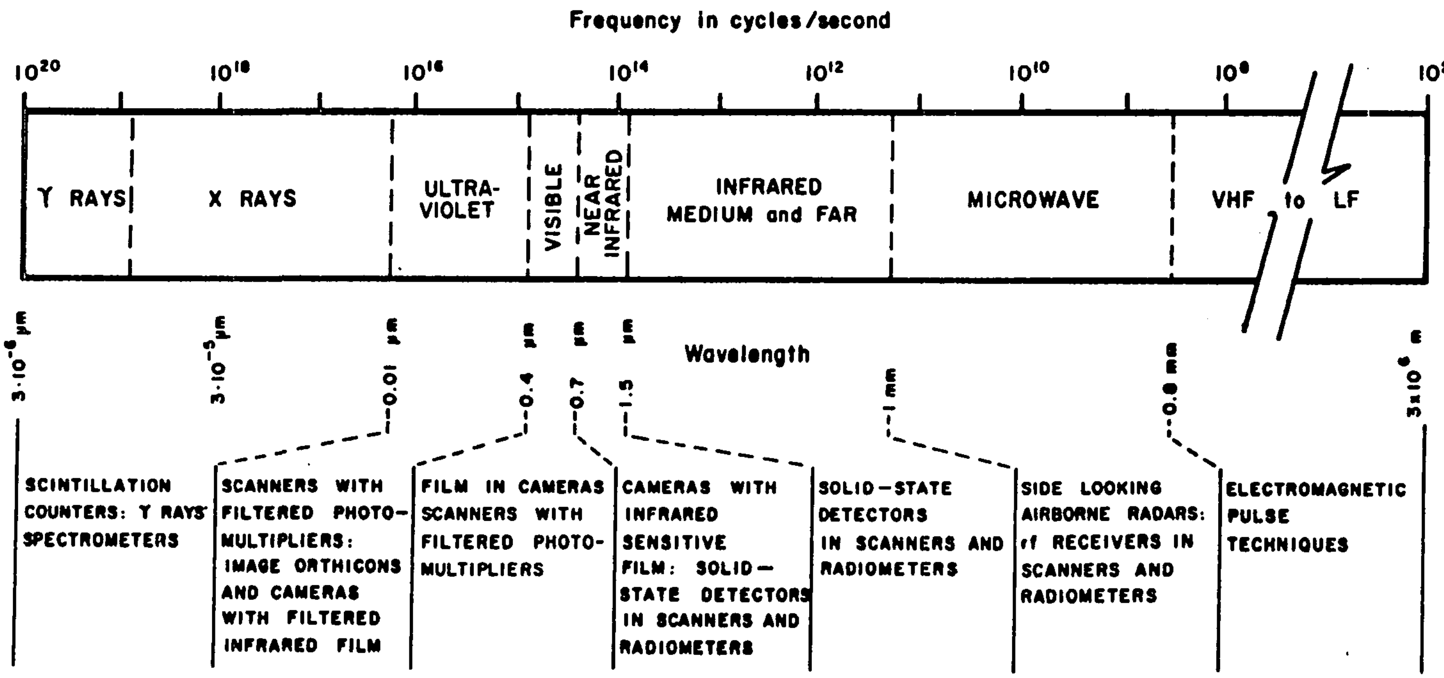
* Denotes the atmospheric conditions which can be penetrated by energy in this portion of the electromagnetic spectrum where: H = Haze, S = Smoke, Sg = Smog, F = Fog or Clouds, and R = Rain.

form of energy waves. The electromagnetic spectrum is a space-time continuum of electric and magnetic wavelengths that extend from the short gamma waves at one end to the long radio waves at the other end. The boundaries of the electromagnetic spectrum are not known and may lie at infinity. Although the wavelengths within the electromagnetic spectrum blend imperceptibly into each other they have been arbitrarily divided into regions. These regions are referred to as the ultraviolet, visible, near infrared, thermal, and microwave portions of the electromagnetic spectrum (Sever 1988).

One of the principal advantages of remote sensor imagery is that it may be obtained simultaneously from several portions of the spectrum that are not visible to the human eye. Consequently, it is necessary that investigators understand the basic principles and characteristics by which various components of electromagnetic energy operate. If an investigator is to successfully analyze remote sensing imagery, he must understand the energy relationships of the electromagnetic spectrum, the capabilities of different sensors, the characteristics of different targets, the mathematical and statistical basis of computerized image analysis, and the interactions between sensors and targets to electromagnetic energy.

The detection, recording, analysis, and interpretation of electromagnetic energy form the basis of remote sensing (Figure 3-1). There is no single instrument that can detect all the emissions within the entire electromagnetic spectrum. In fact, not all electromagnetic radiation reaches the earth's surface. The energy that does reach the surface passes through "atmospheric windows." These are wavelength ranges in which radiation can pass through the atmosphere with little attenuation. The windows in the optical portion of the spectrum are: 0.3-2.5, 3.0-4.0, 4.2-5.0, and 7.0-15.0 micrometers. Gamma rays and X-rays are generally unavailable for remote sensing since they have wavelengths up to 3.0 nanometers and are completely absorbed by the upper atmosphere.

The atmosphere is an extremely complex medium. The changes in the character of solar radiation as it passes through the atmosphere affects the energy levels that reach the sensor system. A complex process of scattering, reflection, and absorption modifies the amount of radiation reaching the earth. The ultraviolet portion of the spectrum lies between 3.0 nanometers and 0.4 micrometers. Only the longer portion of the ultraviolet band is transmitted through the atmosphere



The electromagnetic spectrum and some sensors that image in it. (Adapted from Estes, 1974.)

Figure 3-1. The Electromagnetic Spectrum and its use in remote sensing.

and can be detected through instrumentation. Atmospheric scattering is high in these wavelengths and results in poor resolution. Ultraviolet light is seldom used in remote sensing field analysis and is generally restricted to laboratory analysis.

Visible light occupies a narrow portion of the spectrum between 0.4 to 0.77 micrometers. A large number of remote sensing systems incorporate this portion of the spectrum into their system. This allows the investigator a point of reference to compare images recorded in the non-visible portions of the spectrum. Currently, the largest application of remote sensing research to date has been in the visible range, particularly using black and white aerial photography.

The reflected infrared band lies between 0.7 to 3.0 micrometers. This part of the spectrum is especially useful in studies dealing with vegetation since it allows greater definition (i.e. plant stress, insect infestation, moisture composition) than visible light. This area of the spectrum is useful in the detection of archeological features through crop marks. The photographic infrared is contained within the infrared band between 0.7 and 0.9 micrometers. It is detectable using film or digital sensors and is the longest wavelength detectable on film.

Thermal infrared radiation ranges from 3 to 14 micrometers. Thermal sensors operate in this portion of the spectrum from 3 to 5 micrometers, and from 8 to 14 micrometers. Radiant energy between 5 and 8 micrometers is absorbed by the earth's atmosphere and does not reach the earth's surface; thus, this region is not used in thermal remote sensing studies. Since all matter emits thermal infrared wavelengths both day and night, imagery can be acquired during darkness and viewed on an image display device. In the thermal wavelengths it is possible to detect heat differences and material differences between surface phenomena.

The microwave band is located between .1 to 200 centimeters and like thermal energy, is invisible to the human eye. The long wavelengths of this region minimize atmospheric effects and allow penetration through clouds, fog, rain, snow, and under certain conditions, the ground surface. The Shuttle Imaging Radar (SIR) was able to map geologic features 2 meters below dry sand (Berlin et al. 1985:311-321) and it has been calculated that a sand layer of up to 4 meters thick could enhance the radar return signal (Elachi et al. 1984: 383-387). The Shuttle Imaging Radar is attached to the bay area of the Space

Shuttle (Figure 3-2) and records the return signals through on-board computers. An example of SIR data can be seen in Figure 3-3.

Microwave sensors work in both passive and active modes. Radar is an active remote sensing system which means that it sends out its own microwave signal and measures the strength of the signal as it is reflected from objects. Different radar bands use various wavelengths of microwave radiation all of which exhibit unique properties. Passive sensors, on the other hand, receive only the emitted or reflected energy provided by nature. Most research to date has centered upon the .1 to 30 centimeter portion of the radar frequencies and is generally considered to be experimental. Currently, microwave data are most useful when used in conjunction with optical and thermal imagery. New research is currently investigating regions between the 30 and 200 centimeter bandwidths. The use of the microwave region, especially in the detection of cultural features, will increase as more research is conducted to understand the signal/environment relationship.

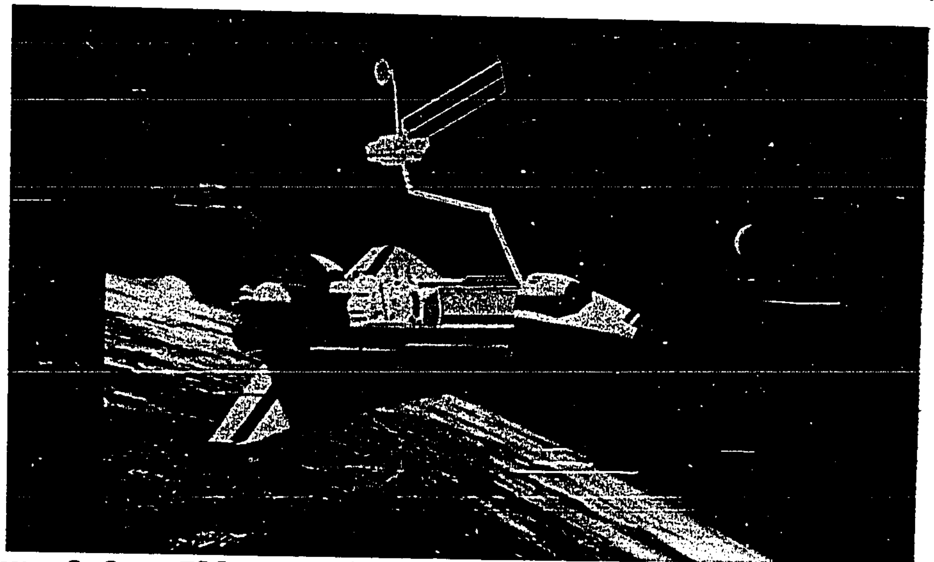


Figure 3-2. Illustration of the Shuttle Imaging Radar (SIR).

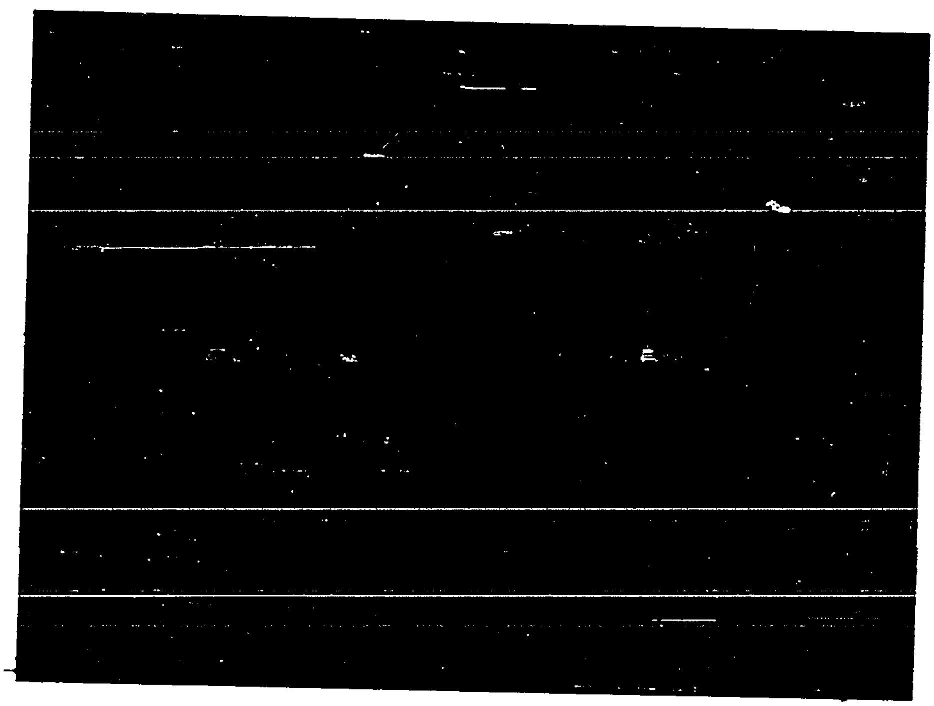


Figure 3-3. Shuttle Imaging Radar Image of the Sundanese Desert showing microwave penetration of the sand surface to reveal the underlying geology.

PHOTOGRAPHY

Photography is an analog technique, in which a light sensitive chemical, through photons of light, is exposed and forms a latent image. Chemical processing transforms the latent image to one which is visible to the human eye. While photography provides the greatest capability in terms of versatility or high resolution of detail, it nevertheless possesses certain limitations. For instance, cameras can generally see only what the human eye can see. In addition, camera systems must acquire photography during clear weather in order to produce an optimum product. Since cameras are not "real time" systems a certain time factor is involved for laboratory processing before the resultant images are available for analysis. This time gap can extend from several hours to several weeks, as is the case for those made by space vehicles.

Four different types of film are commonly used in remote sensing: black and white negative, color negative, color positive, and color infrared positive. Each film type has its particular attributes and chemical processing techniques. It is crucial that an investigator select a film type that is best suited for recording his object(s) or feature(s) of interest.

Black and white negative film is the prominent medium in remote sensing. It is a simple, low-cost technology which provides an excellent spatial resolution that is sensitive to approximately the same range of visible light as the human eye. Black and white film is called panchromatic because it records an image in variations of density of a single color, gray. The film provides moderate to good tonal contrast, reasonable exposure speed, and low graininess, thus making it useful for enlargements. Most countries of the world have black and white aerial photography in the standard 9" X 9" negative format. This large format allows for considerable enlargement of selected areas within the negative before becoming too grainy.

Normal color photography (positive and negative formats) is invaluable for aerial research since the human eye can discriminate a far greater number of color tones than gray scale tones. Since the human eye has different sets of color receptors, different tones or hues of each color can be perceived in the overlap areas. Color film has three emulsion receptors in the form of red, green, and blue. The combination of these three layers forms the photographic image (Horder 1971).

Color infrared (CIR) extends the visible range by detecting wavelengths slightly beyond the red end of the light spectrum. CIR film was initially employed during World War II to differentiate objects that had been artificially camouflaged. While there are a variety of applications for CIR film, the most common uses have been in the fields of agriculture and forestry. In many cases stressed vegetation appears on CIR before it is visible to the human eye. The three dye layers in the CIR film--yellow, magenta, and cyan produce a "false color" image composed of blue, green, and red. The chlorophyllic layers of live vegetation reflect strongly in the infrared region and thus healthy vegetation appears as red in CIR photography (Sever 1987). CIR photography is useful in archeological research because vegetation variations are sensitive to subsurface features such as soils, moisture, buried walls, pits, and other man-made disturbances.

PHOTOGRAPHIC INTERPRETATION

The development of skill and accuracy in photographic interpretation is an iterative process that involves photographic qualities and ground verification. Photographic interpretation is a mental process that involves inference, analogy, and logic. To be successful, the interpreter must have a background knowledge of the land surface, subsurface, and climatic conditions of the study area.

Whether the photography is examined with the unaided eye, a magnifying glass, or stereoscope, the observer can begin to appreciate human/land relationships. There are eight basic characteristics which can assist the investigator in aerial photographic interpretation: size, shape, tone, shadow, texture, pattern, association, and color. If an archeologist understands these characteristics he/she can discriminate physical and cultural variables, determine the site type, and probable site function. For further reading on photographic interpretation see Ambrosia and Whiteford's "Aerial Photograph Interpretation in Remote Sensing" in Remote Sensing of the Environment, edited by Benjamin F. Richason (1983).

As shall be shown in the following chapters photographic interpretation of archeological features was the impetus for incorporating more sophisticated remote sensing technology at both study areas. Many of the controlling elements of human environments can be identified from the study of photographic images. Three of the major indicators in aerial photography for buried or obscured archeological features are plant (crop) marks, soil marks, and shadow patterns.

Differences in the color, density, or height of agricultural crops, grasslands, or vegetation can provide a clue to buried features. Plant or crop marks respond in either a positive or negative manner to subsurface cultural conditions (Figure 3-4). If the subsoil retains more moisture or has been enriched through the addition of organic nutrients such as garbage, plant growth is accelerated during early growth, matures more robustly, and is visible under dry conditions. This stimulation of plant growth is referred to as "positive" crop marks.

"Negative" crop marks appear when plant growth is inhibited due to cultural activity that depletes subsurface mositure and nutrients. The stunted plant growth may be due to buried walls, stone-filled pits, or non-organic house foundations. Positive crop marks are often associated with subsoils composed of chalk or silt. The kind of subsoil is less important in negative crop marks since buried archeological materials commonly inhibit the plant growth overhead.

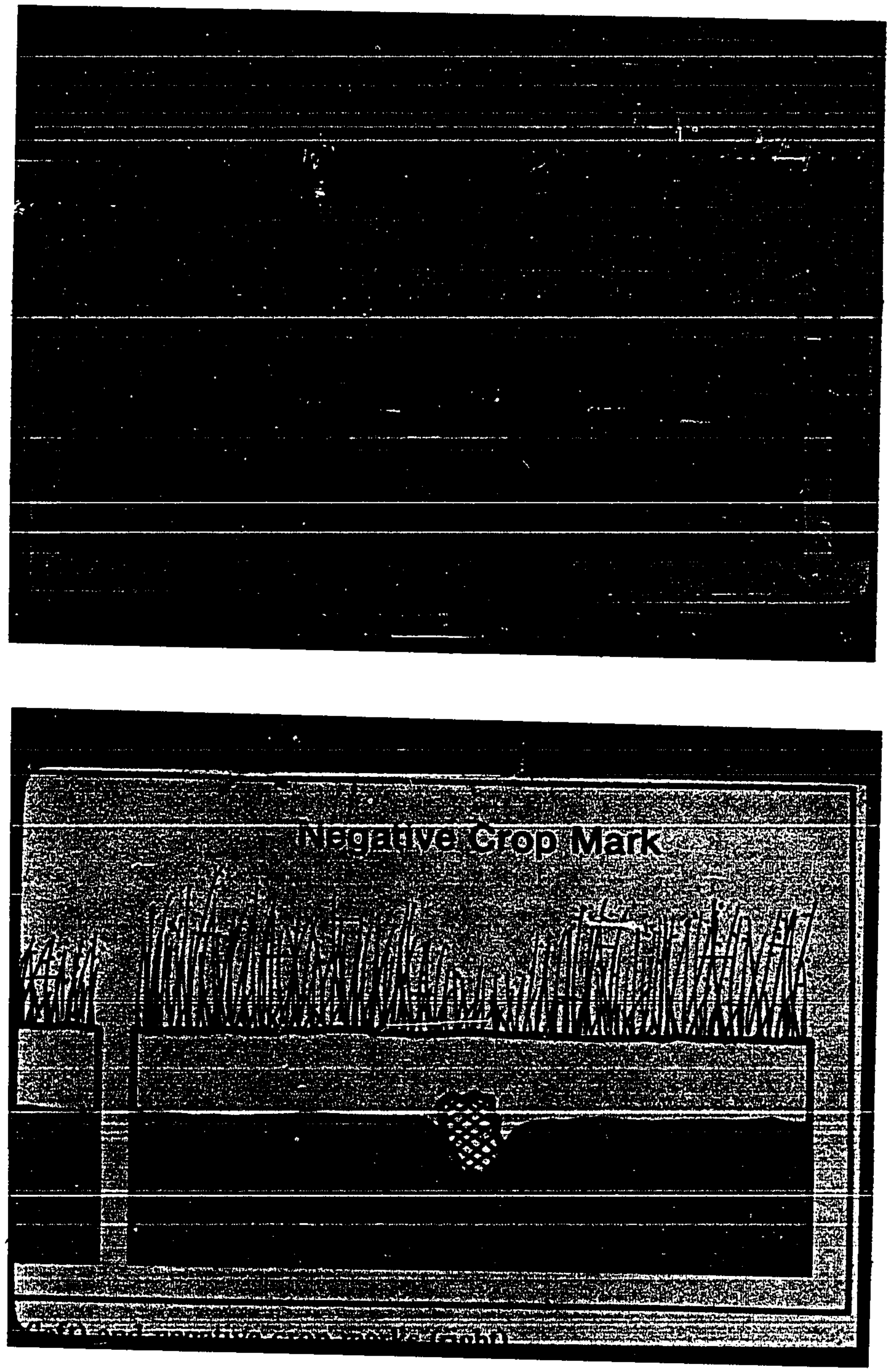


Figure 3-4. Example of subsurface phenomena which result in positive and negative crop marks.

Soil marks are often the most easily distinguished and useable source for locating cultural features. When features such as trenches, pits, or depressions are filled in the result is an anomalous soil profile. Sometimes the soils are mixed in such a way that the original subsoil appears at the surface. Other times the depression is filled in with a mixture of subsurface soils that become mottled through time and appear quite different than the surrounding soil. In addition, areas cleared by burning can change the soil by oxidation or by exposure and erosion. The resultant variations in soil color, texture, and moisture that are caused by prehistoric activity can often be seen on aerial photography; even when these features are not visible from ground level.

Shadow patterns occur on aerial photography when the sun's rays fall obliquely on variable terrain features. Such shadows can indicate walls, ditches, worn-down mounds, roads, earthworks, irrigation systems, and agricultural fields that are not noticeable from ground survey. The most effective use of shadow pattern techniques requires that the photography be acquired in the early morning or late evening when shadows are most prevalent. Since the sun's direction and elevation can be crucial in creating shadow effects of cultural features, specific dates and times must be scheduled for the aerial survey in order to obtain optimum results. Exploratory flights may require that aerial imagery be acquired at different times of the day. Shadow patterns have been responsible for the detection of archeological features such as ridged-field systems on the Yucatan Peninsula and prehistoric roads in Chaco Canyon.

Strict specifications for the acquisition of aerial photography are not universal because the focus of interest varies for each investigator. In general, however, vertical photographs are best used for the mapping of known sites. Oblique photographs are more suitable for the detection of crop marks or low-lying topographic features. Drier seasons reveal greater soil mark delineation since the loss of moisture by various soils reveals greater tonal contrasts. "Leaf-on" conditions are best for the detection of crop marks while "leaf-off" conditions are best for the detection of soil marks and shadow patterns in humid regions.

DIGITAL DATA

In contrast to photography where images are exposed onto film and processed chemically, remotely sensed images from scanner systems are recorded digitally and processed electronically through the use of computers. Multispectral digital images are the product of remote sensing systems that measure spectrally and spatially delimited electromagnetic radiation emitted or reflected from the earth's surface (Kahle and Goetz 1983).

As the sun's radiation passes through the atmosphere and strikes surface objects, those objects emit or reflect radiation which passes back through the atmosphere (Figure 3-5). This radiation then strikes the optical/detector system of a given sensor which causes the sensor to emit electrical pulses which are recorded. In a typical multispectral, optical-mechanical scanner system, the reflected and emitted energy from a small area of the earth's surface is "seen" by a scanning mirror and reflected through an optical system. The incoming reflected energy is spectrally dispersed and optically focused on various detectors that are sensitive to various portions of the electromagnetic spectrum. The size of the resolution element is determined by the platform altitude since the sensor's instantaneous field of view (IFOV) is the result of a fixed field stop in the optical system of the scanner. The smallest area that a scanner system can record is called a resolution element or picture element (pixel) and can vary dramatically depending upon the sensor configuration (Sever 1988).

Resolution can be defined as "the ability of an imaging system...to record detail in a distinguishable manner (Estes and Simonett 1975). It is the ability of an entire remote sensor system, including lens, antennae, display, exposure, processing, and other factors, to render a sharply defined image. For purposes of the research at hand, it is measured in square meters and includes spectral, radiometric, spatial, and temporal elements. Spectral resolution "refers to the dimension and number of specific wavelength intervals in the electromagnetic spectrum to which a sensor is sensitive" (Jensen 1986). Radiometric resolution refers to a sensor's sensitivity in detecting energy that strikes its surface. Spatial resolution is simply the IFOV of a sensor system while temporal resolution refers to how often a sensor acquires data over a given location. In the case of the Thematic Mapper satellite for instance the same 30 meter area is recorded routinely every 16 days.

As the platform passes above the landscape (Figure 3-6) the ground surface is scanned in successive strips, or scan lines, by the mirror. The rotational motion of

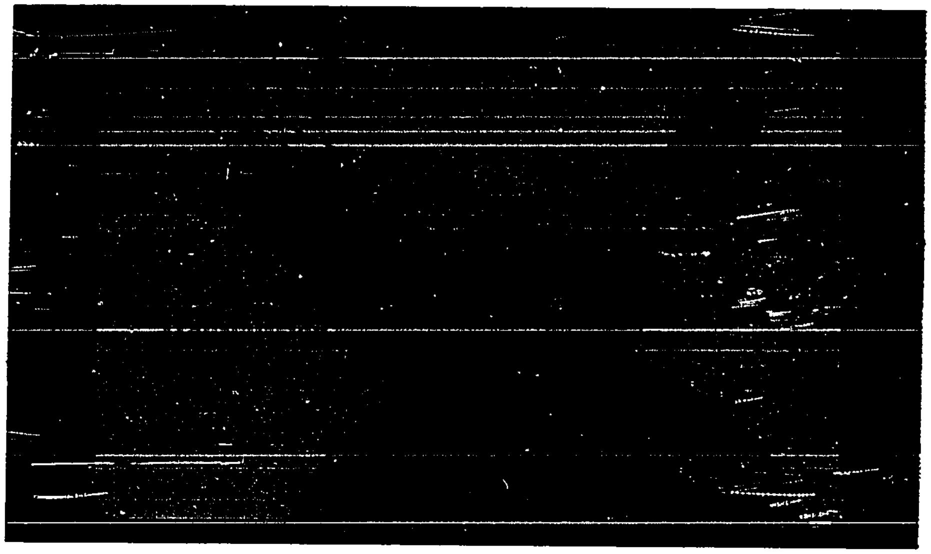


Figure 3-5. Diagram of reflected energy into a remote sensor system.

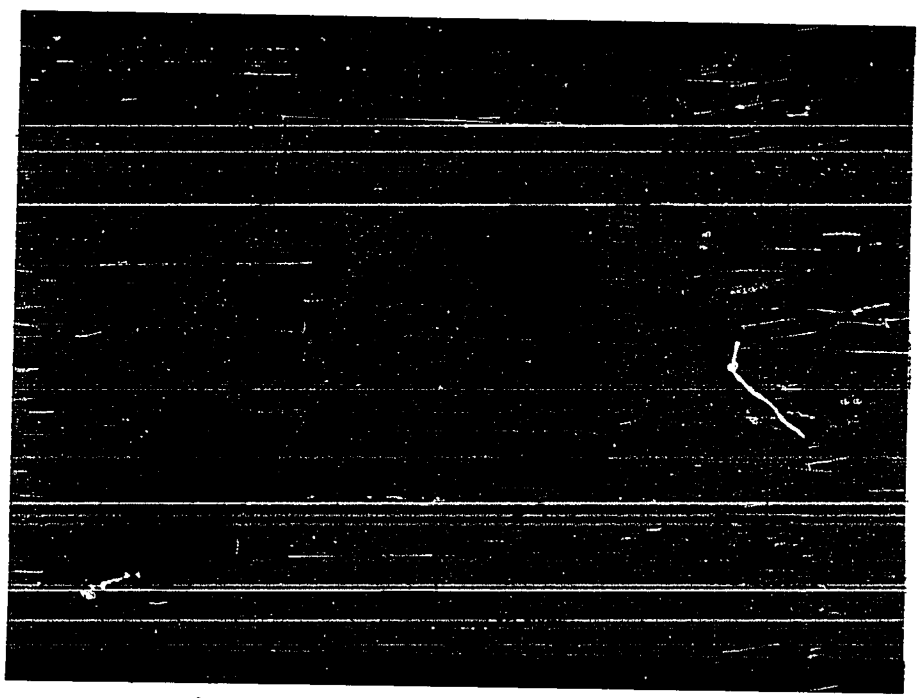


Figure 3-6. Diagram of scanner operating principles showing pixel and scan line acquisition of land surface features into an optical detection scanner system.

the mirror allows the energy to be measured, one resolution element at a time, for the complete scan line. The forward motion of the platform, which is perpendicular to the scan line, gathers successive strips of the terrain surface. The rate of rotation of the mirror is adjusted to the velocity of the sensor platform so that adjoining scan lines do not overlap (Sever 1987;1988). If overlap does occur the repetitious scan lines are removed through a process called decommutation. This is a preprocessing technique that occurs when the data are transferred from analog to digital format.

The energy received by the detector varies in signal strength as the pixels of the landscape vary in character. In an 8-bit system each pixel is assigned a digital value between 0 and 255 by each detector. Thus, if a hypothetical scanner system has 15 detectors, the same resolution element on the ground is "seen" and recorded in 15 different wavelength regions. The output signals from the detectors are recorded on magnetic tape and can be displayed on an image display device revealing an image that looks somewhat like a photograph. Each of the 15 different detectors therefore produces its own image which is sensitive to a special region of the electromagnetic spectrum. The resultant image is seen in black and white but color images can be artificially produced by combining various components of gray-scale information on the blue, red, and green guns of the image display device.

DIGITAL ANALYSIS

The objective of digital image analysis is to identify features or areas of interest in an image. Consequently, numeric data are essential in obtaining accurate quantitative information. Information can be extracted from digital imagery by either visual interpretation of the image or by digital analysis. Images can be visually interpreted by applying the conventional techniques used in photographic interpretation. Digital analysis, however, involves multivariate numerical techniques and computer machine processing. Both visual interpretation and digital techniques are employed in this study. These processes are compared in Table 3-2.

TABLE 3-2

VISUAL INTERPRETATION VERSES DIGITAL ANALYSIS

VISUAL INTERPRETATION	DIGITAL ANALYSIS
-Traditional, intuition, and expreience central	- Recent, specialized training, evolving methods
-Equipment costs low, simple to operate	- Equipment costs high, complicated to operate
-Uses only limited range of data, max 10-20 brightness values, one or at most three bands	- Uses full range of data, uses all brightness values and all bands simultaneously
-Spatial patterning important criteria for interpretation	- With some exceptions, spatial patterns not used in analysis
-Subjective, concrete, qualitative	- Objective, abstract, quantitative

Source: Campbell (1987:244).

Single channel image analysis techniques enhance an image to illustrate features within the data that are of particular importance to the investigator. This is a fairly routine process in which the pixels retain their raw data values. Enhancement techniques such as sun-angle correction, density slicing, band ratioing, edge enhancement, artificial color assignment, and filtering can be employed to isolate features of interest. Sun-angle correction removes the shadow effects in the data; density-slicing converts continuous gray tone values into a series of intervals that create a crisper image; band ratioing divides the values of one band by another, thereby creating a third image which accentuates particular features within the data; edge enhancement highlights borders and emphasizes transition in imagery; artificial color assignment converts gray tone values into color hues which create greater visual separation of features within the data; and, filtering removes certain spectral or spatial frequencies to highlight features in the remaining image. These techniques can be used to reduce atmospheric effects rendering a more distinct image, or can be used to extract linear and curvilinear patterns not readily apparent in the data.

Multichannel analysis can often provide more information by combining the attributes of several different bands of data into one multispectral image (Figure 3-7). The product of this digital classification is a set of spectral classes. These classes group locations that have statistically similar reflective characteristics in the multiple channels imaged by the sensor. Multichannel analysis is based on the fact that a given pixel is registered spatially on the ground in the matrices of all the other channels. The brightness value of each pixel varies from channel to channel and produces a spectral signature. The spectral signatures are statistically developed and combined into a one-channel classified image. By assigning a different color for each class, an image is produced that represents different types of ground information such as water, forest, agriculture, and urban areas. Multichannel digital analysis can employ either a "supervised" or "unsupervised" approach.

In the supervised approach, "the identity and location of some of the land-cover types, such as urban, agriculture, wetland, and forest, are known a priori through a combination of field work, analysis of aerial photography, maps, and personal experience (Heaslip 1975). In this approach the investigator selects

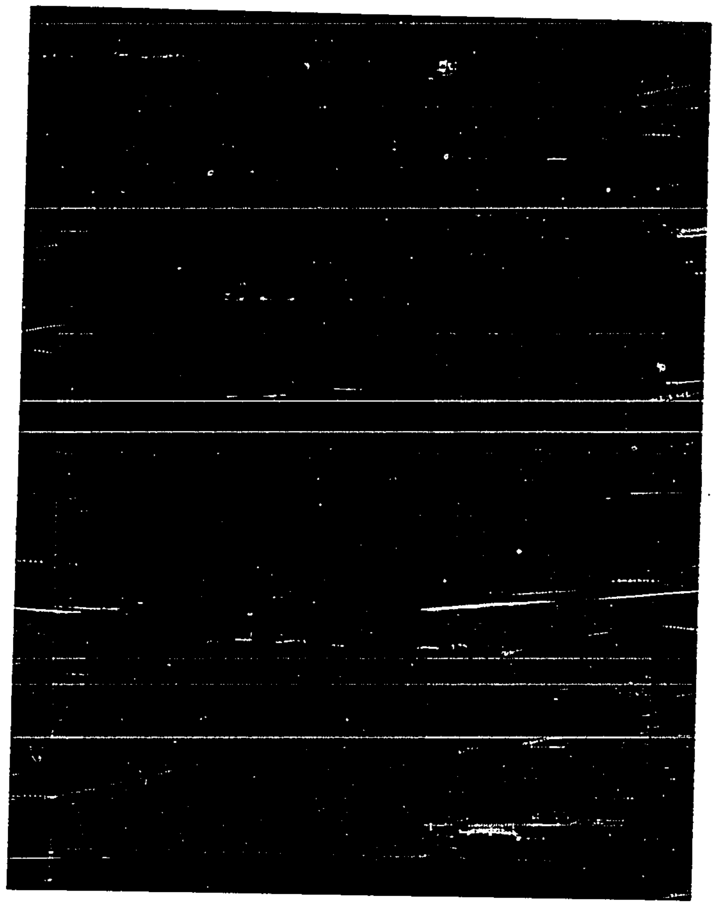


Figure 3-7. Example of a classified image over Big Thicket National Preserve showing land surface composition.

training samples that represent each landcover class that he or she wants identified. "These areas are commonly referred to as "training sites" because the spectral characteristics of these known areas are used to "train" the classification algorithm for eventual land cover mapping of the remainder of the image" (Jensen 1986). To produce an accurate classification, each training sample must contain all the spectral variations within each surface cover category.

In the unsupervised approach the entire data set is examined within the statistical parameters established by the investigator (means, standard deviations, covariance matrices, correlation matrices, threshold, etc.). In this approach the computer system alone determines the groupings based on their numeric properties. Spectral signatures are developed without prior knowledge of the land cover types and the resultant classes must be named and verified by ground truth information.

The development of digital data in an image format allows the investigator a visual representation of the statistical analysis results. Equally important, however, it provides the investigator with easy access to the percentages, acreages, distances, and correlations of diverse features within the image (Sever 1988).

GEOGRAPHIC INFORMATION SYSTEMS (GIS)

Geographic information systems (GIS) are computer programs designed to record, organize, analyze, and display spatial or locational data (Hansen 1983; Tomlinson 1984). Geographic Information Systems are designed to handle large volumes of data such as soils, topography, hydrology, meteorology, population, and geology (Figure 3-8). The GIS efficiently store, analyze, cross-reference, manipulate, and display various types of data as specified by the investigator (Marble et al., 1983). GIS data can be combined with remotely sensed data to help the investigator understand, monitor, and predict phenomena in a specified location. All ancillary layers of information incorporated into a GIS must be accurately georeferenced and properly registered with each other.

Geographic Information Systems describe objects from the real world in terms of their location in a known coordinate system, their attributes that are unrelated to their location (ie. soil type, rainfall), and both their

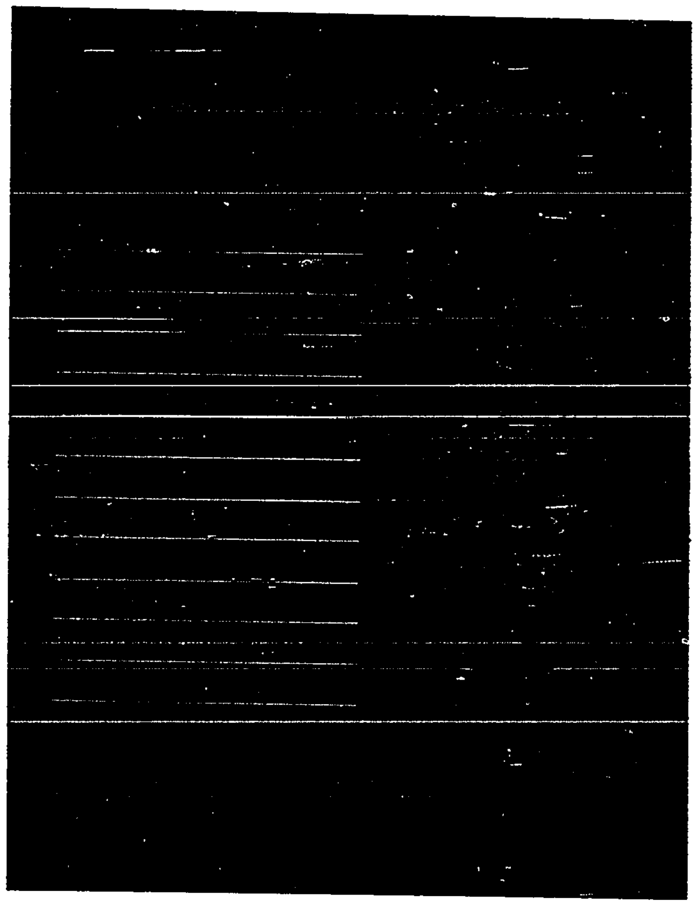


Figure 3-8. Diagram of a GIS showing examples of data base layers.

spatial and temporal interrelations with each other. GIS have three important components: computer hardware, effective application software, and an efficient organizational structure.

A GIS can be an efficient tool in archeological research. The ability to register remotely sensed data with digital terrain data, soils, rainfall, and hydrology can allow the researcher the ability to predict the potential locations of archeological sites. Environmental factors influence the location, distribution, and mode of human adaptation. The interaction between culture and environment has created settlement patterns that indicate a preference for particular locations and situations within the environment. These areas can be analyzed and mapped to understand known site locations and predict additional site locations (Sever 1988). A GIS has been constructed for the Arenal study area in Costa Rica and is included in the archeological research as shall be shown later.

SENSORS AND PLATFORMS

A sensor can be described as any device or instrument that gathers energy, electromagnetic radiation or other, converts it into a signal and presents it in a form suitable for obtaining information about the environment. To gather information, however, a sensor is mounted on a platform such as a satellite, airplane, balloon, or ground sled. Satellite platforms are very stable compared to airborne platforms which are susceptible to the effects of wind turbulence.

MULTISPECTRAL DIGITAL SENSOR SYSTEMS

Since the launch of the first orbiting multispectral scanner system in 1972, there have been a major series of technological developments and data analysis strategies. Multispectral sensor systems include satellites, airborne sensors, shuttle radar and photography, and ground based instrumentation such as ground penetrating radar (GPR). The three most successful satellite systems for surface mapping are the Landsat Multispectral Sensor (MSS), Landsat Thematic Mapper (TM), and SPOT. The SEASAT satellite was a radar based instrument that received limited use and is no longer operational. Shuttle based instrumentation such as the Shuttle Imaging Radar (SIR) and the Large Format Camera (LFC) were experimental sensors that flew on the second Shuttle mission. These instruments have great potential for future studies. A number of aircraft sensors have also been developed. The airborne sensors involved in this study include the Thematic Mapper Simulator (TMS), The Thermal Infrared Multispectral Scanner (TIMS), the Calibrated Airborne Multispectral Scanner (CAMS), and the Airborne Oceanographic Lidar (AOL).

LANDSAT

Landsat satellites are in a nearly polar, sun-synchronous orbit at an altitude of 920 kilometers. They circle the earth every 103.3 minutes (14 times a day), with each successive path occurring 26 degrees to the west. The Landsat paths are at azimuths of about 191 degrees measured from true north. After 252 orbits, or every 18 days, Landsat passes over the same place on earth. The primary sensor onboard Landsat, the Multispectral Scanner System (MSS), acquires data at 79-meter resolution. Although the sensor's IFOV is 79 X 79 meters, there is a degree of overlap from one IFOV to the next, effectively rendering a 59 X 79 meter element. Landsats 1,2, and 3 also had a return beam vidicon (RBV) system (no longer operational) which recorded a black and white image at 25 meter resolution in the visible portion of the spectrum.

The MSS provides continuous coverage of a 185-kilometer-wide section of the earth's surface. The MSS measures reflected sunlight from objects on earth in four bandwidths (Figure 3-9):

Band 1	0.5 to 0.6 micrometers	(green)
Band 2	0.6 to 0.7 micrometers	(red)
Band 3	0.7 to 0.8 micrometers	(near-infrared)
Band 4	0.8 to 1.1 micrometers	(near-infrared).

The area covered by a single Landsat frame (approximately 100 X 100 miles) would require over 1000 conventional 9" X 9" pictures to image the same area using aerial photography. Information such as geophysical data, which was once too costly or impossible to acquire, can be easily gathered from Landsat.

Landsats 1, 2, and 3 were launched between 1972 and 1978. The predicted lifespan of the Landsat satellites had been a year in space. Landsat 1, however, operated for five and a half years before technical problems shut it down in 1978. Landsat 2 was retired in 1982 and Landsat 3 in 1983.

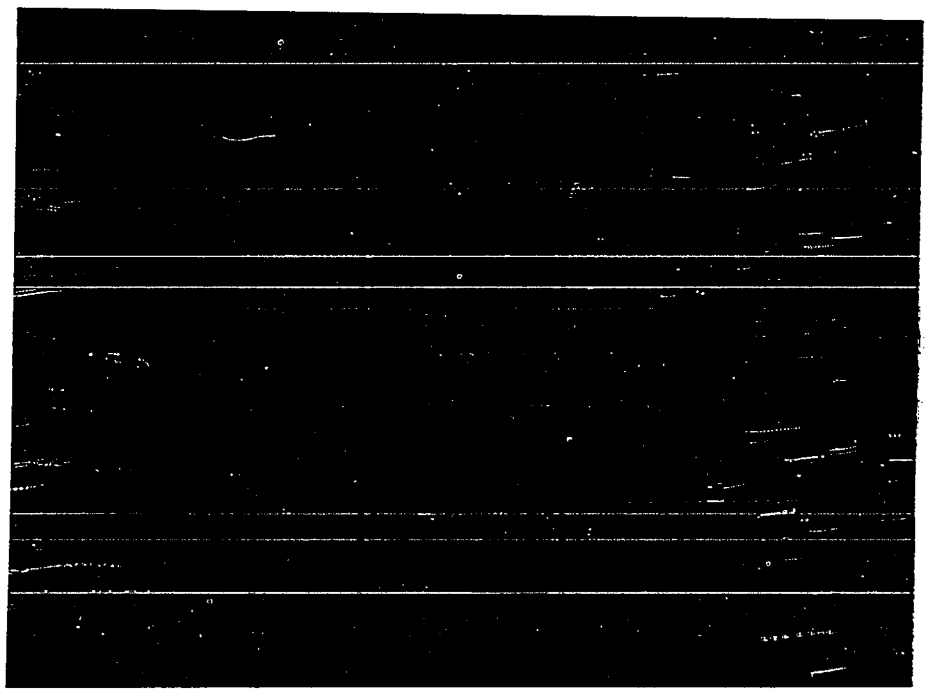


Figure 3-9. MSS raw data images in each bandwidth and a false color composite made from three of the images.

During their operational years the Landsat satellites produced more useful data than any other earth resource sensor (Jensen 1986:28). As researchers learned more about digital analysis, however, it became clear that improved spectral and spatial capabilities were needed. In addition to the MSS placed on Landsats 4 and 5, an experimental sensor called the Thematic Mapper (TM) was also placed onboard these satellites. Although the TM on Landsat 4 is no longer operational, the TM on Landsat 5 provided reliable data for several years. Like most of the Landsat satellites, Landsat 5 has extended beyond its designed life and only recently has begun experiencing technical difficulties.

The TM offers improved spectral and spatial resolution, geometric fidelity, and radiometric accuracy (Sever 1988). The TM has 7 spectral bands that were determined after years of analysis. The TM provides access to new areas of the electromagnetic spectrum resulting in greater spectral signature development. The spatial resolution of the TM is 30 meters with the exception of the thermal band (band 6) which is 120 meters.

A TM scene is equivalent to the same size MSS scene. The TM satellites were placed in an orbit at 700 kilometers and image the same location on the earth's surface every 16 days. While the MSS is still used, most researchers prefer TM data for their research analysis due to its superior spectral and spatial capabilities.

Landsat 6 is currently being developed but a launch date has not yet been set. The satellite will carry the Enhanced Thematic Mapper (ETM) with a 15 meter panchromatic in addition to the 7 bands of the Thematic Mapper. The thermal band will be improved from 120 meter resolution to 30 meter resolution. The ETM will also have a wide field sensor (WiFS) which will provide low resolution coverage if needed. Landsat 7 is scheduled for launch in 1991 and will carry a multiband thermal capability in its ETM design.

SPOT

In 1986 the French launched the Systeme Probatoire d'Observation de la Terre-1 (SPOT). SPOT has three multispectral bands at 0.5-0.59, 0.61-0.68, and 0.79-0.89 micrometers. The resolution of these three sensors is 20 meters. In addition, SPOT can also operate in the black and white panchromatic mode (0.51-0.73 micrometers) at 10 meter resolution. The satellite has off-nadir viewing which allows data to be gathered over a study area several times per week and can be used to develop stereoscopic images. Consequently, the same area can be acquired several times in a short time period compared to the 16 day lapse of the TM.

RADAR

Radar (Radio Detection and Ranging) uses microwave energy rather than light energy to image the earth's surface. It is an active system that can be used day or night. A number of systems use imaging radar. These include the SEASAT satellite, the Shuttle Imaging Radar (SIR), the L-band radar system at the AMES Research Center, and Ground Penetrating Radar (GPR).

Radars operate by releasing short powerful bursts of microwave energy at regular intervals in specified directions. These pulses strike a target and are reflected back to a receiving antenna. This returned energy can be displayed as an image. The radar signal is affected by surface roughness, angle of incidence, and the polarization of the received signal. Microwave sensors operate in one portion of the microwave region and are identified by a letter code. These letters were developed during World War II and have remained part of the remote sensing vocabulary:

Radar Frequency Band	Wavelength
P	136-77 cm
UHF	100-30 cm
L	30-15 cm
S	15-7.5 cm
C	7.5-3.75 cm
X	3.75-2.40 cm
Ku	2.40-1.67 cm
K	1.67-1.18 cm
Ka	1.18-0.75 cm

Radar data requires complicated analysis and is still in the developmental stage. It is one of the most expensive remote sensing approaches both in data acquisistion and data processing. Airborne L-band radar was used in the Arenal study in Costa Rica.

LARGE FORMAT CAMERA

The Large Format Camera (LFC) is a high resolution camera that produces conventional, but superior quality, negatives on 23 X 64 cm photographic plates. These images can be treated as photography or they can be digitized and analyzed as digital imagery. The LFC is a two-way system with one part imaging the earth's surface while the opposite part images in a 180 degree direction at the stars. In this way precise geometric fidelity is achieved. LFC data is recorded in stereo pairs and represents a source of detailed low-cost analysis. The LFC was flown on the Challenger shuttle in 1984 and imaged only small sections of the earth's surface. It is scheduled to be flown on a future shuttle mission and may eventually be installed on the Space Station.

AIRBORNE SENSORS

Although the design of airborne sensors is compatible to that of satellite platforms there are some notable differences. Airborne platforms are susceptible to cross winds and air turbulence. The roll, pitch, yaw, and drift of the aircraft can cause distortions in the imagery and must be corrected either by onboard processing or at the data analysis laboratory. Different angles of solar illumination and fluctuating atmospheric conditions (temperature, pressure, and humidity) must also be corrected to provide more reliable data.

The advantage of airborne sensors is that they are much less expensive to construct than a satellite, they can be flown at the discretion of the investigator, and they offer improved spatial resolution. As opposed to the fixed spatial resolution of most satellite sensors, an airborne sensor's spatial resolution is a function of aircraft altitude and sensor optics. The swath width of a sensor is also a function of altitude. A major problem is encountered, however, when trying to merge adjacent swaths into a collective image of geometric accuracy. Several airborne sensors were used in this study, each achieving varying degrees of success. Specific characteristics of these multispectral scanner systems are listed in Table 3-3.

The TMS, TIMS, and CAMS were flown in a NASA Learjet 23 (Figure 3-10). During daylight missions CIR photography (Eastman 2443) was simultaneously acquired, with 60% forward overlap for stereoscopic viewing and to aid in digital analysis. An inertial navigation system (INS) in the Learjet allowed for precise data acquisition over the selected area. In Chaco Canyon the data was acquired with a 10% side overlap in the eventuality that the flight lines might need to be georeferenced together for future research.

TABLE 3-3

AIRBORNE
MULTISPECTRAL SCANNER
CHARACTERISTICS

BANDWIDTH	TMS	TIMS	CAMS
CH 1	0.46-0.52	8.2-8.6	.45-.52
CH 2	0.53-0.60	8.6-9.0	0.52-0.60
CH 3	0.63-0.69	9.0-9.2	0.60-0.63
CH 4	0.77-0.90	9.6-10.2	0.63-0.69
CH 5	1.53-1.73	10.3-11.0	0.69-0.76
CH 6	2.06-2.33	11.3-11.6	0.76-0.90
CH 7	10.43-12.33	n/a	1.55-1.75
CH 8	n/a	n/a	2.08-2.35
CH 9	n/a	n/a	10.5-12.5
IFOV	2.5 mrad	2.5 mrad	2.5 mrad
SCAN RATES	46.66 rps	7,7,8,7,12,25	6-60 rps
FOV	86.61°	76.67°	100°

SOURCE: EARTH RESOURCES LABORATORY, SSC

THEMATIC MAPPER SIMULATOR (TMS)

The TMS was the prototype of the TM satellite. TMS data allowed investigators to understand data characteristics and develop data analysis techniques prior to the availability of the TM satellite system. The TMS has seven bandwidths ranging from 0.46 to 12.33 micrometers (Table 3-3). With a 2.5 milliradian aperture, the TMS was configured to produce a 30 meter resolution at 12,000 meters above mean terrain elevation. The basic optics consist of a rotating mirror and a 4 inch diameter Cassegrainian telescope which transmit energy into the system to illuminate detectors which simulate TM band frequencies. The TMS can also be flown at lower altitudes to provide greater spatial resolution.

THERMAL INFRARED MULTISPECTRAL SCANNER (TIMS)

The TIMS is a six channel thermal infrared multispectral scanner capable of measuring target radiation in 400 nanometer intervals from 8.2 to 9.4 micrometers, and in 800 and 1000 nanometer intervals from 9.4 to 12.2 micrometers (Table 3-3). The 6 thermal bands were originally designed for geological research. The scanner has been improved through time and has been successful in vegetation research (Sader 1986), soil research (Pelletier and Ochoa 1986), and archeology (Sever and Wiseman 1984).

TIMS uniqueness lies not only in its thermal infrared capability but also in its multispectral nature. Each of the six bands measures thermal radiation as temperature in degrees of centigrade. Emissivity of the target is also a contributor to the measured return. Emissivity is the ratio of radiant emission of a source to that of a blackbody at the same temperature. Emissivity is a function of the type of material and its surface geometry. When atmospheric corrections are applied for temperature, pressure, and humidity, TIMS can achieve a sensitivity of less than a tenth of a degree Centigrade (Palluconi and Meeks 1985:5). The scanner's primary optics consist of a rotating mirror and the 7 1/2 inch diameter Newtonian telescope, but the design of the spectrometer portion of the scanner is unique because of the thermal infrared application. (NASA 1985).

CALIBRATED AIRBORNE MULTISPECTRAL SCANNER (CAMS)

The CAMS (Figure 3-11) was designed and constructed at the Stennis Space Center in 1987 to meet the demands of investigators who requested that calibration data be recorded in real time with their mission data. The CAMS is a nine channel airborne instrument that provides coverage from 0.45 to 12.5 micrometers (Table 3-3). Like the TIMS, the CAMS is a calibrated instrument, but it is calibrated throughout the visible, infrared, and thermal portions of the spectrum.

The calibration system consists of high and low temperature blackbodies for thermal data calibration and an 8 inch integrating sphere illuminated by a 35-watt tungsten-halogen lamp for the calibration of visible and reflective infrared data. Additionally, CAMS has a variable-speed 360 degree rotating mirror which references the pixel below the aircraft with known radiation values in each of the 9 bands. Scan speeds are adjustable from 6 to 60 scans per second, in one scan per second increments. The CAMS remains an experimental sensor as ongoing research is completed.

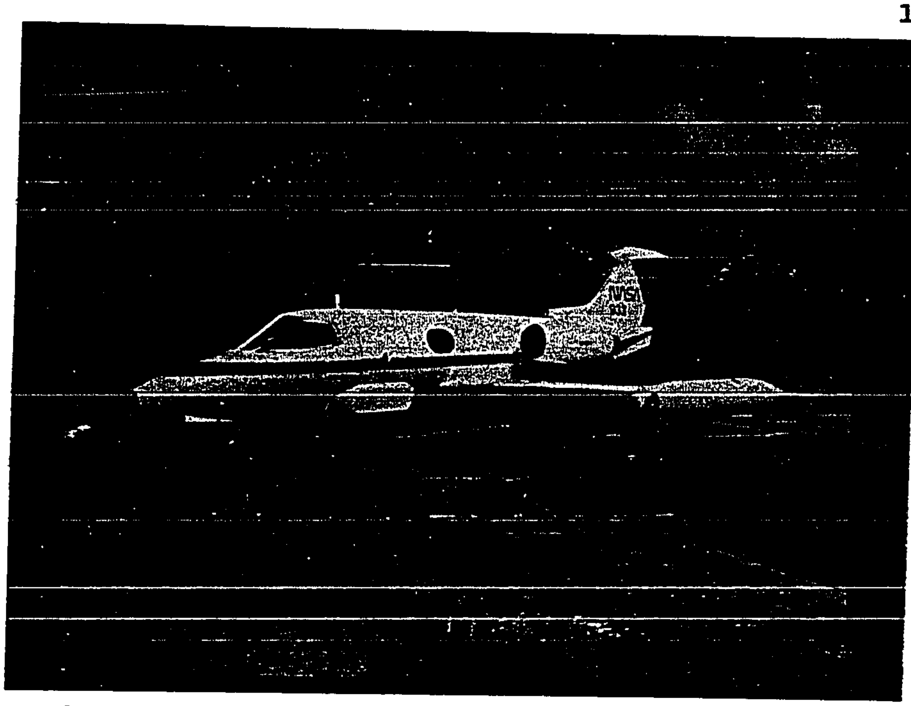


Figure 3-10. NASA Learjet which was used in this investigation to fly airborne scanner systems over study areas in Chaco Canyon and Costa Rica.

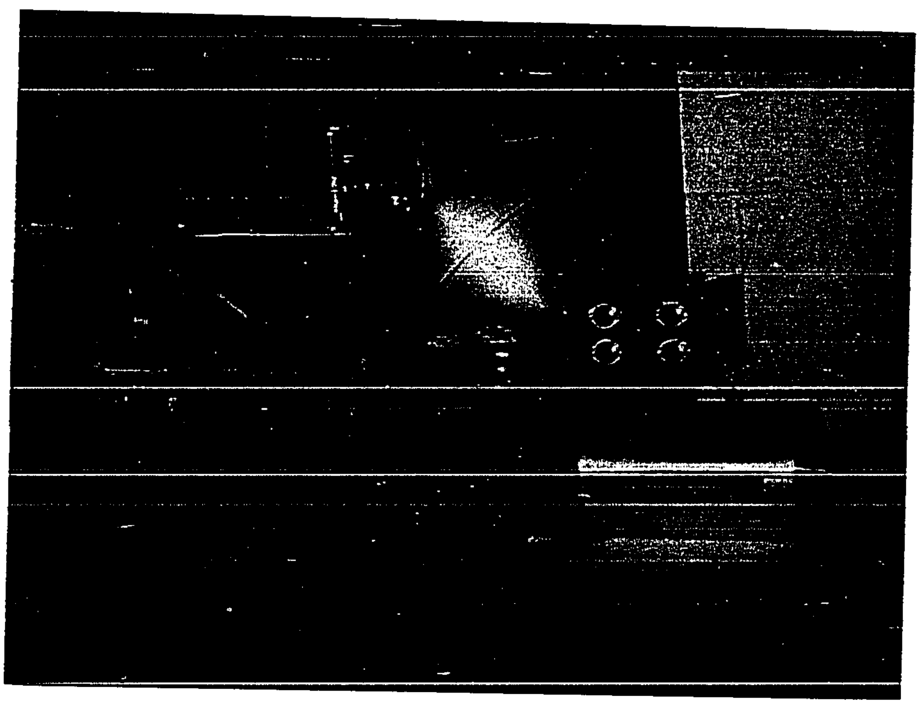


Figure 3-11. The Calibrated Airborne Multispectral Scanner (CAMS).

AIRBORNE OCEANOGRAPHIC LIDAR (AOL)

The potential of laser and lidar (light detection and ranging) terrain profilers for topographic mapping was realized in the late 1960's. Originally, the systems were developed for plotting ocean wave profiles, oil spills, and other oceanographic applications. It was soon recognized that laser/lidar profilers had great potential for forest canopy height measurement and other applications. Since the AOL was involved in a tropical forest study in Costa Rica under the direction of Dr. Armond Joyce, it was decided to investigate the AOL's archeological potential with research at Arenal, Costa Rica.

The AOL profiling system was developed in 1977. It is a conically scanning, pulsed laser system. The system includes an Arco C-5000 pulsed nitrogen laser that operates at an emission wavelength of 337.1 mm (Krabill et al. 1980). The instrument is flown in an aircraft at 300 meters above terrain. Previous research had indicated that 39% of the AOL's laser pulses could penetrate the tree canopy to the surface in forests that were 99% dense. The signal reflected to the aircraft can be processed to produce ground level terrain as well as the tree heights upon that terrain to an accuracy sometimes less than 1 meter.

SUMMARY/CONCLUSIONS

Remote sensing technology has evolved rapidly in the last two decades and holds revolutionary potential for the discipline of archeology. Although aerial photography has been used in many research investigations of the past, it is the application of multispectral digital analysis that represents the greatest capability for future research. Multispectral digital analysis measures the relationships and interactions of electromagnetic energy with the earth's surface. The energy can be recorded by satellite, airborne, and ground based sensors and analyzed through the combination of computer hardware and software. The digital representation of this information allows it to be analyzed through advanced statistical processes. Multispectral digital data can also be combined with a variety of other computerized databases such as geographic information systems and relational databases. Through the use of remote sensing technology an archeologist can view otherwise invisible, complex multivariate relationships in the data and can see the effects of prehistoric human activity upon the landscape.

Remote sensing is a tool which continues to experience rapid development as a result of space exploration in the earth and planetary sciences. New satellite systems, airborne scanners, and remote sensing instruments that will be attached to the space station are currently being developed and will be available in the near future. Major research and development programs are also concentrating upon new innovations in hardware and software technology. The importance of remote sensing and its potential for the future is recognized by most scientific disciplines both in the United States and abroad. Remote sensing technology will see increasing application in the field of archeology as researchers continue to expand their knowledge of multispectral digital analysis in their search to answer questions concerning prehistory.

CHAPTER 4

CHACO CANYON

INTRODUCTION

This chapter investigates the prehistoric roads in Chaco Canyon that were built by the Anasazi between the 11th and 12th centuries. The objective of this research is to determine the function of the roadway system and how it related to the daily activities of the Anasazi. In order to arrive at an interpretation of the roadway system this chapter will examine the previous work conducted in Chaco Canyon, the archeological evidence, the characteristics of prehistoric roads, previous and current remote sensing data, and the ethnographic evidence. In order to understand the roadway system it is first necessary to map the locations of the prehistoric roads. This research will incorporate new techniques in digital airborne remote sensing analysis to verify past locations and to see if the technology can determine the locations of previously unknown roadway segments. By mapping the roadway system and examining the archeological and ethnographic evidence it is anticipated that the function of the roadway system will be realized.

ENVIRONMENTAL SETTING

Chaco Canyon is located in the northwest corner of New Mexico at the center of the San Juan Basin (Figure 4-1). As a structural subunit of the Colorado Plateau, the San Juan Basin consists of an expanse of broad plains that is dissected by mesas, steppes, and badlands. Although Chaco Canyon is an erosional incised feature 20 miles long and no more than a mile wide, the rest of the area is essentially canyonless (Figure 4-2). Thus, Chaco Canyon is physiographically unique. For more information on the physiography of Chaco Canyon see Simons, Li, and Associates (1982), and for further reading on the geology of Chaco Canyon see Bryan (1954).

The Canyon is bisected by the Chaco River, a 100 mile long San Juan tributary, of which 15 to 20 miles flows through the canyon. The river is actually an intermittent stream and is generally dry for most of the year, flowing only after a heavy rain. Rainfall is sparse, ranging from 6 to 15 inches and falls during the rainy season of July through August. The San Juan Basin receives its rainfall from the northern Pacific in winter and from the Gulf of Mexico and tropical Pacific in

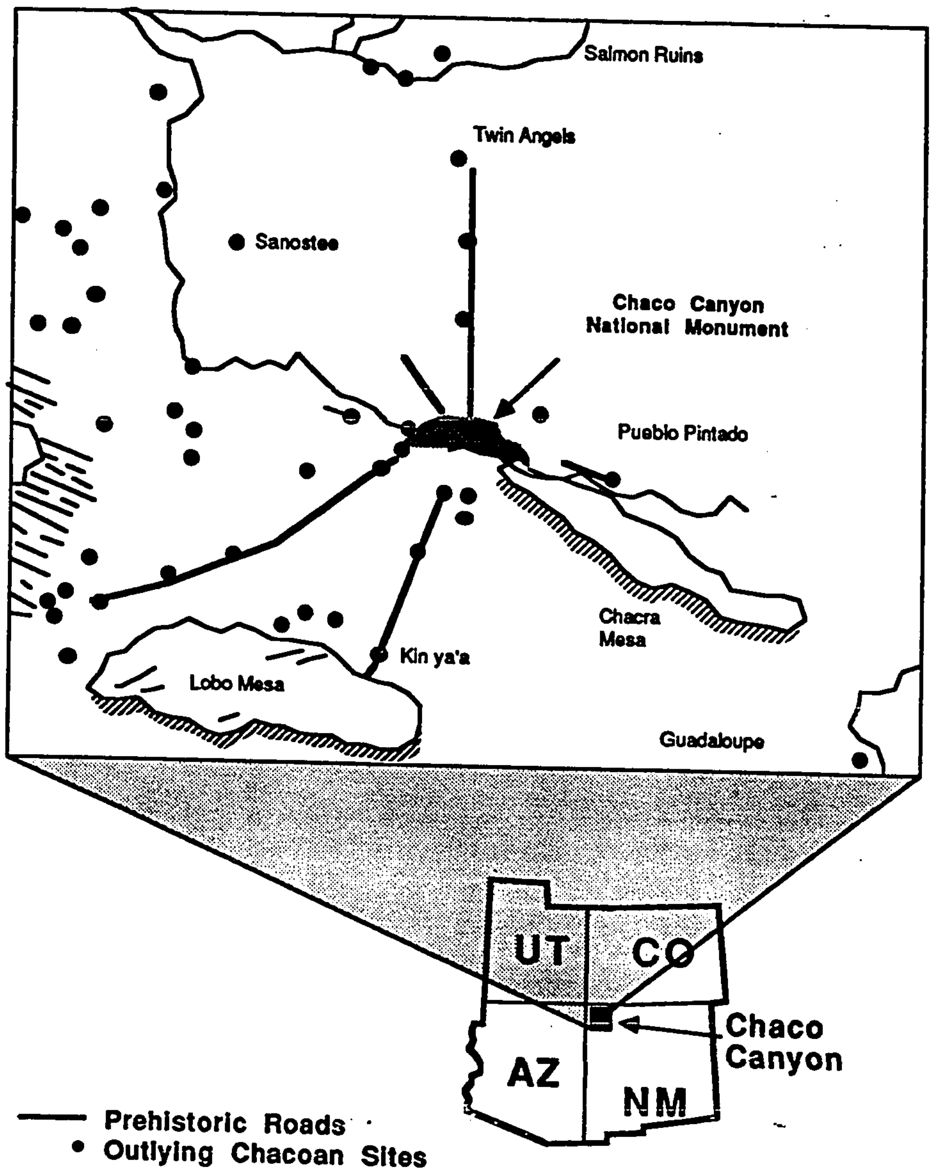


Figure 4-1. Map of the location of Chaco Canyon, New Mexico.

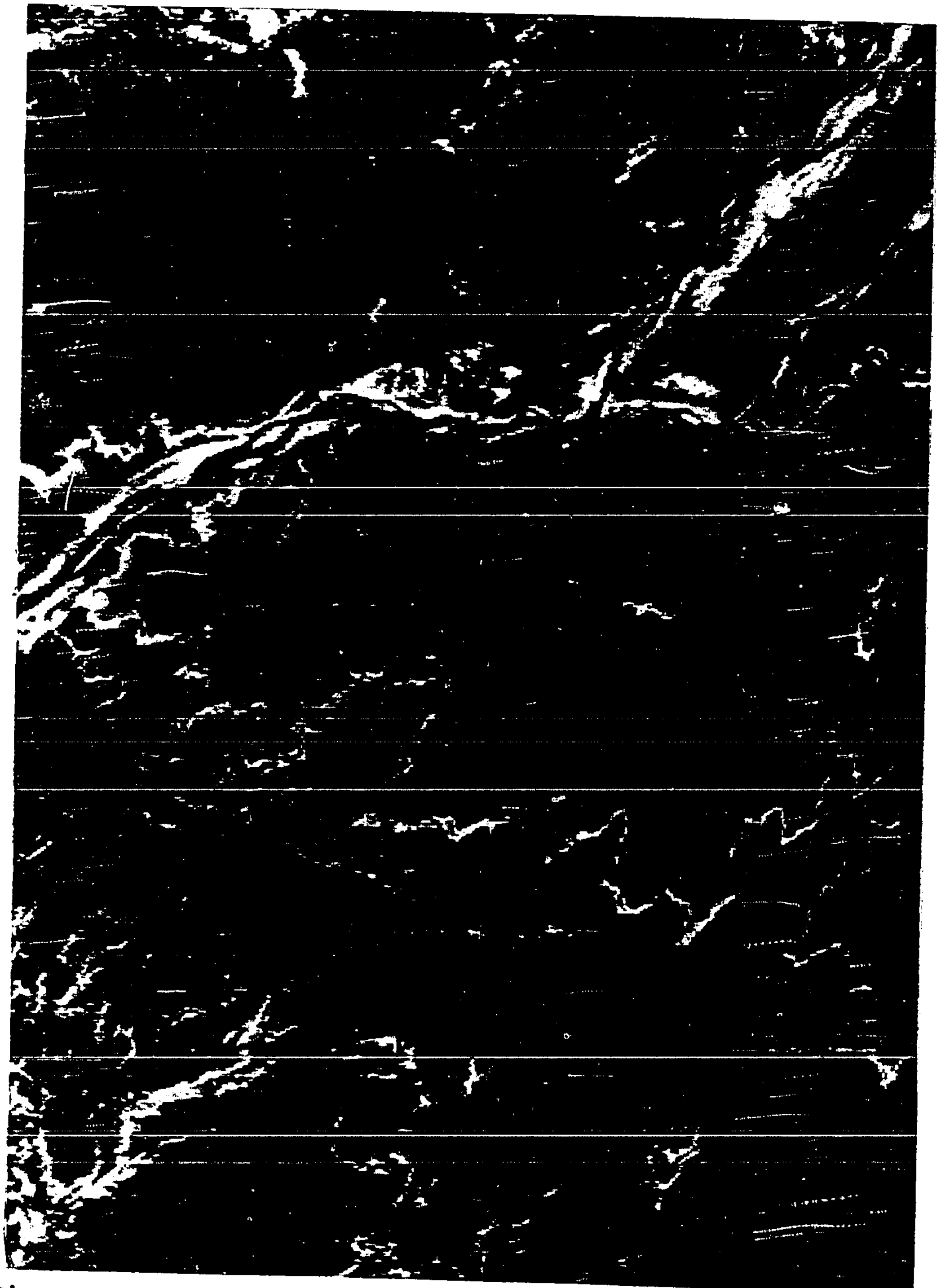


Figure 4-2. TMS image (band 2) of Chaco Canyon at 30 meter resolution.

summer. The Chuska Mountains to the west and the Zuni Mountains to the south of Chaco cause a rainshadow effect by reducing rainfall. Temperatures are those of a temperate region with annual mean temperatures ranging from 47-60 degrees Fahrenheit, although daily temperatures may fluctuate between 40 to 50 degrees (Bryan 1954). The climate of the region has been classified as varying between cold desert and steppe (Brand, et al. 1937:45).

The Canyon runs east-west and is the only significant area in the region which maintained sufficient alluvial soil for large-scale farming (Vivian and Mathews 1965). Inhabitants used run-off water from the canyon walls for irrigation and grew a variety of crops (Vivian 1970). The characteristic rocks of the canyon are shale and sandstone, with the latter being used extensively for building and construction. The depth to bedrock is variable but generally averages 91 feet. The average depth to the water table is 41 feet as it dips to the west 1 degree to 5 degrees (Ross 1978). Cly's Canyon contains the largest reserve of surface water from seeps occurring between lenses of carbonaceous shales and overlying sandstone. Stairways, ceramic debris from water storage jars, and a prehistoric road leading to Pueblo Alto bear testimony to Cly's Canyon prehistoric importance to survival in the Chaco desert.

Despite the sparse vegetation in contemporary times, it appears that prehistorically there was once abundant timber in the area that could be used for building and fuel. Likewise, it appears that floral and faunal sources were initially sufficient enough to support an early hunting and gathering population and later supplement the diets of agricultural inhabitants (Vivian and Mathews 1965:7).

PREHISTORIC ROADS IN CHACO CANYON

The discovery of prehistoric roads in Chaco Canyon initiated a number of investigations whose goal was to explain the purpose and time of construction for these Anasazi features. Many imaginative research designs were developed to assist archeologists in attaining this goal. These research trends included complete or partial components in the detection, description, and interpretation of the roadway system (Ware and Gummerman 1977; Ebert and Hitchcock 1980; Allan and Broster 1978; Judge et al. 1981; Powers et al. 1983; Obenauf 1980; BLM 1983, 1987).

Past field studies and aerial photographic interpretations have produced a large corpus of information on Chaco roads. Many interpretive results have been presented regarding the function of the prehistoric roads and how they related to the social, political, and economic development in the Chaco Basin. Various models were developed to explain the roads. Many of these were economic redistribution models with some emphasizing spatial analysis and others stressing economics. In these interpretations the roads were used for the transportation and redistribution of goods and materials. Other models see the roadways as a communication and signalling system. A few researchers have postulated that the roads served a ritual function that effected religious integration and stabilized social interactions. And finally, others see the roads as being multi-functional in scope, combining economic, social, and religious components.

Most of the past research designs centered around an economic interpretation suggesting that the roads were used for the transportation and exchange of goods. One of the most accepted interpretations that emerged after many years of research was that Chaco Canyon was a center for redistribution and the roads connected Chaco Canyon with "outlier" communities (Allan and Broster 1978; Judge et. al. 1981). Using the tenets of Judge's redistribution system, Drager (1976) proposed a signalling communication system throughout the basin area that was controlled from Chaco Canyon. Architectural features and even hearths were found that would have been critical to a visual communication system to support the signalling system premise.

By the mid 1980's the redistribution theory seemed to be the most accepted for explaining the purpose of the roadway system as it linked Chaco Canyon to 50 or more satellite communities. It was not known if these outliers were absorbed into Chaco Canyon through incorporation or through colonization. Research by other investigators (Powers et al. 1977; Toll et al. 1980; Toll 1981) seemed to substantiate the redistribution theory. Interpretations for the extent of the Chaco roadway system, however, have varied and range from localized exchange within and adjacent to the canyon proper to regional exchange to the periphery of the San Juan Basin and beyond. As Lekson et al. state:

> We are just beginning to comprehend the extent of the roads beyond the San Juan Basin....that the roads probably extend as far north as the San Juan Range in the Rocky Mountains and as far south as the Mogollon Mountains. Although we are less certain of their paths east and west, we believe they may have extended as far east as the turquoise mines near Santa Fe and as far west as the Little Colorado River valley, perhaps even as far as the San Francisco peaks near Flagstaff

(Lekson et al. 1988:106,108).

Recent evidence has cast doubt upon the redistribution theory originally proposed by Judge (Lekson et al. 1988; Roney 1989, personal communication). Judge, himself, has been instrumental in this re-evaluation (Lekson et al. 1988). As a result, the function of the Chaco roadway system remains unclear. The Chaco roadway phenomenon was first recognized by Neil Judd (1954;1964) who proposed that the roads were used for localized resource exploitation. The fact that he refers to these as "ceremonial highways" suggests that he also suspected a religious purpose for the roadways (Judd 1954). This religious interpretation was seldom incorporated into later research designs, but Obenauf (1980) suggested that a roadway system would enhance religious integration, particularly if Chaco Canyon was viewed as a "ceremonial center" for the Chaco or San Juan Basins. In light of all the past evidence it is time to examine the possible religious (ideological) purpose for the Chaco roads. Although the roads may have served a multi-purpose function, i.e. transportation to and from agricultural fields, water sources, and exchange, it is possible that religious or ceremonial factors may have heavily influenced roadway construction. This investigation will use remotely sensed data to help determine if the roads functioned predominantly for economic or religious purposes.

HYPOTHESES TESTING

The hypotheses to be tested in Chaco Canyon are:

If the prehistoric roads had an economic function then:

1. they took the "path of least resistance" as they traveled from one place to another, resulting in curving or meandering patterns in areas of difficult terrain;

2. they incorporated greater constructional effort in making travel easier at difficult places, i.e. areas of steep slope, than in areas of flat or level relief;

3. they by-passed and avoided areas of high topographic relief;

4. and, they provided linkage to Chaco Canyon for the storage and redistribution of goods.

Conversely, if the prehistoric roads served a religious function then:

1. they will connect to a major center of ritual activity (Chaco Canyon) where they will be associated with religious features such as shrines, kivas, great houses, and ceremonial ceramic breakage.

2. they will incorporate elevated areas of topographic relief into their course

> such as pinnacles, mesa tops, or other observational areas, and they will be associated with ritualistic concepts such as directional symbolism, orientation, and astronomy; ie., they continue on their predetermined course in spite of topographic obstacles.

In order to understand the function of the Chacoan road network it is first necessary to map the locations of the roads. This has been a major problem throughout all the investigations dealing with Chaco Canyon's prehistoric roads. Locating and following the roads from ground level is extremely difficult, expensive, and time-consuming. As shall be shown, aerial photography and remote sensing have contributed inestimably to this process. In order to arrive at any understanding of the Chacoan roadway system it is essential to know their location, their physical characteristics as determined from the archeological evidence, the time-frame for their existence, and the areas that they connect in the context of the surrounding landscape.

CULTURAL HISTORY

Chaco Canyon was a major area of prehistoric human occupation and is one of the most important archeological regions in North America. Human occupation of the canyon extends back 12,000 years and remains a part of the cultural heritage of several Native American groups: the Pueblo, Navajo, Apache, and Ute. The area is a major scientific and archeological resource since it contains a relatively complete record of prehistoric occupation in an area of well-defined ecological boundaries.

Paleo-Indian occupation extended from 10,000-5,500 B.C. with subsistence based upon the hunting of late Pleistocene mega-fauna and the gathering of wild plants. Archaic occupation dates from 5,500 B.C. to A.D. 450 (National Park Service 1980:2). As the mega-fauna became extinct, Archaic subsistence was based upon small game hunting and wild plant food collection. Populations increased and seasonal occupations transpired as evidenced by shallow pit houses, hearths, and grinding implements. A great change in southwestern culture occurred in response to the domestication of maize which took place between 3400-1000 B.C. Between 1000 B.C. and A.D. 1, the culture called the Anasazi (Navajo for "ancient ones") began to develop in the San Juan Basin. It is worth noting that archaic adaptive strategies may have continued in some areas despite the development of the Anasazi culture.

Differing chronologies for Anasazi development have been proposed by various investigators. Anasazi development in Chaco Canyon is generally dated between A.D. 450 and 1300 (Windes 1988). The Anasazi culture is marked by an emphasis on the exploitation of domestic plants, particularly corn, beans, and squash. At this time people became more stationary while individual groups reduced their defined territory. Changes in architecture took place as pit house villages developed into spacious, multi-storied pueblos. It is projected that corresponding changes occurred in social organization. By Pueblo I times (A.D. 700-900) trends toward more elaborate and complex architecture, farming practices, social control, and trade were beginning to emerge. Mexican contact as evidenced through trade items such as copper bells, cloissonne work, macaws, and pottery may have influenced development (Reyman 1971).

Eventually, the development resulted in the "Chaco Phenomenon" whereby the occupants of Chaco Canyon may have controlled the economic, social, and political system of the entire San Juan Basin. This occurred sometime between the Pueblo II and Pueblo III time periods. Pueblo II or Classic Bonito dates from A.D. 1040 - 1100 while Pueblo III dates from A.D. 1140 - 1200 (Windes 1988). The architecture at this time is referred to as "Bonito-style" construction. It is during this time that major engineering and architectural accomplishments were realized including the Chaco roadway system which is the focus of study for this chapter. In addition, "great houses", ceremonial or administrative centers, intensive irrigation systems, and hundreds of small villages existed during the Pueblo II and Pueblo III phases.

The nine Great Houses were the foremost accomplishment of the Chaco culture and were constructed between AD 900 to 1115 (Lekson et al. 1988). These structures are named Pueblo Alto, Hungo Pavie, Kin Kletso, Chetro Ketl, Pueblo Bonito, Pueblo del Arroyo, Una Vida, and Wijiji. Although difficult to date, the Chaco roads seem to have been constructed in conjunction with the great houses. The roads radiate out from the great houses, across unpopulated areas of the Chaco desert. Some of the roads appear to lead to "outlier" sites on the canyon's periphery. The rapid and monumental construction of great houses and roads came to an abrupt halt in the 12th century. The reason(s) for this collapse is/are not certain.

By 1300 A.D. most of the San Juan Basin was abandoned. Although speculations of drought, warfare, political collapse, and social disorganization have been offered, no reason for abandonment has been presented to date. Around 1500 A.D. the Apache and Navajo entered the empty San Juan Basin and began to repopulate the area. Shortly thereafter, minor infiltrations by the Utes and Puebloan cultures occurred. In addition to the sheep-herding and hunting practices, the Navajo practiced raiding and were even temporarily removed from the San Juan Basin by the U. S. government. American pioneers who were settling the region generally avoided the occupied lands of the Navajo; this is why the prehistoric ruins in Chaco Canyon were rediscovered relatively late.

DISCOVERY OF PREHISTORIC ROADS IN CHACO CANYON

One of the major problems in the discussion of prehistoric roads, not only in Chaco Canyon but elsewhere in archeology, has been the fact that these features were only given limited attention by investigators. This fact can be documented in Charles Trombold's Ancient Roads (n.d.) and may be associated with a general tendency to record site-specific information as opposed to the complexity of regional analysis. Another reason appears to be a bias on the part of the investigator. As Trombold states:

> Although some data have accumulated on Old World roads, comparatively little attention has been paid to those of the New World. Part of this may be due to a very early realization that Precolumbian technological development was markedly different from that of the Old World. Thus in the history of technology relating to transportation, most emphasis has been placed on the development of the wheel and innovations to harness the energy of draft animals. Associated with this is perhaps a feeling that roads are synonymous with wheeled vehicles. Since vehicles were not used in the New World before European contact, it followed that the few known Precolumbian roads would be of little real significance, or curiosities at best. We are now discovering that they were more widespread than previously realized and that in terms of construction techniques and engineering of comparable time periods, New World roads frequently showed a marked superiority over their Old World counterparts (Trombold, n.d.).

In Chaco Canyon, for instance, Obenauf (1980a) records that Edgar Hewett was aware of the roads and showed them to his students during his excavations at Chetro Ketl. Despite his familiarity with the roads, Hewett makes no mention of them in his Chaco Canyon publications.

History of the Roads

References to the existence of aboriginal roads in the Southwestern area can be found in many early reports by Spanish chroniclers and American survey and military parties (Vivian 1983). Thompson, for instance, made the following statement based on his observations from 1872-74:

> Their trails are remarkable, extending as they do in a straight line from one pueblo to another, and even traced from ruin to ruin. These deeply-worn paths, even on the rocks, passing without swerving to right or left, over valley, plain, or ascent of mesa--as though the trail was older than the mesas, or before the canyons, gnawed into the plateaus by erosion, had reached their pathway--speak more powerfully than all else of how old a people they are (Thompson 1879:322).

The first authentic map and account of the ruins in Chaco Canyon was made in 1849 by a young first lieutenant of the topographical engineers, James H. Simpson. From a Mexican guide, Carravahal, Simpson recorded and mapped the pueblos of Wijiji, Una Vida, Hungo Pavie, Chetro Ketl, Pueblo Bonito, Pueblo del Arroyo, and Penansco Blanco--names which have survived until today. A Jemez Indian named Hosta, however, convinced Simpson with the erroneous information that these were the remains of the Aztecs under Montezuma and that after living here for awhile, some of them dispersed east along the Rio Grande while others headed south into Old Mexico. Despite his detailed observations and meticulous accounts of the ruins and features in the Chaco area, Simpson made no known mention of roadways. From his account it is obvious that the canyon and the ruins appeared very similar in 1849 as they did to Richard Wetherill in 1895.

The first one to record the existence of roads in Chaco Canyon was S.J. Holsinger, an agent for the Government Land Office who was sent to investigate the homesteading claims of Richard and Marietta Wetherill. Holsinger states:

> ...the remains of an ancient roadway...can be traced from Chettro Kettle stairway to Alto ruins. This road-way was 20 feet wide and walled up to a grade with loose rock and filled with soil. It commenced near the top of the stairway referred to and followed a narrow shelving or terrace of this rock westward, parallelling the canyon. It followed this ledge for about a half mile to a point where there are indistinct remains of a broad flight of steps, twenty-one in number...It is near this point where the first traces of the groove is found and it follows this road-way to a point where it crosses a wash and enters the sand covered mesa where both disappear (Holsinger 1901:67-68).

It appears that Holsinger's observations resulted from conversations with the Wetherills. Forty-seven years later, Gordon Vivian recorded that in the course of his conversations with Marietta Wetherill, she mentioned that:

> North of Alto in certain lights you can still see what appears to (be) a wide roadway running down to the Escavada. In the old days this was very clearly defined in the spring or early summer because the vegetation on it was different from any other and it could be traced clear to the San Juan (Vivian 1948:3).

Today this is called the Great North Road and will be discussed in greater detail below. In the fall of 1983 I was able to successfully view portions of the Great North Road at sunset, from Pueblo Alto, particularly that on the north side of the Escavada. This was at a time when the vegetation on the north mesa was dead as opposed to vibrant spring vegetation mentioned by Mrs. Wetherill. It should be mentioned that none of the roads I viewed in 1983 were visible throughout the day and that the north road was only visible for a few lingering moments prior to sunset.

In the northern San Juan Basin near Aztec, New Mexico, Earl H. Morris recorded that the stone used in the construction of the Aztec site "was brought over a broad road which is still visible, winding over hills and across arroyos..." (Morris 1915:666). A photo of this road appeared a year later with the caption: "Ancient Road Near Aztec, N.M.: The road is perhaps thirty feet wide, its sides being marked with pebbles and boulders. It is very well defined and may be seen from the train several miles away" (Wadleigh 1916:52). J. Walter Fewkes was aware of the Aztec road when he referred to it to support his explanation for a road segment he found south of Chaco Canyon at Kin Ya'a. He mentioned that other such trails had been found in the State and that they were probably used to haul building stone (Fewkes 1917:15).

Neil Judd was acutely aware of the roads in the 1950's and 1960's and indicated that he planned a future publication on them, although this was never realized. His first exposure to the roads seems to stem from his work with Navajo informants in Chaco Canyon between 1921-1927. During Judd's excavations, which were sponsored by the National Geographic Society, a 95 year old Navajo informant, Hostten Beyal, commented upon the roads. Judd records:

> When asked about the so-called "roads" on both the north and south cliffs, Beyal remarked that they were not really roads, although they looked like them. He says that they were built by the Chaco people. One road led from Pueblo Pintado to Pueblo Bonito and one to Penasco Blanco. Another led from Pueblo Bonito to Kin-Yai; a third from Kinbiniyol to Kin-Yai; still another from Kinbiniyol to, or through, Coyote Canyon and on to a point near Fort Defiance. On each of these "roads" one could see until recently, cuts where the road passed through small hills (Judd 1954:346).

I would like to draw attention to Beyal's statement that "they were not really roads, although they looked like them." I believe that this is an insightful statement which demonstrates that our westernized concept of "roads" may be misleading if directly applied to these features. For the purpose of this investigation in Chaco Canyon I will use the term "road" in a broadened sense rather than in the transportation sense of our modern-day usage.

Judd appears to have provided the information for an article which appeared by an anonymous author in a 1928 article. The article states that:

> The stairways are from 5 to 10 feet wide and some of them have a 10-in. tread. The roads, if that is what they were, vary in width from 15 to 20 ft., and are usually lined with boulders, which were rolled to one side in the clearing process. On sloping ground the lower side of the road was built up, and where the mesa changes levels abruptly, steps were cut in the rock (New Mexico Highway Journal 1928:9).

Judd also notes that stairways are associated with all the major ruins and that the roads connect to these structures:

> Jackson's stairway is one of the best, but what was its purpose? The diverse "roads" are equally beyond convincing explanation. There is the broad pathway extending southeast from Pueblo Alto with 10-20-footwide hammer-battered steps at every ledge and a pecked groove throughout much of its length; there is the retaining wall edging a 30-foot cliff at the end of the trail. There is another step series across the canyon, irregular and cramped, and a cleared path from rimrock toward Tsin Kletsin. There is a magnificent stairway overlooking Hungo Pavie and a conspicuous "road" dug through a sand ridge south of the Gap. Each was a prodigious undertaking of which the Late Bonitans or their contemporaries were thoroughly capable but each remains a mystery (Judd 1964:142).

Unfortunately it took over forty years for Judd to publish his comments on the Chacoan roads. During that time the focus of Chaco research centered upon the puebloes and shifted away from ancillary features such as water control devices, roads, and outlier sites. For instance, Brand states that in regard to the subject of irrigation that there was "neither evidence or need for such an assumption (Brand et al. 1937:114).

The subject of roads was resurrected when Gordon Vivian discovered linearities on Soil Conservation Service aerial photographs in the late 1940's. He also studied aerial photographs taken by Charles Lindbergh in 1929 and even contracted for the acquisition of new photography. Although he interpreted these features as "canals", his son Gwinn Vivian, who took over the project, determined in 1967 that many of the features were in fact prehistoric roadways rather than canals. He altered his research of the canal system and identified a system of six "road systems." He described the roads as containing:

> ...one or more of the following attributes: wide, cleared, primary roads averaging nine meters in width with edges of banked earth or low masonry walls and bases of earth or bedrock...spur roads averaging four and one-half meters in width with edges and bases similar to primary roads; stairways cut into native sandstone with squared sides and widths up to nine meters...wide masonry stairs at minor cliff edges, and masonry and earth

> ramps at major cliff edges. In some instances roads were cut through low hills. Roadways also were marked by relatively straight courses showing occasional slight alteration in degree of orientation (Vivian 1972:10,12).

Recent Research

As a result of the energy crisis of the 1970's, archeological research expanded in Chaco Canyon. Chaco Canyon held some of the richest coal and uranium deposits in the U.S. and was also rich in oil and natural gas. Although Chaco had been studied archeologically since the turn of the century, little was known about the cultural features away from the canyon proper, with the prehistoric roads being the least understood of all.

Three major sponsors were to have a prominent effect upon the Chaco roads investigation: the National Park Service, Eastern New Mexico University, and the Bureau of Land Management. All three sponsors included in their objectives the detecting and mapping of the prehistoric roads as well as the development of new analytical techniques such as stereoscopic analysis. As a result, new aerial photography was gathered and new techniques were applied to the road study. An example of this is recorded by Obenauf:

In April of 1972 the first of a series of flights

> was made over Chaco Canyon for the specific purpose of locating prehistoric roads. The new black-and-white photographs, flown at a scale of 1:6000, proved useful in mapping the complex network of roads within the Monument boundaries. Experimentation with scale, however, showed that the smaller scale imagery, such as the USGS imagery at 1:32000 was better suited for locating and mapping the roads (Obenauf 1980a:41).

The Bureau of Land Management (BLM) was charged with the task of mitigating economic development in conjunction with cultural resource protection. The BLM Chaco Roads Project used a multidisciplinary approach to the study of the roads and was conducted in two phases. The results of this project (Phase I:1983 and Phase II:1987) advanced the Chacoan roadway study considerably. The BLM-sponsored project determined that the roadway system extended far beyond Chaco Canyon and that it had been built in the few decades prior to the abandonment of Chaco Canyon. These dates of construction were determined from ceramic materials and roadway association with architectural features such as earthworks and great kivas. An important conclusion they reached was that the road system is an architectural manifestation of the great houses which they join.

One observation that was readily apparent from all the investigations was that the earlier photography was superior. Tom Lyons, for instance, compared the same scale photography from the mid 1930's to that taken in the 1960's. He determined that the roads were more apparent in the earlier photography due to more distinctive vegetational differences. This may be the result of overgrazing in Chaco Canyon during the 1940's and '50's (Sever 1983). Overgrazing had also taken place at the turn of the century.

Many models were tested to explain the purpose and function of the Chacoan Roadway network. These models included geographic models based on central place theory such as the Christaller model, dendritic model, and Garrison model. A complete description and interpretive results of these models can be found in Chapter 3 of the Chaco Roads Project Phase I: 1983.

In general, most of these models do not work in light of recent archeological evidence. As will be seen, previous archeological interpretations have been altered with respect to climate, population, and even the room functions within the pueblo itself. To date, no convincing explanation for the purpose of these roadways has been satisfactorily presented.

CHACO ROAD CHARACTERISTICS

The roads in Chaco Canyon exhibit a number of constructional similarities along their course that appear elsewhere in the San Juan Basin. These similar characteristics are used to differentiate prehistoric roads from other linear features which appear in remotely sensed data such as irrigation systems, historic fence lines, and geological faults. The extent of the roadway system is not known and there may yet remain other distinguishing characteristics which have not yet been identified. The roadway characteristics presented here are based on a number of ground level investigations conducted between 1972 and 1987.

One goal of the present project was to locate prehistoric roadways which had not been found through either ground survey or aerial photography. The purpose for using multispectral digital airborne imagery was to see if it could locate features that had not emerged from conventional photography. Geological processes, which have been recognized in other remote sensing research (Rickman and Grant 1985), have tended to modify the roads through time.

> Past and present environmental characteristics in the San Juan Basin area are only moderately conducive to the preservation of linear features such as roads. Although the climate is relatively

dry, the combination in many places of loose, sandy substrate, windiness, limited vegetation, sometimes intense, flashy rainfall, and cold winters which facilitate frost heaving of damp sediments have all served to gradually obscure prehistoric roads. In addition, intense overgrazing, especially during the late 1800s and early to mid-1900s resulted in erosion which further obscured these features (Nials 1983:6-1).

The time of construction for the roads in Chaco Canyon is not known with certainty. In general, they appear to be manifestations of the 11th and 12th centuries as evidenced by ceramic scatter and their association with Bonito-style architecture. The chronology in which the roads were built is not known nor does there appear to be an evolutionary development in construction. The roads seem to be part of the Chaco phenomenon and their association with great houses, earthworks, and shrines suggest an 11th-12 century date. One possible exception is the South Road which, contrary to other opinions (Windes 1982), the BLM ascribes an earlier date to the 10th century based on its analysis of ceramic material (BLM 1983:9-77).

Straight Linear Course

The most common feature of the Chaco roads is their straight line course which is maintained in spite of topographic obstacles (Figure 4-3). This consistent pattern has been recorded by a number of investigators (Lyons 1973; Lyons and Hitchcock 1977; Ware and Gummerman 1977; Obenauf 1980a; Hayes 1981). The Bureau of Land Management's Chaco Roads Project states:

> Detailed measurement of road segments for this project revealed that the reportedly straight roads actually consist of a series of approximately aligned straight segments, which together often produce a straight trend for a larger portion of the road. Any individual segment may deviate slightly from the trend. These deviations are hypothesized to represent adjustments to maintain the desired course. Minor course adjustments appear to have been accomplished by meands of slight angle changes usually occurring either at higher topographic positions such as ridge tops or in drainage bottoms. It is usually not possible to see the actual angle change on the ground (Nials 1983:6-27).

When the roads do change direction, they do so abruptly in a "dog-leg" fashion. These abrupt angle changes generally occur only at sites, at topographic features such as high passes and wash crossings, or at a confluence of roads. Although they occur infrequently, I have walked on Anasazi roads that do make lazy or curving bends. In general, however, the roads are remarkable in their linearity. The purpose for the straightness is not entirely clear and has never been satisfactorily answered. Most researchers feel that the straight roads do not "represent the most efficient trajectory through the hinterlands" (Morenon 1975:8-10). Nials, on the other hand, compared the Great North road to the modern Chaco Canyon-Blanco Trading Post road and determined: "Somewhat surprisingly, the North Road, despite going straight over obstacles, appears to be the more 'efficient' of the two roads, having less total elevation change and a shorter distance between endpoints" (Nials 1983:6-27). Nials himself warned that this was not a completely valid comparison since the roads were not exactly parallel. While he does not explain his approach fully, it appears that he does not include enough variables or weight factors in his model to warrant an accurate conclusion either way.

Width

The width of the roadways is as distinguishing a characteristic as their linearity. Generally, they maintain a consistent width of nine meters. Occasionally they may narrow at a shrine or "herradura", at areas of steep terrain, or they may widen as they reach a great house. A secondary type of road is about half this width and is associated with localized "spur" roads. The purpose and destination of these secondary roads is not known. The reason for this consistent 9 meter width of the primary roads remains obscure since it is wider than necessary for pedestrian use and the Anasazi did not have the wheel or beasts of burden. The width of the roads in Chaco Canyon is a unique feature that separates them from other trail systems in North America with the exception of the consistently wide Maya sacbes (roadways).

Stairways

In order to maintain the straightness of the road it was often necessary to make rock-cut stairways as the road entered and exited Chaco Canyon (Figure 4-4). Many of the stairways, but not all of them, are associated with the roadway system. The stairways fluctuate dramatically from minor modifications of access routes with simple hand and toe holds to formally laid flights of wide masonry stairs. Two of the foremost stairways in Chaco Canyon are Jackson stairway, located in the eastern part of Canyon, and the stairway above Pueblo Bonito. In both instances the stairways are directly associated with verified roads. Another stairway associated with the roadway system is located to the north of Chaco Canyon along a prehistoric road leading to Kutz Canyon.

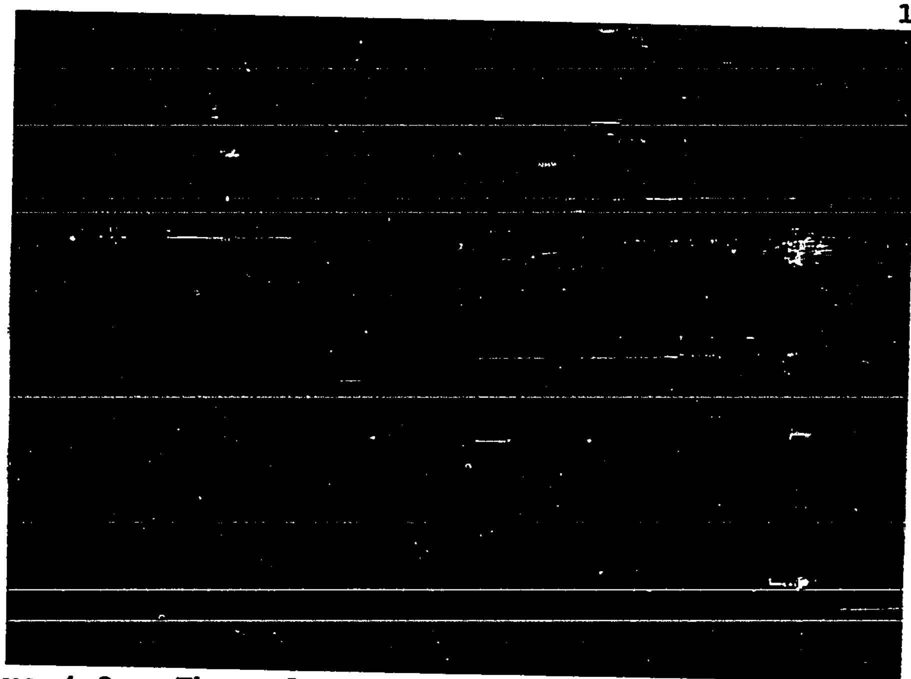


Figure 4-3. Thermal Infrared Multispectral Scanner Image showing the straight linear course of Anasazi prehistoric roadways (in white) and a dog-leg turn along the North Road as the roads enter and exit the north gate at Pueblo Alto.

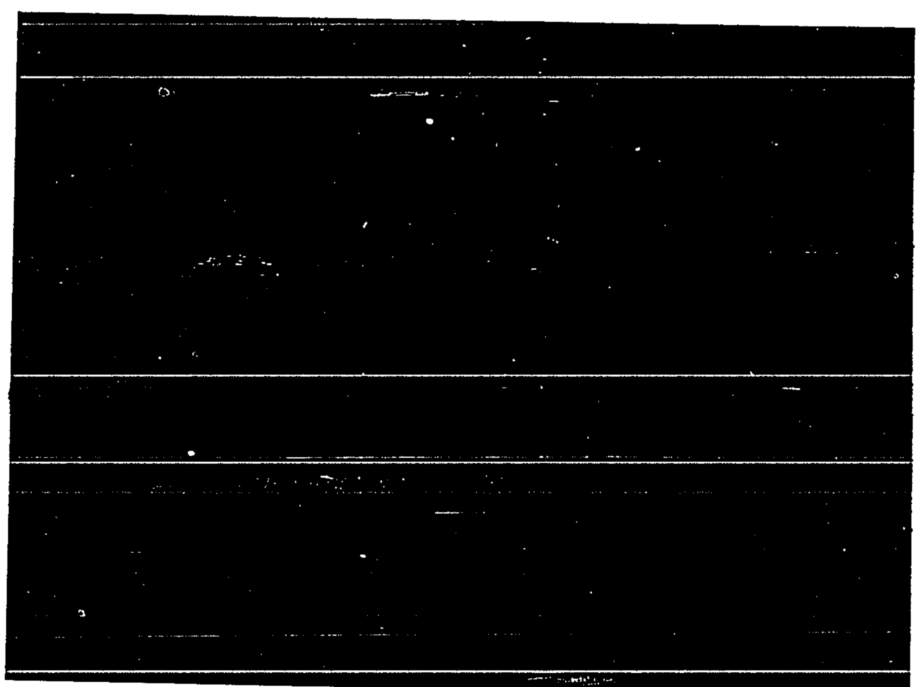


Figure 4-4. Ground photo of Jackson's staircase on the north side of Chaco Canyon.

Causeways

A causeway is defined as a raised road which maintains both sides above the surrounding terrain. Confusion occurs when only one side is found and the investigator must decide between classifying it as a "wall" or part of a causeway. The so called "causeway" at Pueblo Alto (Lyons and Hitchcock 1977:123,125) lies directly between road segments and stairways. This appears to be more of a wall, however, than a causeway. Walls have been found only in the Pueblo Alto and Tsin Kletzin areas and consist of from 1 to 6 courses of masonry.

The only two causeways which have been confirmed with confidence each lie in low areas near Penasco Blanco. One of these two causeways is visible on aerial photography (Obenauf 1980a) and a prehistoric road is visible on both sides of the causeway as it crosses an arroyo. Other low-lying causeways that may have crossed streams would have long disappeared as a result of centuries of destructive flooding and lateral movement of channels. Investigators classify causeways with caution since many natural features can be responsible for the apparent elevation of the road. For instance, materials eroding along the road can collect at a low area giving the appearance of intentional fill-dirt.

Roadcuts

Roads often form depressions at the tops of hills and dunes. While there is occasional evidence of deliberate cutting, roadcuts are primarily caused by erosion and compaction. Sometimes the roads can be seen leading to a roadcut while othertimes the roadcut may be the only indication of a possible road.

Ramps

Ramps occur at cliff edges and are made by piling stones in order to provide access from one ledge to another. Sometimes the ramps occur in conjunction with stairways although it is not known whether or not the ramps were covered with soil in order to provide a smoother surface. Several ramp structures have been located in Chaco Canyon such as the one near Chetro Ketl (Figure 4-5). Hayes located 11 ramps and notes that:

> ...an earth filled masonry retaining wall was...placed at the foot of a stairway, probably for a ramp or landing stage. All of these were associated with roadways (Hayes 1975:84).

Borders

Borders (or curbing) are constructional features, such as stone alignments, that occur at the edges of roads (Figure 4-6). Border elements are difficult to classify because of their varied nature. They are seldom continuous for more than 20-30 meters and are often present only on the downhill side of a slope. It is not known whether the borders were made by deliberately placing stones at the edge of the roadway or were formed as a by-product of clearing stones off the roadbed and tossing them toward the edge. Sometimes the borders are composed of low masonry edges up to a meter in width, while at other times they are formed from large sandstones up to a meter in length that are laid end to end. Generally they are formed from small stones and soil and are often difficult to recognize from surface survey since they are badly eroded or buried. Compared to the extensive lengths of the roadways, borders occur very infrequently.

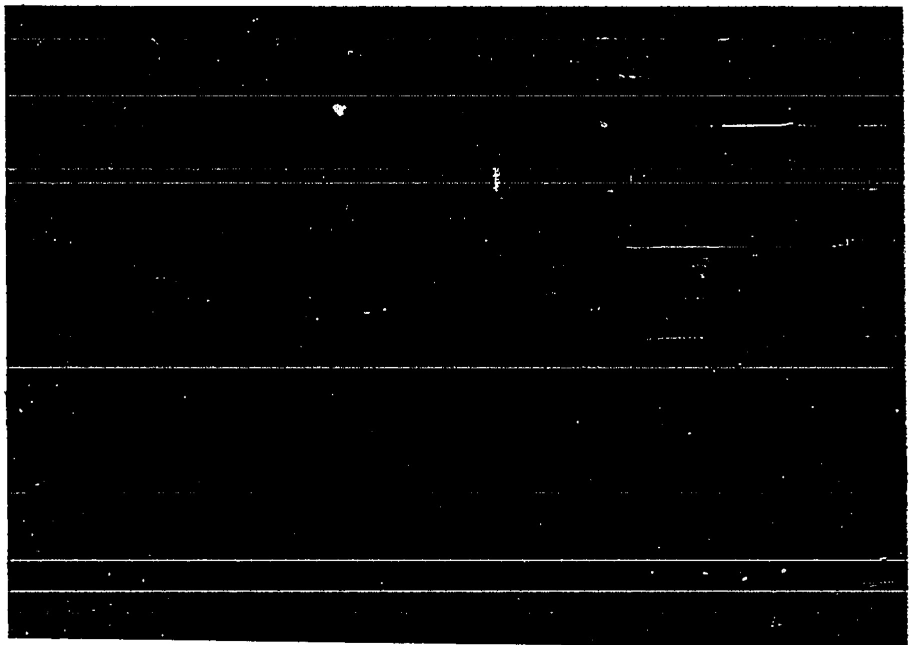


Figure 4-5. Ramp outside of Chetro Ketl.

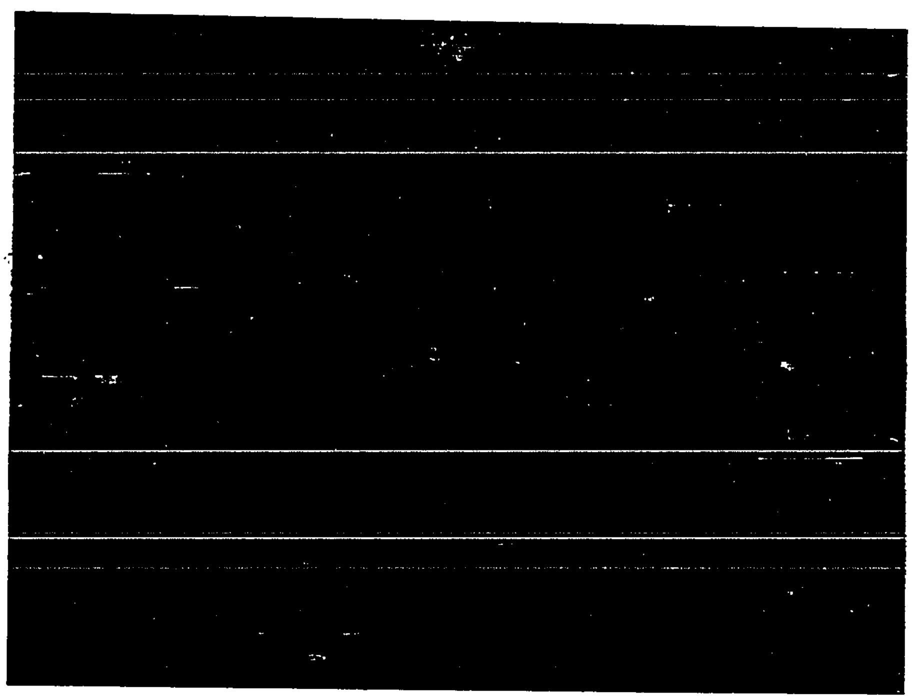


Figure 4-6. Fred Nials of the Bureau of Land Management study pointing to the stone alignment border of the road between Pueblo Alto and Pueblo Bonito.

Cairns and Herraduras

A number of stone structures such as cairns are found in association with roads. The features can be confusing, however, since they are not associated with diagnostic material and may trace to either Anasazi, Pueblo, or Navajo occupations. A number of cairns are found in Chaco and are often associated with the roads. The cairns are circular piles of stone that are generally only a meter in height and diameter. Cairns are often located in prominent positions upon the landscape but the historic reuse and reconstruction of prehistoric cairns as well as the recent construction of new cairns makes it difficult to determine their association, if any, with prehistoric roads.

When the roads reach a high pass or a major topographic break a small masonry horseshoe-shape structure is found adjacent to the road. This structure is called a herradura. In general, the opening to the herradura faces the road. Most of the herraduras are located on the west side of the road with the opening to the east. The function of a herradura is not known but is sometimes interpreted as a "shrine." Nevertheless, a herradura is considered a reliable indicator of a road. Nials states:

> They appear to have been hastily constructed, possibly incorporating both masonry and jacal elements. Material assemblages consist primarily of ceramic debris with no evidence for formal midden deposition, repeated camping, manufacturing, or processing activity. ...the herradura form is seldom found on the southern and western road systems, occurring only at major topographic breaks where visibility for some distance in at least two directions was possible (up to 7 km)... Other than great houses, herraduras are the most common feature marking the intersection of two prehistoric roads (BLM 1983:9-16).

Herraduras show no evidence for burning and thus were not used for pyrotechnic signalling. Herraduras are the most useful structure in locating roads between great houses. They are consistently located on top of major topographic breaks and are built in a horseshoe-shape. Their location always affords an excellent view in both directions along the road which generally appears as a depression with berms as it encounters the herradura. The structures are indigenous to the late 11th and early 12 centuries and are made in the Bonito style tradition. This time frame makes them compatible with the construction of roads and great houses. Herraduras often mark the locations where roads make dog-legs, or slight linear changes in direction, suggesting that the builders are going out of their way to include topographic projections into the overall road pattern. The locations of herraduras have been successfully used to schedule aerial flights which indicate roadway segments not seen from ground level.

Parallel Routes

An intriguing characteristic of the roads is the occurrence of parallel road segments. These segments have been identified in aerial photography but are difficult to recognize from ground level (Morenon 1975). Seven parallel segments have been discovered and confirmed while many other segments have been reported but not confirmed. Twelve miles north of Chaco Canyon, near Pierre's Ruin, two sets of parallel segments have been found which form a 4-lane strip. These four segments appear to be almost perfectly parallel to each other in the photography and the TIMS imagery, but have not been verified, since they are invisible from ground level, and as Nials states:

> ...initial reconnaissance efforts to locate them on the ground were fruitless. A few sherds and occasional stones were found, but conclusive verification was not possible using reconnaissance techniques (Nials: 1983:6-29).

The purpose of the parallel roads is not known although similar phenomena have been reported elsewhere in the New World such as at La Quemada, Mexico (Trombold, personal communication 1989) and in Peru. One obvious explanation is that a new segment was constructed to replace an older one. This can be seen at Arenal, Costa Rica where short segments appear adjacent to a path after it has worn down to the slippery clay surface. Another postulation is that the parallel segments were used by different groups within the society. This view is supported by the existence of parallel roads in Peru which were used by different segments of the Inca population:

> There existed along the sea five roads that crossed the Lurin Valley. The fifth...bordered the sea and belonged to the chasques. The fourth served the traffic in which fish was carried to Lima...there is no indication of who used the remaining roads (Rostworowski de Diez Canseco 1977).

In Chaco Canyon no conclusion concerning the relative age or function of parallel roads can be made without further research.

HISTORIC ROADS

Historic roads are generally easy to distinguish from prehistoric roads both from ground level and from photointerpretation. These distinguishing characteristics have been well documented (Nials 1983:5-23,27). The edges of historic roads are usually sharply defined while prehistoric roads are generally poorly defined. The width of historic roads is from 2-3 meters while prehistoric roads are 9 meters. Historic roads are often rutted and eroded while prehistoric roads have a broad, shallow, concave profile. Historic roads curve and meander as they avoid obstacles upon the landscape while prehistoric roads are linear and typically do not make major deviations in alignment. Historic roads may show turnarounds at their destination while prehistoric destinations are often associated with prehistoric sites. Historic roads can be seen on alluvial valley bottom lands while prehistoric roads have disappeared due to erosion and/or deposition. In the aerial photography historic roads are often lighter than the surrounding landscape while prehistoric roads commonly appear darker than the adjacent landscape. Historic roads may incorporate modern features such as dams and fields while these same features are superimposed upon or obscure the prehistoric roads.

DISAPPEARANCE OF THE ROADWAY SYSTEM

The Chaco roads have been disappearing at an accelerating rate due to a natural and human processes. This disappearance can be documented by early descriptions of the roadways and a comparison of aerial photography between 1929 to present. A major handicap in the mapping of the roadways has been the discontinuous preservation of the roads themselves. Some segments are found over six feet below the surface while other segments have disappeared completely. The major road88s that have been mapped are often no more than a series of discontinuous segments. The South Road has an eight mile gap in it where there is no evidence for a road whatsoever. It could be argued that perishable markers, such as wooden posts, could have been used to mark these missing road gaps, or that erosion had completely erased any evidence of them. It is also possible that there was simply no road in these areas in the first place.

Multispectral imagery from NASA sensors was therefore acquired and analyzed to address these questions. It was thought that advanced remote sensing technology might be able to locate road segments that were not visible from ground level or apparent in aerial photography.

ANASAZI ENGINEERING

In an attempt to explain how the linearity of the roadways may have been achieved, it was initially thought that the Anasazi traversed the landscape by sighting on a distant landmark and walking toward that feature. One argument states:

> It appears that the Chaco road system was not formally engineered--in the sense of being "constructed" or "built"--in its entirety but was instead the result of "navigational" routes that facilitated foot travel between points of population aggregation. These routes in some cases ran in the direction of topographic landmarks that were known by the inhabitants of Chaco to lie near desired locations. This might account for the surprising linearity of the roadways through the region's uneven terrain (Ebert and Hitchcock 1980:188).

Closer inspection of the roads, however, reveal that they deviate only slightly from their linear trajectory even though the landmark is hidden by a topographic feature. The only way to account for the linearity is a system of foresights and backsights similar to those used today in surveying work. In this technique a surveyor uses a theodolite at a fixed point and sights to the previously marked point behind him. He then reverses the telescope 180 degrees to the next point on the horizon and waves the flagman to that point who then marks that position. By moving forward to this new point, backsighting to the previous point, and projecting 180 degrees to a new point, a straight line can be constructed across the landscape. Anasazi engineers could have created straight patterns in the same way using a combination of 3 landmarks and/or people.

Current evidence shows that the Chaco roads were extensively engineered. The consistency of the road characteristics throughout the area reveal a prescribed engineering template that was followed with remarkable consistency. It may be possible that some of the 1 meter stone cairns are artifacts of the survey itself prior to road construction and that they were not functional components when the road was used. The cairns may have been similar to survey flags. One way to test this possibility is to record the position of all the prehistoric cairns upon the landscape and see how many are associated with roadway alignments.

Anasazi engineering extends throughout all aspects of Chaco Canyon construction (Figure 4-7):

> Overengineering, typified by the masonry walls, is a prevalent feature at Chaco Canyon...The sandstone blocks fit together tightly, forming walls that are as much as a meter thick at ground level and decrease slightly with each successive story...as many as 50 million pieces of sandstone

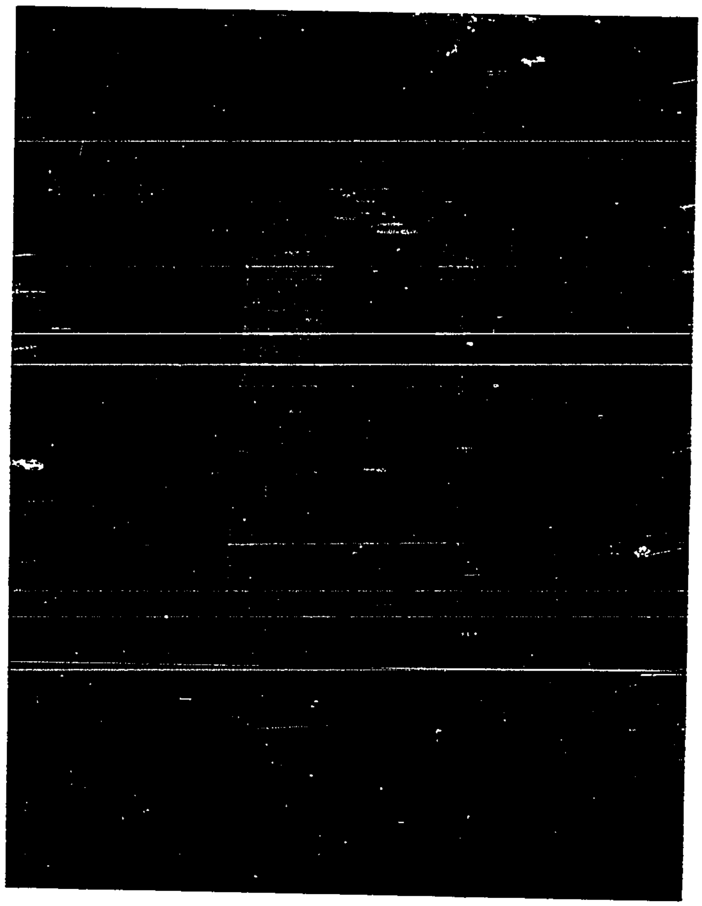


Figure 4-7. Rooms in the back of Pueblo Bonito showing the masonry and "over-engineering" typical of the great houses. Over 50 million pieces of stone are incorporated into the architecture of Pueblo Bonito.

> may have been cut to build Chetro Ketl alone...The formal geometry of the floor plans is another prominent feature of Chacoan architecture. Rooms and kivas...are arranged in gridlike patterns...Such linear precision and complexity could not have been accomplished without advance planning and the active involvement of architects (Lekson et al. 1988).

It is apparent that the Chacoan roads are not simple trails that have been created through prolonged wear but carefully surveyed and engineered constructions. This factor is important for the later discussion of the roadway system.

REMOTELY SENSED DATA

Aerial Photography

During the 1970's and 1980's several investigators used aerial photography to locate prehistoric Chacoan roads (Vivian 1970; Vivian and Buettner 1971; Ware and Gumerman 1977; Ebert 1973; Hitchcock 1973; Morrison 1973; Lyons 1973; Marshall et al. 1979; Lyons and Mathien 1980; Obenauf 1980a, 1980b; Flynn 1981; Sever 1983; Bureau of Land Management 1983,1987). With the exception of the Bureau of Land Management study, most of the investigators discovered that vegetation was the primary factor responsible for the appearance of the roadways in the photography. As Potter and Kelley state:

> In summary, changes in vegetation in the arid and semiarid Southwest occur in response to relatively minor environmental conditions, especially as these affect the soil-plant moisture relationship. Thus, there is a close link of vegetation to features of geology, physiography, and soils. It is almost imperative that the investigator become familiar with these relationships before mapping from the aerial photographs. With these basic relationships in mind, one can turn to the aerial photos and apply an understanding of a multiplicity of ecological factors to the interpretation of the photos and, thus, produce a more meaningful designation of vegetational types (Potter and Kelley 1980:103).

Due to the complexity of geological and environmental factors in Chaco Canyon, however, the proposed technique of Potter and Kelley has not been successful. As Nials concludes:

> The presence or former presence of roadways may in some instances be indicated by modified vegetation. Prehistoric roadway vegetation characteristics are highly variable, and no definitive criteria for the use of vegetation for consistent recognition of prehistoric roads have yet been developed (Nials 1983:5-2).

An important aspect of photointerpretation in the detection of the Chacoan roads is the elevation and azimuth of the sun. Hackman's (1967) geological research determined that sun angles of 10 degrees or less could reveal subtle variations that are otherwise unrecognizable in the photography. This approach was used successfully by archeologists in many of the Chaco photointerpretation studies.

Low sun angle photography is helpful in road recognition since it accentuates low topographic relief variations. Low sun angle photography favors linear features that run north to south over those that run east to west. Topographic variations can be due to the slight depression in the road that is caused either culturally or by erosional processes. Outcropping in the roads can also cause vegetation to be slightly taller in the roadbeds as opposed to the bordering sides. It should be remembered that in most cases these subtle topographic variations are not visible from ground level and thus create a problem in field verification.

Originally, radar data was scheduled to be collected for this study. Since the radar supplies its own energy, it was thought that low angle acquisition would be useful for detecting prehistoric roads. Unlike the fixed movement of the sun, flight paths could be arranged to produce optimum angles for road detection. In addition, radar data can be processed to reveal lineations that are far superior to aerial photography. Unfortunately, the NASA airplane with the radar system crashed on take-off in 1987 and both were destroyed. The use of radar data still remains a viable approach in the detection of the Chacoan roadway system and will be investigated in future NASA studies.

An important question in the detection of prehistoric roads is what is causing them to appear either in the photography or the digital imagery? Crisp lineations on the photography or imagery are often invisible from ground level and thus it is difficult to determine what properties are causing them to appear. The photography itself is affected by factors such as time of day, time of year, scale, processing, and type (black and white, color, or color-infrared) causing lineaments to appear on some photographs but not others. The factors which are responsible for the lineaments which can be seen from ground level include vegetation, soil, erosion, and topographic expressions.

The Bureau of Land Management arrived at several conclusions about low angle photography in the Chaco Road study (Obenauf 1983:4-20):

1. Best photography is acquired within one hour of sunrise; early morning is clearer than the dust and haze of the afternoon.

2. Roads are enhanced in the spring growing season, approximately two weeks after the first heavy rain.

3. Roads are most visible on low sun angle photography, at a scale from 1:20,000 to 1:30,000.

4. Even for an experienced photointerpreter, the roads are difficult to see in photography gathered in broad daylight.

Although not mentioned in the BLM report it should be added that another preferable reason for early morning acquisition is due to the fact that wind turbulence increases in the afternoon making the aircraft less stable. While a successful approach had been developed for aerial photography, little was known about what type of approach to use for digital imagery. This research was therefore initiated to learn about the potential of multispectral image analysis for the detection of the Chacoan roadway system.

Digital Imagery

Several sets of remotely sensed digital imagery have been collected by NASA over Chaco Canyon. This data acquisition is an outcome of a feasibility study in 1982 to test NASA technology for application to the discipline of archeology. The objective of the research was to develop remote sensing techniques for delineating and inventorying archeological sites and features in order to expedite survey and excavation. As a result of this original study, new state-of-the-art sensors were flown over Chaco Canyon in a continuing effort to develop effective instruments and methodologies for archeological research in arid environments.

The following remotely sensed digital imagery has been acquired for Chaco Canyon:

Table 4-1

SYSTEM	MISSION	DATE	RESOLUTION
TMS	284	1 APR 82	10m
TMS	284	1 APR 82	30m
TIMS	518(DAY)	28 AUG 82	5m
TIMS	518(NIGHT)	28 AUG 82	5m
TIMS	645(DAY)	1 SEP 87	5m
TIMS	645(NIGHT)	4 SEP 87	5m
TIMS	FCF(DAY)	29 JAN 88	5m
CAMS	416	16 OCT 88	5m

With the exception of nighttime flights, all data was collected simultaneously with CIR photography (Kodak 2443) at 60% forward overlap for stereoscopic viewing. The photography is also used to relate ground truth information with the digital data. A complete archive of all the photography and digital data acquired by NASA over Chaco Canyon and used in this investigation is listed in Appendix B.

All analog Pulse Code Modulation (PCM) tapes from the aircraft were decommutated into a computer-compatible format and overlapping scan lines were removed. Since all data acquisition conversion and digital analysis were conducted at the Science and Technology Laboratory (formerly the Earth Resources Laboratory), the data were reformatted into the ELAS software format. Because the data were not acquired with the aircraft oriented parallel to solar azimuth, the ELAS module CRSX (Junkin et al. 1981) was used to analyze the effects of sun angle and atmospheric scattering (Rayleigh and Mie scattering). These effects were minimized using the ELAS programs RAMP and DRMP (Junkin et al. 1981) before initiating data analysis. RAMP computes the column means and standard deviations for the data file while DRMP uses correction coefficients to average the response across a desired number of elements, thereby correcting a data set for sun angle effects.

In 1976 a Bendix MS multispectral scanner was flow over Chaco Canyon in support of a National Park Service study. The results of this effort (Lyons 1981) were basically inconclusive, particularly in regard to the detection of prehistoric roads. It was felt, however, that the use of the TMS might be more successful for similar investigations in Chaco Canyon. This was based on the fact that the TMS offered improved spectral and spatial radiometric fidelity over the Bendix MS scanner. In addition, the data could be analyzed by the Earth Resources Laboratory Applications Software (ELAS), which contained advanced statistical analyses packages that made it one of the most powerful analytical tools for image processing available at the time.

The applicability of advanced digital remote sensing for archeological investigations were basically unknown at this time. As we have seen, Chaco Canyon has an extensive history in aerial photointerpretation and ground truth reconnaissance. Consequently, Chaco Canyon was selected as an initial study area so that the response of the sensors and data analysis could be compared with the results of previous studies.

THEMATIC MAPPER SIMULATOR (TMS) DATA

Previous Chacoan roadway research had indicated that the best time for data acquisition would be in the spring, when the roadways would be accentuated by vegetational differences. Preliminary TMS research had indicated that it was a useful instrument in separating vegetational species. Based on this premise several flight lines of TMS data were gathered over Chaco Canyon on 1 April 1982.

After reviewing the raw data channels on an image display device, the SRCH program was used to perform an unsupervised signature development on the data from the area of the North Mesa around Pueblo Alto where most of the prehistoric roads converge. The SRCH program progressively moves a square, nine-pixel (3X3) window throughout the data and evaluates each block of values for homogeneity. Each block of data is assigned a spectral signature and compared to the signature previously collected. As a result of this comparison the block signature is either assigned a new signature or merged with an existing signature. Various input parameters were designed to produce optimum signature development. The same approach was employed using the PTCL program which is similar in concept to SRCH but develops statistics one pixel at a time. This was necessary due to the 10 meter diameter of the roadways.

The selected area was classified using MXAP, which calculates maximum likelihood class assignments. The end product of this technique is a land cover classification which visually illustrates the occurrence of ground surface characteristics. An analysis of the developed statistics can be used to reveal the nature of the classes depicted in the final classification scene. It was hoped that this approach would separate the roadways through the vegetational components that were discussed so frequently in past Chacoan research. The SRCH technique produced 16 classes while the PTCL technique produced 31 classes. Both signature development techniques, however, failed to locate the Chacoan roads in the TMS imagery. The reason for this will be explained shortly.

Since the signature development approach was unsuccessful, several image enhancement techniques were tested. These techniques consisted of linear stretching, band ratioing, and principal components. These techniques have been successfully applied in geological and urban studies for linear enhancement and extraction (Moore 1980).

In the linear stretching technique the DBAS module in ELAS was programmed to increase the dynamic range of the data. The lowest and highest 1 percents of the data were discarded since they represented noise rather than actual data responses. The remaining 98 percent of the data were scaled and stretched to count values 0 to 255. This process was performed on all seven TMS bands (Table 4-2) and produced an enhanced black and white image that was more conducive for visual analysis.

TABLE 4-2

LINEAR STRETCHING OF TMS VALUE COUNTS

Channel:	1	2	3	4	5	6	7
Low Value	87	92	88	93	99	116	47
High Value	207	234	232	233	221	235	208

Linear stretching was more successful in distinguishing road segments than either principal component analysis or band ratioing. Of the seven channels, channel 7 (10.43-12.33 micrometers, the only thermal channel) revealed more roadway segments than the others. While the other six channels revealed short isolated roadway segments, channel 7 alone disclosed extended roadway segments and their characteristic linearity (Figure 4-8). Although channel 4 (0.77-0.90 micrometers, an infrared channel) detected vegetative differences in some of the roadways, spectral confusion arose between roadways, gulleys, and other erosional features. In addition to the roadways, channel 7 also revealed a number of archeological features such as site

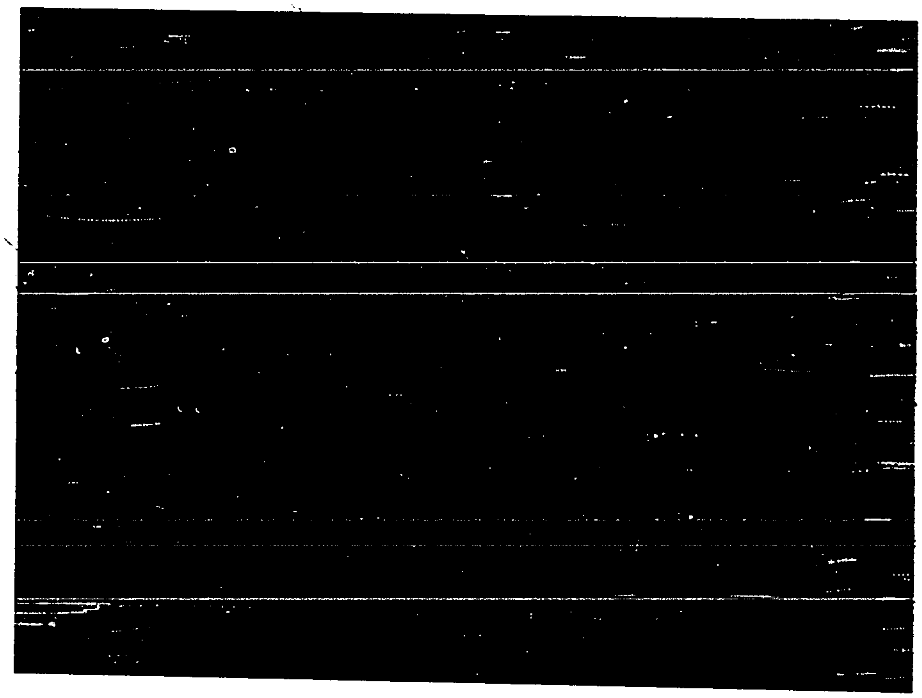


Figure 4-8. Comparison of TMS thermal band (channel 7) with infrared band (channel 4). The thermal band detected more prehistoric roadway segments than any of the other 6 TMS bands.

locations, buried walls, and prehistoric agricultural fields that were not apparent on the other 6 bands.

The road segments that were revealed in channel 7 were extracted and used in a scattergram classification. The ELAS modules SCAT and SCCL are companion modules that are used to generate scattergrams and to classify data contained in a specified portion of the scattergram. This technique allowed the roads to be viewed statistically against the spectral content of the entire data set. The scattergram approach confirmed previous archeological ground truth investigations which indicated that the roadways are composed of diverse vegetational, geological, and erosional components. Laid against the background of the surrounding terrain, the pixels representing the roadways are scattered throughout the entire data set. In short, a unique spectral signature does not exist for the roadways since they are composed of a multitude of soil proliferations and vegetational differences. This is why the original SRCH and PTCL classification techniques were unsuccessful and why a supervised approach would be unsuccessful.

THERMAL INFRARED MULTISPECTRAL SCANNER (TIMS) DATA

Analysis of TMS data suggested that the thermal region of the spectrum offered the greatest potential for prehistoric road detection. The Science and Technology Laboratory had just completed construction of the thermal scanner (TIMS) and an immediate opportunity arose for the acquisition of TIMS data over Chaco Canyon on 28 August 1982. The TIMS was a new six channel research instrument and extremely limited research had been conducted in thermal imagery in the field of remote sensing at the time. After careful evaluation it was decided to acquire daytime data at solar noon and night data at 10:00 pm local time for comparative study. Only two flight lines were flown on this mission. One line started north of Escavada wash and went south over Pueblo Alto and Pueblo Bonito to a point just south of the canyon. The other flight line crossed Fajada Butte from the south and went across the north mesa. The same two lines were flown for both the day and night mission.

Principal component analysis was performed in order to reduce noise problems that were recorded in bands 4, 5, and 6. In this technique a set of axes is selected so that the maximum amount of a data set's variation is accounted for by a minimum number of perpendicular axes (Rickman and Kalcic 1982). The first principal component constitutes the majority of the data, while the remaining components contain logarithmically decreasing proportions of the data. This technique improved the clarity of seeing prehistoric road segments as well as other archeological features in the imagery.

Image enhancement techniques were used to accentuate the roadways in the imagery. Several approaches to lineament enhancement, extraction, or delineation are possible with digital imagery (Moore 1980). Since conventional lineament interpretation analysis is subjective, the results depend upon the investigator and the purpose for the interpretation. One study demonstrated that only 0.4 percent of a total of 785 lineaments were seen by four different investigators with significant differences in length, location, and densities (Podwysocki et al., 1975). Comparison of the lineaments mapped by different investigators using Chaco Canyon photography demonstrates this variability. One such lineament map (Obenauf 1980b:157) was developed to project potential roadways. Subsequent field research revealed that most of the lineaments were not roadways. The map did, however, demonstrate the ability of remote sensing to significantly reduce the area for analysis over conventional ground survey techniques.

Several filters were developed using the FLAP module in ELAS. These filters allow for edge enhancement in all directions simultaneously or can be designed for a specific direction. Since the roads on the north mesa appear to run predominantly in a north-south direction, filters were designed to accentuate lineaments in this direction. The analytical power of these filters is demonstrated in Figure 4-9. In this image a barbed-wire fence is extracted from 5 meter data along the north-south axis that is not apparent in the raw data. Since the filter is directionally biased the fence is not visible when it turns to an east-west direction.

Analysis of the TIMS daytime data revealed prehistoric road segments that were not visible in the simultaneously-acquired CIR photography. It also recorded segments that were not seen in previous black and white photography. The improved spatial resolution and thermal bandwidths of the TIMS were often able to detect and map both known and previously unknown roads. In addition, several other features such as puebloes, buried walls and small sites were revealed. In the night data, however, the roads and other features are not visible. What does appear in distinct clarity is a prehistoric agricultural field that is not visible in the daytime data (Figure 4-10). In the night data the Chacoan roads had reached thermal equilibrium and are therefore no longer distinctive. The day/night comparison demonstrated that the thermal/emissive properties of the research target must be considered in scheduling optimum times for data acquisition missions. Subsequent TIMS research has shown that certain targets are only detectable for a few minutes of the day (Rickman, personal communication 1986; Luvall, personal communication 1988).

TIMS data provided reliable information that was superior to TMS data, black and white photography, and CIR photography in the detection of prehistoric roads. Consequently, it was decided to acquire more TIMS imagery over a larger area of Chaco Canyon. Due to the prohibitive costs of field verification, flight lines were flown that would take advantage of the work conducted by the Bureau of Land Management's intensive ground study. TIMS flights were flown on 1 September 1987 and 29 January 1988. Working in cooperation with researchers of the BLM study, new TIMS data was acquired to see if more roadways or more complete roadway segments could be detected. The results of this research could then be used to confirm or deny previous interpretations of the Chacoan roadway system.

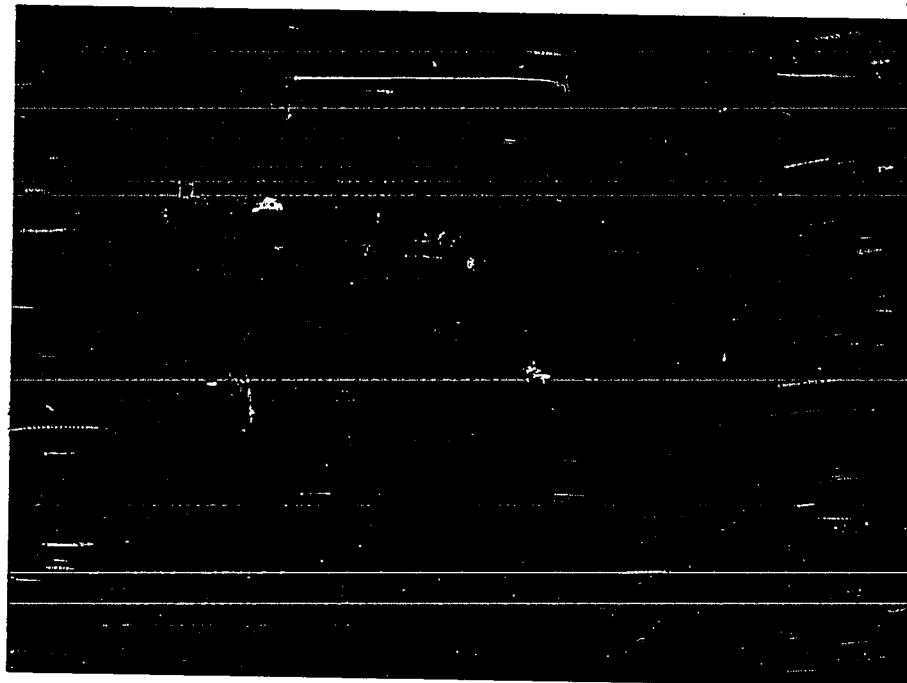


Figure 4-9. Filtered image of 5 meter TIMS data on the north mesa showing the prehistoric roads running diagonally and a barbed wire fence running north-south.

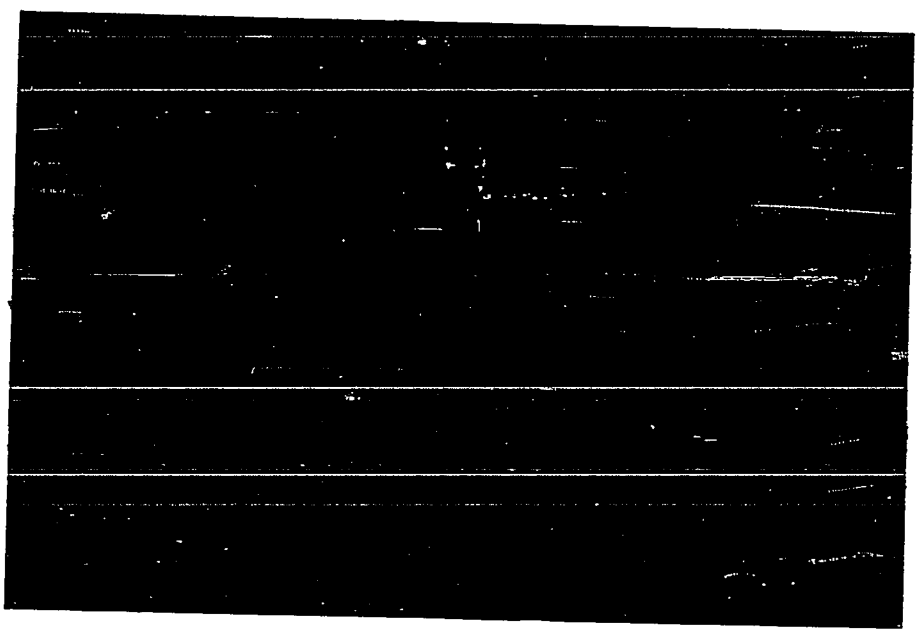


Figure 4-10. TIMS data acquired at 10:00 p.m. showing the location of a prehistoric agricultural field in Chaco Canyon. This field is not visible in the daytime data.

Since it would be impossible to apply filtering techniques to all the TIMS flight lines due to volume of data, a new technique was added. This approach consisted of rotating a sine function on the image and overlaying a graphic onto the road segments as they became visible. In this way many road segments that were not visible on the simultaneously acquired CIR photography or readily apparent on the imagery could be mapped in a time-cost effective manner. The completed graphic was then displayed against a linear function to clearly demarcate the location of the roads across the terrain. This technique had been successfully employed in previous TIMS research at NASA's Science and Technology Laboratory. In one study for example, boat wakes in the Gulf of Mexico were not apparent using a linear function but readily apparent using a sine function. Filtering techniques were employed only in crucial areas where roads were suspected (ie. areas of linear ceramic scatter) but not visible using the sine function technique.

CALIBRATED AIRBORNE MULTISPECTRAL SCANNER (CAMS) DATA

Calibrated Airborne Multispectral Scanner (CAMS) data was acquired over Chaco Canyon on Mission 416 (Table 4-1) with simultaneously acquired CIR photography. This CIR photography was of superior quality and represents the best aerial photography acquired during any NASA mission over Chaco Canyon. The CAMS imagery is also of excellent quality except for the thermal channel (10.5 to 12.5 microns) which was not operational at the time of data acquisition. Filtering techniques that were used in TIMS analysis were also applied to the CAMS imagery. In general, the CAMS imagery worked best in areas where vegetation differences exposed the prehistoric roads and was less effective in areas where the roads crossed sand and soil exposures.

APPRAISAL OF THE CHACO ROADWAY SYSTEM

Photointerpretation research over the last two decades has resulted in a complex of potential Chacoan roads. Many of these roads have not been verified to date although several attempts have been made. These roads do not appear, for instance, in either the CIR photography or TIMS imagery, nor were they able to be recognized from ground level by the BLM study (1983;1987).

The remainder of the discussion will concentrate only upon five major road patterns which have been identified and verified (Figure 4-11). These road patterns are:

1. Great North Road (Pueblo Alto to Salmon ruins).
2. South Road (Chaco Canyon to Kin Ya'a).
3. Ah-Shi-Sle-Pah Road (Penasco Blanco to Ah-Shi-Sle-Pah Canyon).
4. East Road (Chaco Canyon to Pueblo Pintado).
5. Coyote Canyon Road (Grey Ridge to Standing Rock).

Analysis of the TIMS imagery also revealed a large number of individual road segments spread throughout the canyon area. Many of these segments have been verified by previous research while many have never been recorded before. The confirmed traces of these roadway segments suggests a complex system in and around the Canyon. Over 640 kilometers of these possible roads have been mapped. Some of these road segments include the Kin Ya'a to Ruby Wells Ranch Road, Southeast Road, Casa del Rio to Lake Valley Road, Padilla Well, Kin Bineola to Bee Burrow, and West Road. Although these linear segments contain many of the Chaco Road characteristics and many have been

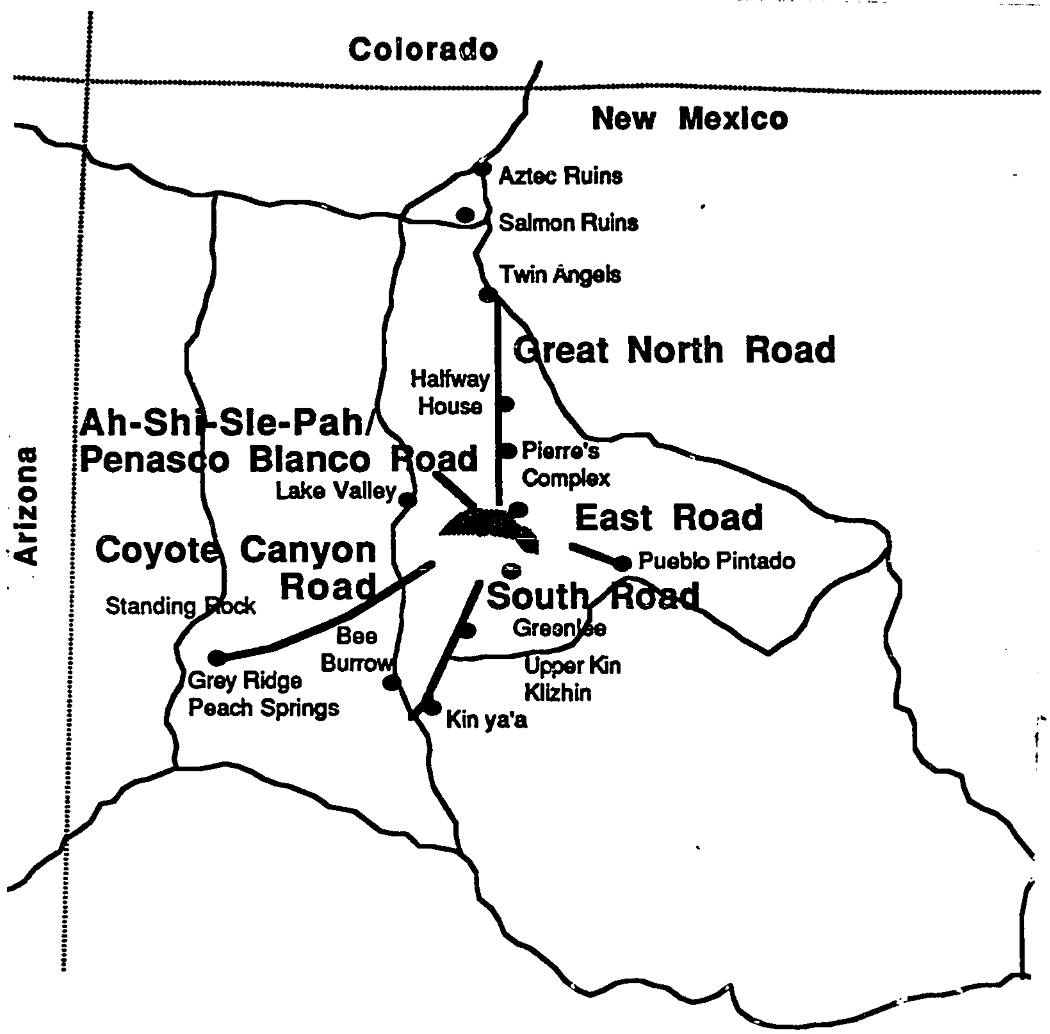


Figure 4-11. Map of the 5 major prehistoric road patterns currently known at Chaco Canyon.

verified as being prehistoric, their diagnostic value is limited since neither their source nor eventual destination is known with confidence.

Road segments are found in direct association with the outlier sites outside the canyon. As Obenauf states:

> Since possible roadways were discovered at almost all outliers which were in an environment where preservation of a road could reasonably be expected, it is probable that they were once present at most, if not all, outliers (Obenauf 1980a:60).

Yet despite all the speculation on the part of past investigators only the North and South Roads have been confirmed to connect from Chaco Canyon to outlier sites (Roney, personal communication 1989).

ROADWAY DESCRIPTIONS

Great North Road

The Great North Road (also called the North Road) lies to the west of five linear features which radiate from a gate in the north wall of Pueblo Alto and extend across the north mesa (Figures 4-12 to 4-14). Four of these features end either on the north mesa or at small settlements along the Escavada Wash 3-5 km away. The

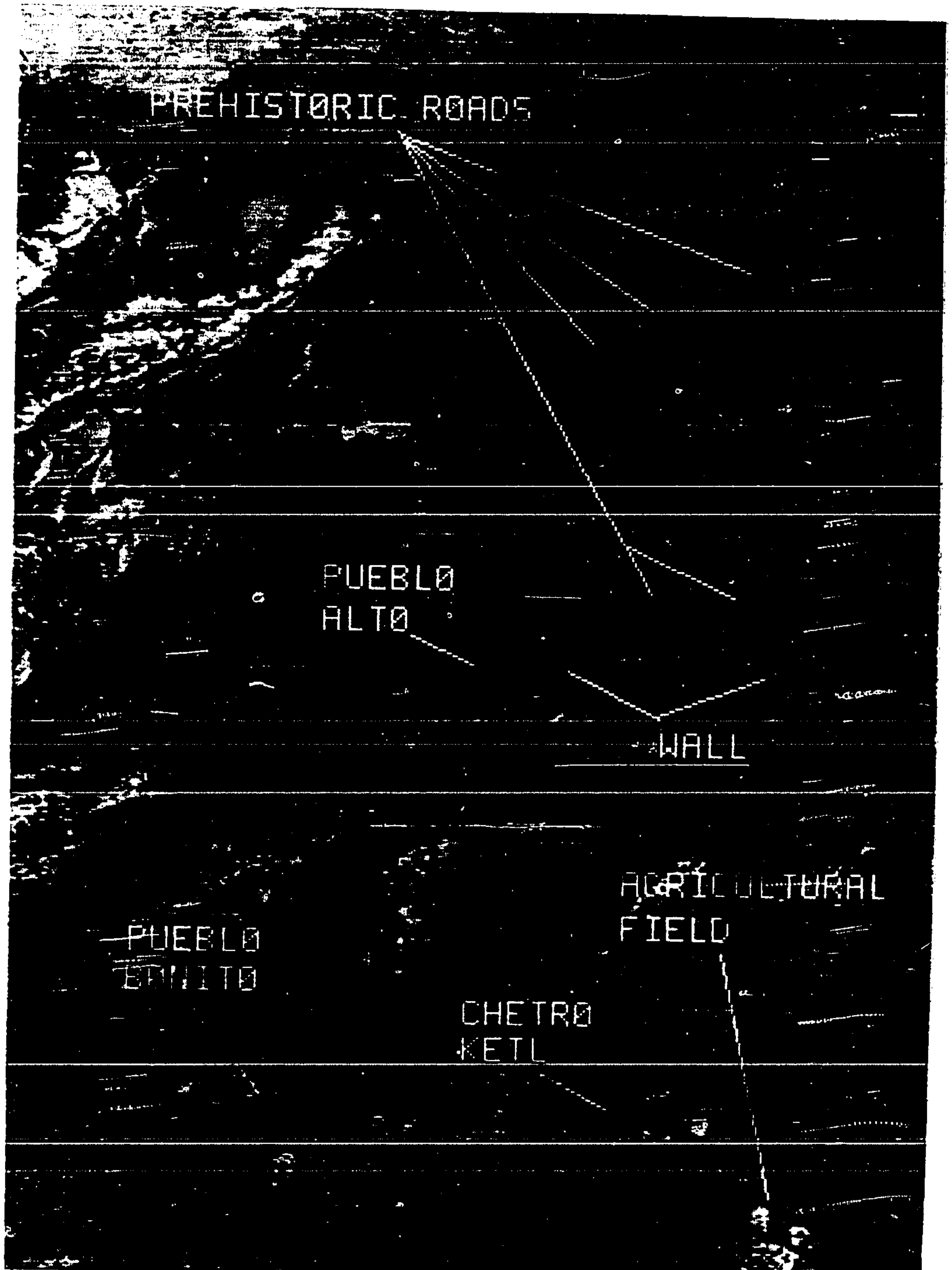


Figure 4-12. TIMS image (band 3) of the north mesa showing Anasazi sites and roadways.

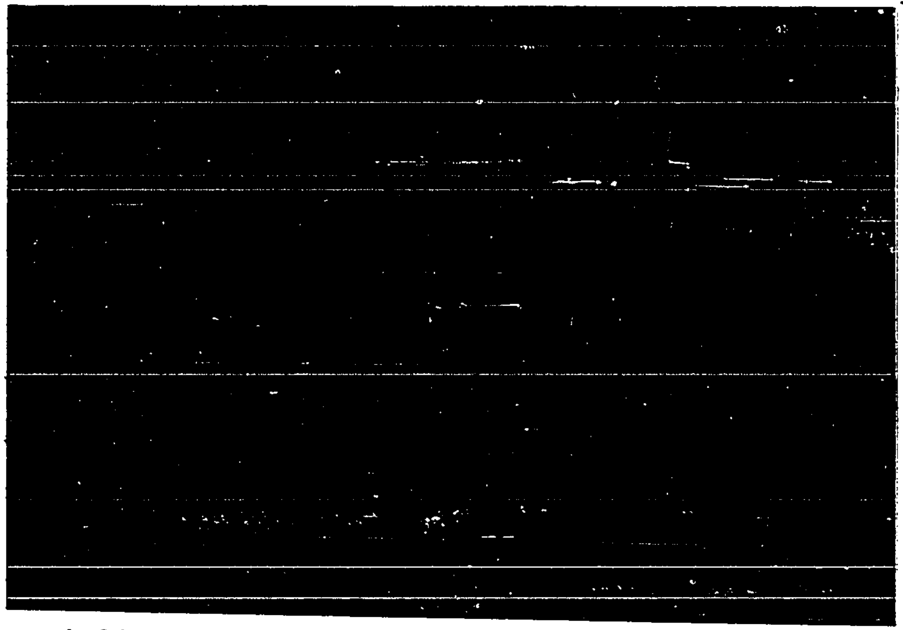


Figure 4-13. Ground photo of Pueblo Alto.

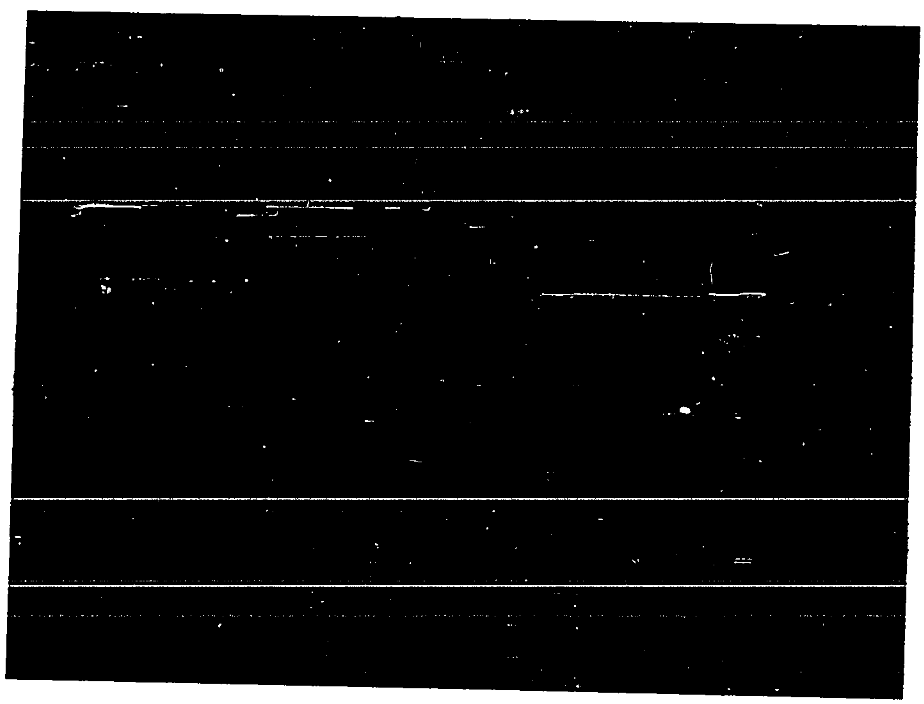


Figure 4-14. Looking from the north gate at Pueblo Alto toward the northeast. Several prehistoric roads coverage at this gate although the phenomenon is invisible from ground level.

North Road continues, however, in a due north direction as it traverses rolling sagebrush country until it reaches a stairway at Kutz Canyon approximately 50 km away from Pueblo Alto. From here the road may continue down Kutz Canyon as it passes Twin Angels Ruin enroute to the Salmon Ruins, but there is little ground evidence to verify this.

The road has its origin in several routes which exit Pueblo Bonito and Chetro Ketl and ascend the canyon by staircases to Pueblo Alto. The North Road is part of the northern road system which seems to link Chaco Canyon to the northern outlying communities. The North Road heads on a direction 13 degrees east of north as it leaves Pueblo Alto until it reaches the Escavada Wash 3 km away. From here the road maintains a remarkable true north direction within 1 degree of North; an impressive accomplishment when one considers the void of useful topographic features normally required for ground orientation (Figure 4-15). From the Escavada the road continues for 16 km until it reaches Pierre's Complex which is a group of small Bonito-style buildings atop the summit of pinnacles, or knobs (Figure 4-16). The evidence of many fires can be seen in a hearth atop the cone shaped pinnacle, El Faro, from which visibility is excellent in all directions (BLM 1983). Predictably, the

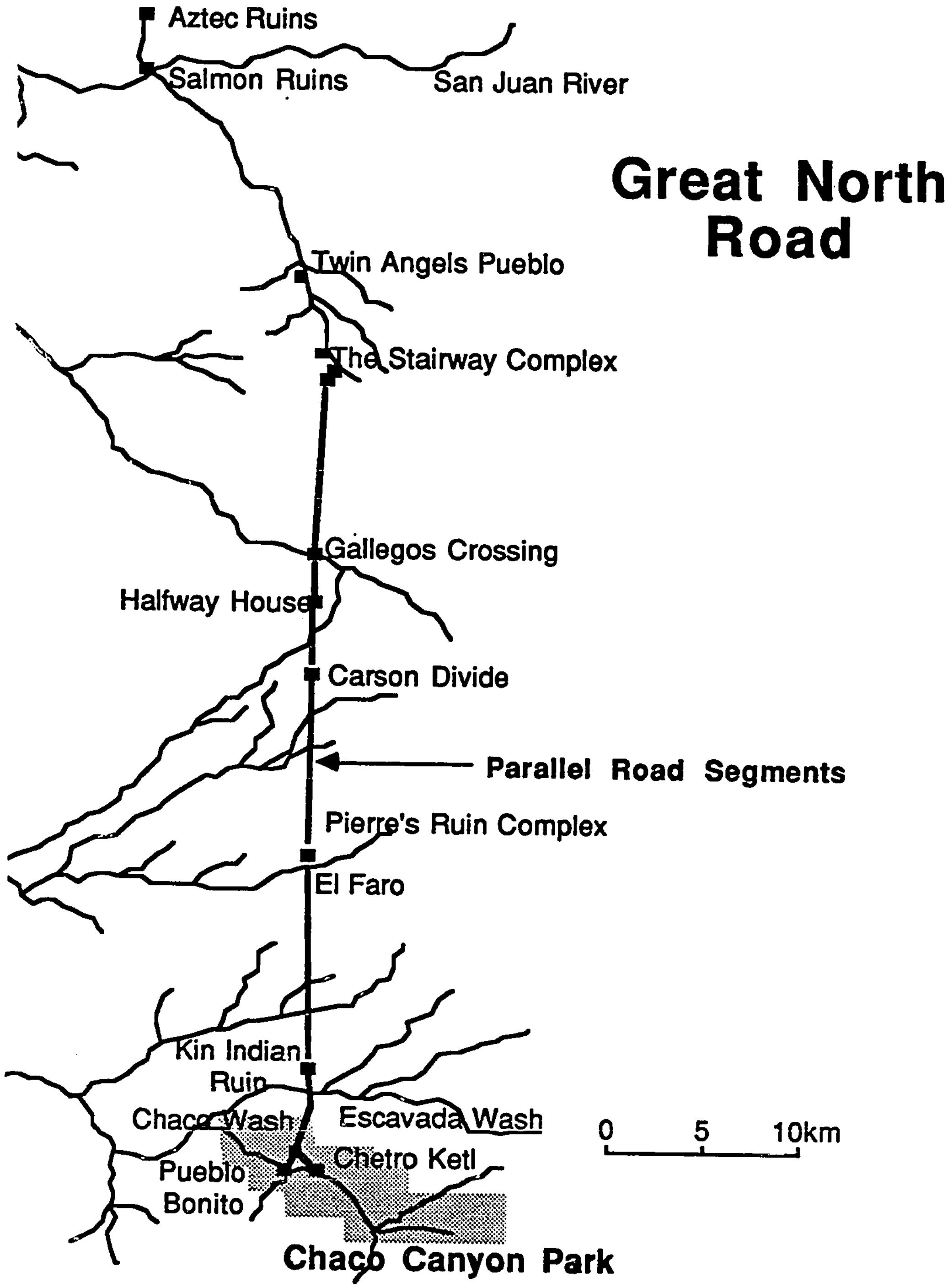


Figure 4-15. Map of the North Road.

hearth marks the center of the projected course of the North Road. From here it continues for another 31 km until it reaches three shrine-like sites and a stairway at Kutz Canyon (Figure 4-17). The Aztec and Salmon Ruins sites are located 20 and 30 km to the northwest and it is speculated that the road may head in that direction. Severe erosion in the canyon reduces the possibility of finding ground evidence for the road since it may be either buried or destroyed.

Like all Chaco roads the North Road is not visible in its entirety either from ground level or in aerial photography. It is best seen from the ground in an area south of Pierre's Complex where it cuts across a succession of dunes. The linearity of its course suggest it was "laid out as a single unit" (Morenon 1977a) while the material remains such as ceramics and road-related structures imply that it was built as a single constructional event in the late Bonito Phase (Kinkaid 1983, 9-76).

No major sites are encountered from its origin at Pueblo Alto to Kutz Canyon. No road segments have been seen in aerial photography from Kutz Canyon to Salmon Ruins, although ground-based evidence has been collected in this area (Roney, personal communication 1989). Often

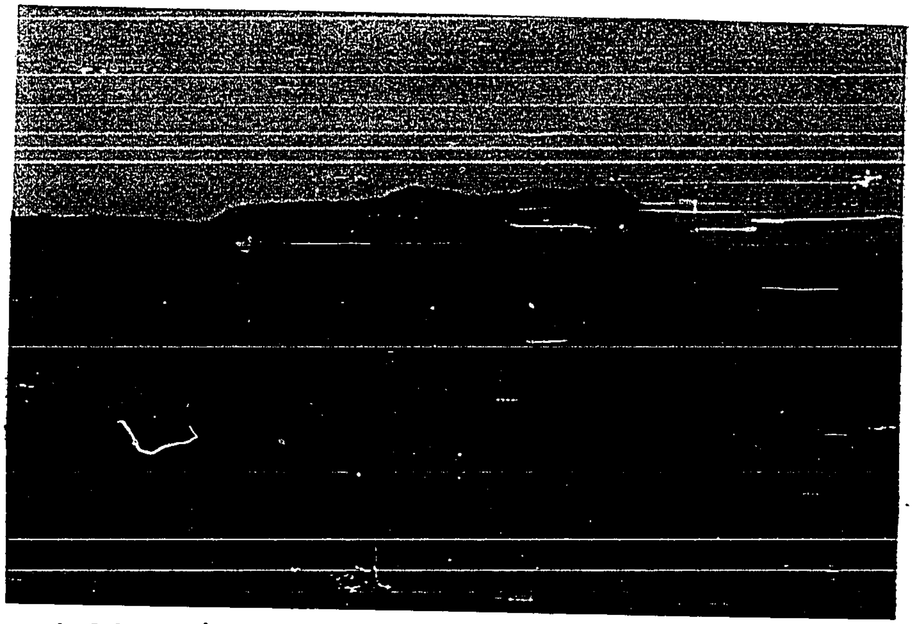


Figure 4-16. Pierre's Complex.

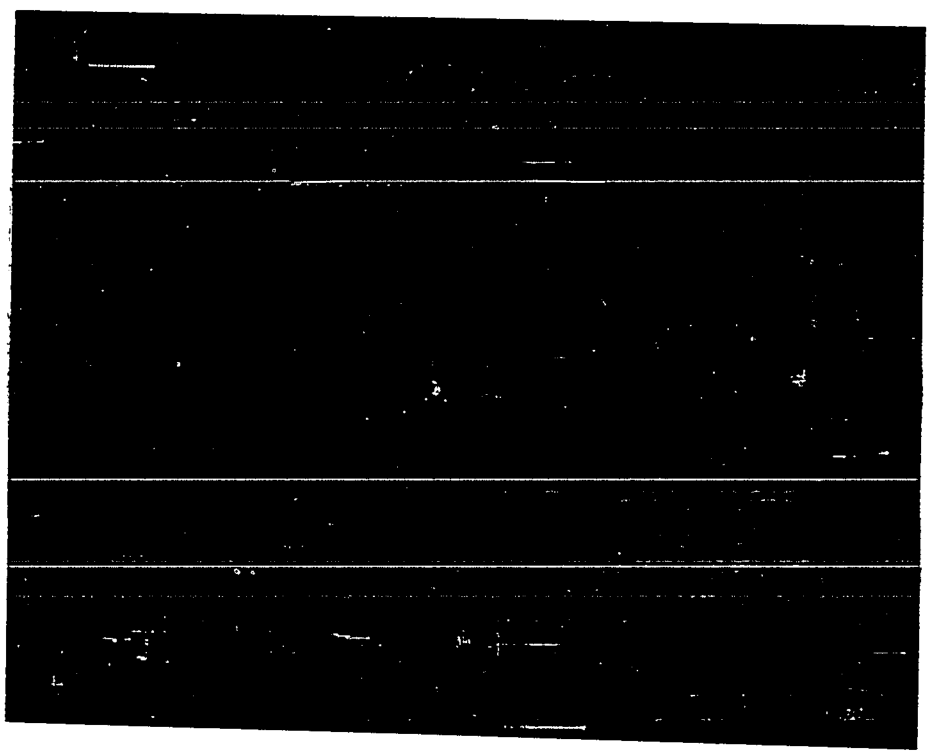


Figure 4-17. CAMS data (channel 3) showing the North Road as it continues north toward Kutz Canyon.

the road exists as two, and sometimes four, parallel roads.

The TIMS instrument was successful in detecting longer roadway segments and previously unrecorded segments along the North Road than prior photointerpretation research. TIMS mission FCF (Table 4-1) was flown after a light snow had fallen throughout the San Juan Basin and was particularly useful in identifying such features as the four parallel segments located 4 km north of Pierre's Ruin. These segments had been originally identified by the BLM in 1981, but TIMS data and CIR photography recorded them more distinctly under the winter conditions. As determined from photointerpretation, the segments are actually double "parallels" consisting of two sets of segments approximately 30-40 meters apart with each set being about 15 meters apart. Nials was unable to verify these parallels from the ground using their reconnaissance techniques (Nials 1983, 6-29). It should be mentioned at this point that many other instances of parallels were found in TIMS imagery throughout the Chaco road complex that were previously unrecorded. Like so many of the lineaments detected in the remotely sensed imagery, they are often difficult to identify from ground level. The temporal and functional differences, if any, of the parallel segments remain unknown.

Evidence from the BLM survey indicate that the North Road was built no earlier than AD 1050 and terminated by the middle of the 12th century. In addition, the road crossed a region that was sparsely populated and never intensively utilized (BLM 1983). The road also demonstrated the difficulty of crossing the featureless terrain from one point to another and maintaining a consistent linear route using blind reckoning alone. This supports the premise that the roads were intentionally laid out using some type of surveying technique such as that discussed earlier.

South Road

The South Road system is composed of several arteries which integrate Chaco Canyon with outliers on the southern and western periphery. The landscape to the south of Chaco consists of buttes and expansive shallow valleys. The desert floor is covered with various species of grasses rather than the sage cover that typifies the area to the north of Chaco. Upon the basin surface the rock outcrops, rincons, and pinnacles blend with Anasazi ruins. This makes field verification more difficult since it is hard to "sight" projected road alignments onto features on the distant horizon. The South Road is believed to provide contact to areas as far as 160 km from Chaco Canyon. This is based on projected alignments to distant archeological sites but the extreme southern limits are unconfirmed either from remote sensing or ground reconnaissance. The area that has been confirmed extends for approximately 64 kilometers from Chaco Canyon to Kin Ya'a and beyond toward Hosta Butte with a number of spurs leading to Bonito Phase sites.

Starting in Chaco Canyon at South Gap (Figure 4-18), the road curves out of the canyon toward the direction of Kin Klizhin. Approximately 12 km from Pueblo Bonito, the road enters the Kin Klizhin Valley and passes 200m to the west of the tower kiva at Upper Kin Klizhin. This building is composed of 12 single-story and eight second-story rooms which served to buttress the mass of a four story kiva (Stein and Levine 1983:C-28-32). A road segment spurs off the main road to join this site.

The main road continues and jumps a mesa as it passes a great kiva called Casa Patricio and continues to the southern edge of the valley. Here, a site atop a pinnacle, La Mesita de la Junta, provides a spectacular view to the horizons. The road now angles more to the southwest as it heads in a straight line passing Nose Rock Herradura, Seven Lakes Herraduras, the Bee Burrow great house, and eventually reaching Kin Ya'a (Figure 4-19). The Bee Burrow great house is unique in that the road does not seem to be formalized as it approaches the structure as generally occurs at the other great houses. At Kin Ya'a the road breaks into parallel segments and exits to the south but the road's ultimate destination has not yet been determined.

The prehistoric agricultural intensity, fluctuating terrain, and density of material culture make it difficult to distinguish road-related sites. However, the road itself is often visible for extensive segments and other road characteristics such as herraduras, stairways, hearths, and ceramic linear scatters assist in its detection. At Seven Lakes Herraduras, for instance, two herradura structures exist in close proximity to the road. One of these structures contains a complex of ceramic shards that include Red Mesa Black-on-white, Escavada Black-on-white, White Mountain Red Ware, and San Juan Red Ware (BLM 1987). It is clear that many different items were being moved along the road. In

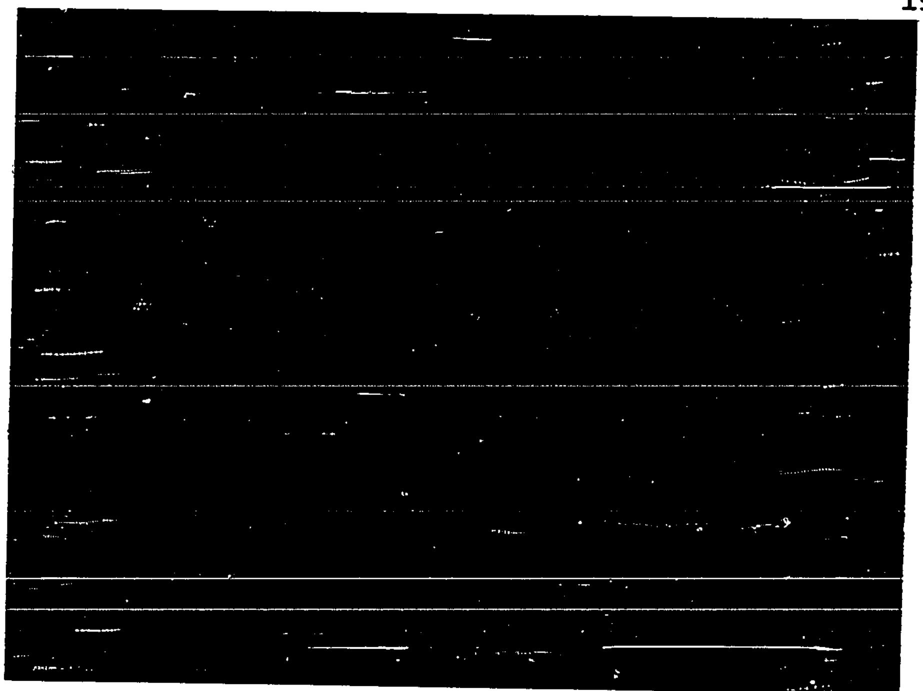


Figure 4-18. Looking southwest toward South Gap as it enters Chaco Canyon.

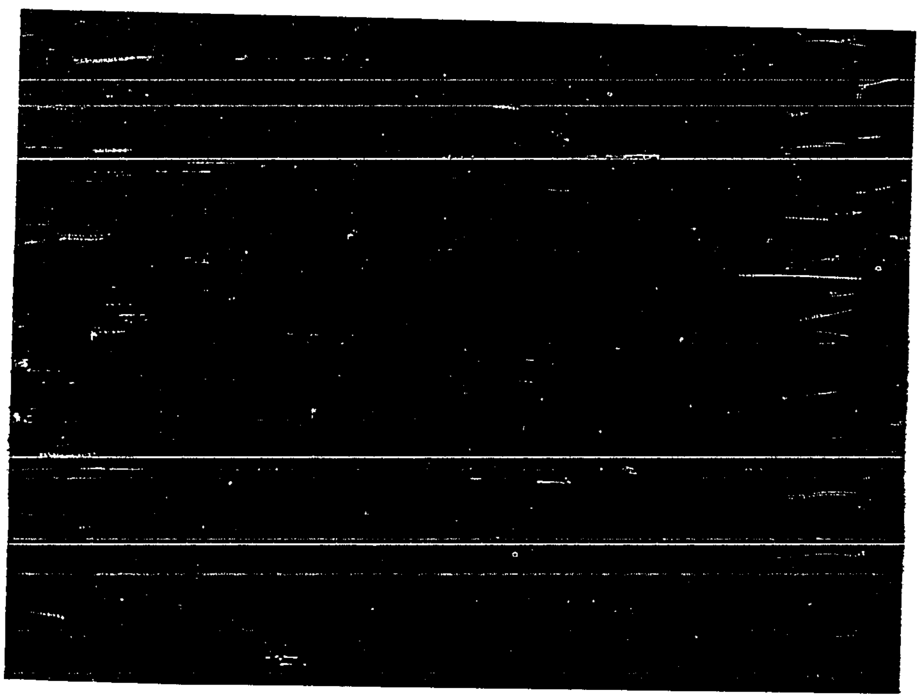


Figure 4-19. The Kin Ya'a site. A prehistoric road can be seen as light vegetation in the center of the photo as the road approaches the site.

addition, Bonito style architecture occurs frequently throughout the course of the South Road.

The parallel road segments at Kin Ya'a are readily apparent on most remotely sensed imagery and from ground level. Kin Ya'a is a multi-storied structure of 26 ground floor rooms that contains a five-story kiva (Marshall et al. 1979:201-206). Artificial mounds are located on the road segment immediately east of the site while two great kivas exist nearby. The area offers the best evidence of prehistoric road construction and engineering outside Chaco Canyon and serves as an excellent place to view the surrounding landscape.

The TIMS instrument from Mission 645 (Table 4-1) was able to detect a larger number of South Road segments and associated spurs than any previous photography. In fact, this area of Chaco Canyon was better than any other area for road detection using TIMS imagery. The reason for this is not known. If vegetation was the primary factor responsible for this it should also be visible in the CIR photography. But the TIMS is recording segments that are now visible on the CIR photography. The last known segment of South Gap as it enters Chaco Canyon was more visible in TIMS than CIR photography and apparently better than previous black-and-white photography. TIMS data readily recorded a fork in the road just north of Casa Patricio. This fork was recognized by the BLM in 1987 but the TIMS data also shows a number of linear features in the immediate area, one crossing atop a nearby mesa (Figure 4-20). These same lineaments were recorded on two different flight lines of the same area. On both flight lines the segments were either less visible or not visible at all on the simultaneously-acquired CIR photography.

One of many examples of the utility of TIMS data can be seen on the Southeast road which had originally been identified as speculative by Obenauf due to the major gaps between imaged segments. The road was believed to extend from Upper Greenlee Ruin to San Mateo Ruin. The road was not visible on BLM low-sun angle photography and there was no archeological evidence enroute to suggest its location. Although the road is not seen in any photography or from ground level, a lineament is seen in the TIMS imagery clearly leading up to and passing the Upper Greenlee site. The same situation occurs at Rams Pasture Herradura as well as other locations.

The South Road is without question a formalized Anasazi road that fits prominently into the Chaco roadway

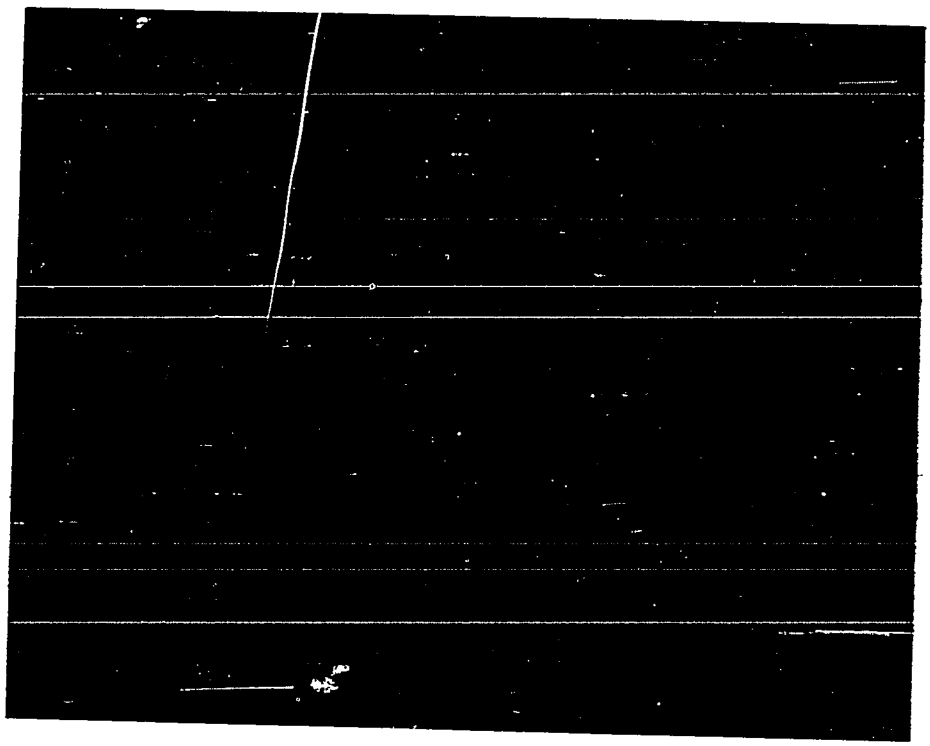


Figure 4-20. TIMS data showing South Gap road as well as potential road segments which have not been verified from ground level.

system. The limits of the road are not known at this time. The road incorporates one of the few sweeping curves into the Chaco road system as it leaves Chaco Canyon and then immediately regains the characteristic linear pattern. The South Road crosses an area of greater population and activity than other Chacoan roads and articulates with many cultural features as evidenced by herraduras, kivas, great houses, and topographic expressions.

Ah-Shi-Sle-Pah to Penasco Blanco Road

Gordon Vivian originally recognized a segment of the Ah-Shi-Sle-Pah to Penasco Blanco road in 1964, but identified it as a causeway. What is known of the road today is that it is a relatively short stretch of prehistoric roadway (6.3 km) that extends from the Penasco Blanco Ruin to the Ah-shi-sle-pah Wash. Starting at Penasco Blanco (Figure 4-21) the road ascends through a series of rock-cut and masonry stairways until it reaches a mesa top. The road crosses the mesa until it reaches the slickrock bench of Arroyo de los Aguages. A Bonito Style structure, Los Aguages, is found in association with the road as it drops off the mesa top. Also located here is a complex of bedrock cisterns. The road continues to the Ah-Shi-Sle-Pah Wash encountering cut-rock steps, a masonry mound, and a sandstone ramp. Attempts to find extensions of the road beyond the wash have been unsuccessful. Visible areas that can be seen to confirm the road's existence from ground level range from 10 to 250 meters. The road is unique in that there in no known association with a great house.

The Los Aguages Site along the road's course consists of three structures of Bonito Style architecture located between the road and the complex of cisterns. The area was basically uninhabited by Anasazi groups prior to the road's construction and material remains indicate a similar pattern to that of the Great North Road. In areas where the road could not be seen five ceramic/lithic scatters were found to suggest its position, repeating a pattern found elsewhere throughout the Chacoan roadway system.

Results of TIMS and CAMS analysis revealed continuous road segments in areas where they were previously unrecognized. The TIMS data also reveals another linear feature in the road near the Ah-Shi-Sle-Pah Wash that was not visible in the CAMS imagery or CIR photography (Figure 4-22). The feature is seen on two different flight lines that were gathered on different headings which demonstrates that the feature does not

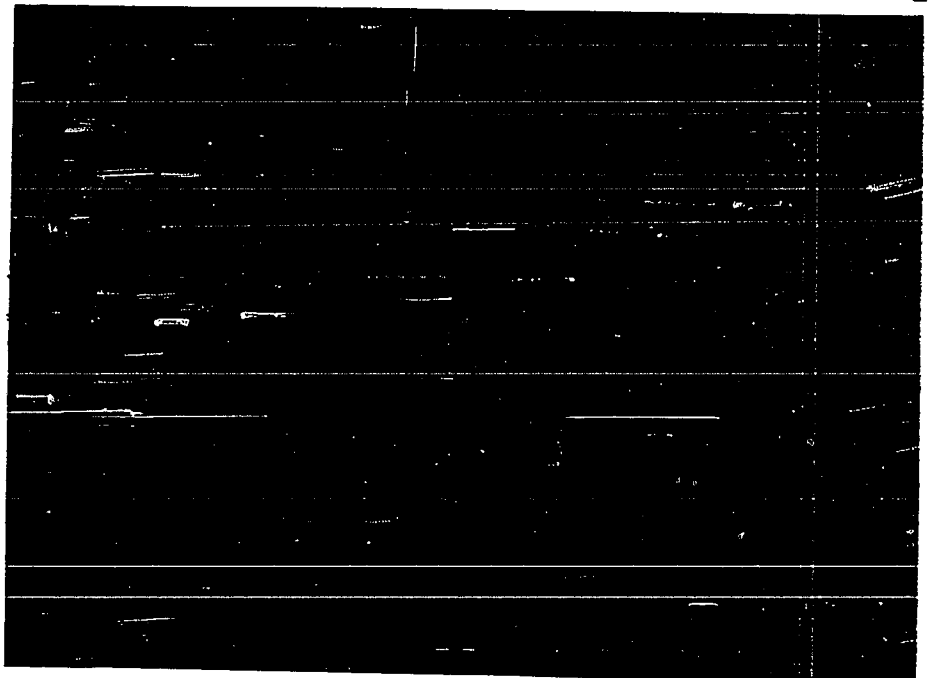


Figure 4-21. CAMS data showing road segments at Penasco Blanco.

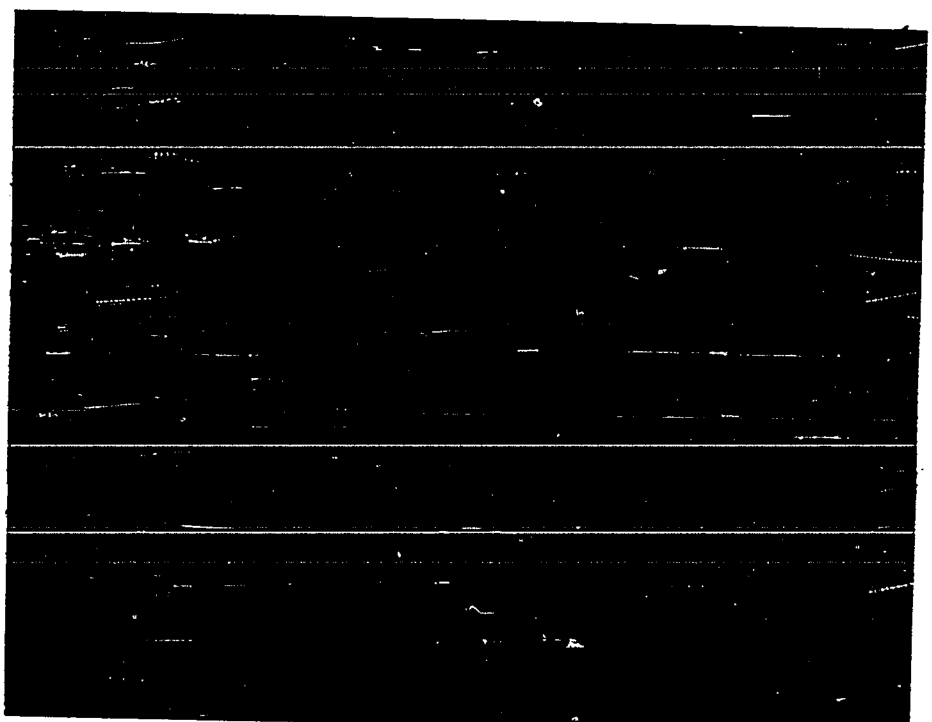


Figure 4-22. TIMS data showing a prehistoric road and a linear feature near the Ah-Shi-Sle-Pah Wash.

result from scanner noise; rather it is an actual surface manifestation.

The Ah-Shi-Sle-Pah to Penasco Blanco road appears to be a localized road that does not connect to other Chacoan roads. The ceramic assemblage of water vessels and cisterns suggests that water sources influenced the direction of the road. Unlike the roads which extend outside of the Canyon, this road does appear to have an obvious economic function related to water resources. It can also be argued that the road leads to a sacred area and that the road itself has both religious and economic functions. Although extensive archeological survey was conducted to locate road remains and projected alignments northwest of Ah-Shi-Sle-Pah Wash, no possible destination for the road has been identified to date.

East Road

The East Road extends from Pueblo Pintado to the head of Chaco Canyon where it apparently enters into the canyon. This brief stretch of road is visible in the imagery as well as from ground level. The visibility of the road is enhanced by sagebrush growing within the road margins. This vegetational difference contrasts sharply with the grasslands of the surrounding flat terrain. No further trace of the road can be seen after its apparent descent into the canyon.

Other lineaments have been seen emanating from Pueblo Pintado but they quickly disappear in aerial photography and cannot be verified from ground level. One lineament has been projected to extend south to Chacra Face Road (BLM 1983). No evidence of the Chacra Face Road was seen in any of the TIMS imagery or CIR photography. Based on this observation and the lack of supporting ground truth evidence, it is more probable that Chacra Face Road is of historic origin. The destination of the lineament heading south of Pueblo Pintado is not known.

Coyote Canyon Road

The Coyote Canyon Road represents the best example of roadway construction in the Chaco Canyon network. The geological and topographic conditions in this area are excellent for roadway preservation. The road is on a northeast to southwest course and is most evident between Grey Ridge and Peach Springs which lie to the southwest of Chaco Canyon. The road disappears as it nears Chaco

Canyon but the projected alignment suggests that it enters the Canyon through South Gap.

One segment of the road between Grey Ridge and Peach Springs is visible from the ground for over 4 km, making it one of the longest visible segments in the road network. Major road-leveling efforts took place along this segment and ceramic densities increased as the road approached herraduras. Other constructional evidence included cairns, berms, a 330 meter long engraved groove in bedrock, sandstone clasts along the border, a consistent 10 meter width, and masonry steps. The road reaches Peach Springs which is a great house with an enclosed kiva and plaza, earthworks, and a great kiva lying nearby (Marshall et al. 1979:307).

From Peach Springs the road continues to another great house, Standing Rock which has a hearth, plaza, earthworks, and a great kiva 300 meters to the southwest (Marshall et al. 1979:232-233). Like Pueblo Pintado and Pueblo Bonito, several roadways emanate from the structure, but only the Coyote Road alignment is confirmed. The massive earthworks which border the road as it exits the great house align the road with a panel of petroglyphs near Standing Rock Wash (BLM 1987). Other road segments leading away from the great house can be traced for a short distance until they blend imperceptibly into the terrain. The main road continues northeast as it passes Standing Rock Herradura and eventually disappears on its apparent route to South Gap. Along the entirety of the road many segments, which cannot be seen from ground level, are visible in the aerial photography.

SUMMARY OF REMOTE SENSING ANALYSIS

The Bureau of Land Management Project concluded that there were 640 km of documented prehistoric roads with 160 km residing within the Park boundaries and 480 km throughout the San Juan Basin. The addition of digital remote sensing analysis and CIR photography to the BLM study has added to this total. Many of the road segments were seen in the digital imagery that were never seen before either from ground level or in the aerial photography. These segments filled in "gaps" along routes that had been verified as being prehistoric. Previous research had indicated, for instance, that linear sherd scatters occurred along the course of a prehistoric road which could not been seen in aerial photography. Sometimes the digital imagery recorded this phenomena and at other times it did not. The reason(s) for this is/are unclear at this time and can only be explained after measurements have been acquired from ground based remote sensing instrumentation.

Many additional linear segments have been mapped as a result of this study whose characteristics suggest that they are prehistoric roads but have not been substantiated from ground level. In addition to a number of isolated linear segments, several parallel segments were seen in the imagery which were not recorded previously. These parallel segments were found in association with verified road patterns. Occasionally, road segments could be seen in the CIR which were not visible in the digital imagery, but generally the digital imagery was superior to photography for the mapping of prehistoric roads.

While the digital imagery was able to map many unknown roadway segments, many other potential roadway segments were not detected. Ideally, it was hoped by many researchers that remotely sensed data would be able to locate all the roadways in their totality. This expectation, perhaps, might represent a subjective belief on the part of the investigator, that the roads were treated equally by their prehistoric constructors from one point to another. Geological and erosional processes have obviously destroyed many sections of roadways, particularly on the Canyon floor. But in looking at the patterns of these erosional processes I have reached the conclusion that many sections of roadways received scant, if any, attention in constructional effort or maintenance in the first place. The roadways are highly visible as they enter and exit great houses and near topographic features. They seem to disappear in areas where there is either little topographic relief, no associated structures, or low prehistoric population. In short, the constructional design in Chaco Canyon does not appear to be like Roman roads or modern-day interstate highways where similar effort is spread somewhat evenly throughout the length of construction, but rather a staggered or uneven effort where some portions receive more attention than others.

An archive of remotely sensed imagery and CIR photography has been acquired and catalogued (Appendix B). The data were acquired with the hope that they may someday be as valuable to future research as the historic black and white photography is to current research; for natural and man-made forces continue to destroy prehistoric roads and cultural features in Chaco Canyon. The data can also be used as input to a database or GIS for future analysis and predictive modeling.

A major problem encountered by the BLM study was the inability to discriminate road segments from the ground that could be easily seen in the aerial photography. This problem is further exaggerated when using instruments recording information (i.e. thermal data) invisible to the human eye.

PREHISTORIC ROADWAY FUNCTION

The original hypotheses that are stated at the beginning of this chapter are designed to test whether the prehistoric roads in Chaco Canyon primarily served an economic function or a religious function. The evidence and information that will be examined to test and support these hypotheses are: great houses, labor investment, earthworks, herraduras, ceramic scatters, orientation, astronomy, road width, ethnological evidence, other road systems, and a re-examination of Chaco's role in redistribution.

ECONOMIC FUNCTION

Path of Least Resistance

The first hypothesis stated that if the roads have an economic function, then they will take the "path of least resistance" as they travel from one place to another resulting in curving or meandering patterns in areas of difficult terrain. Although there are a few curving patterns in the Chacoan roads, such as the South Road as it exits the Canyon through South Gap, the roads are primarily, and characteristically, linear. This curve in the South Gap road is intriguing because it was structurally and topographically possible for the road to exit the Canyon in a straight line. In Figures 4-23 and 4-24, the prehistoric roads (in red) can be compared to the modern-day roads (in yellow) on the north mesa of Chaco Canyon by extracting them from the TIMS imagery. The modern-day roads not only curve through the difficult topographic relief as they reach the steep edges of the Canyon, they also bend around subtle relief on the north mesa. The prehistoric roads, however, maintain a straight course as they cross the mesa and enter into the north gate at Pueblo Alto.

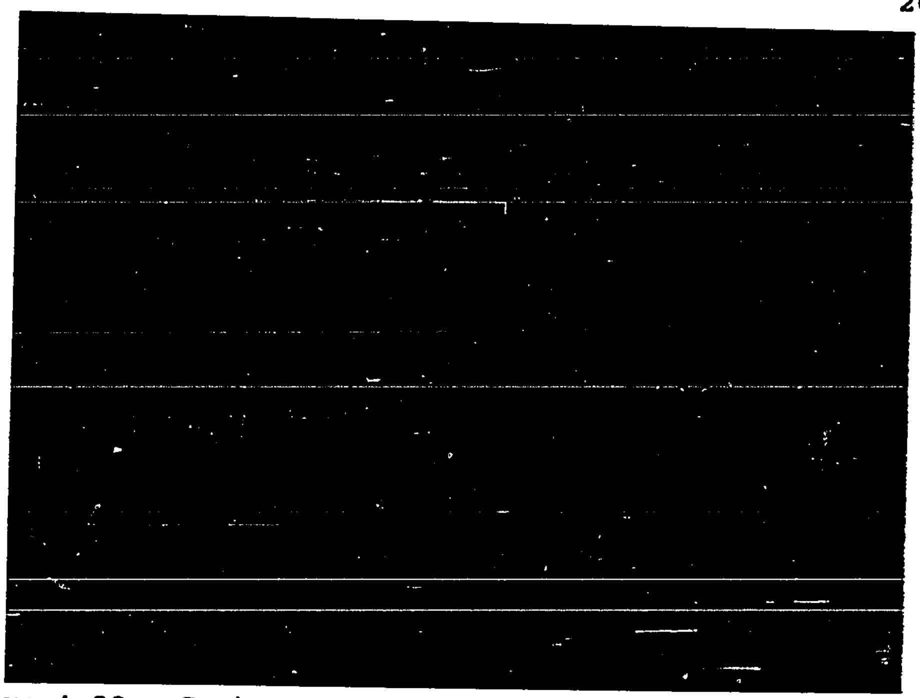


Figure 4-23. Contemporary roads (in yellow) on the North Mesa against a background of TIMS data.

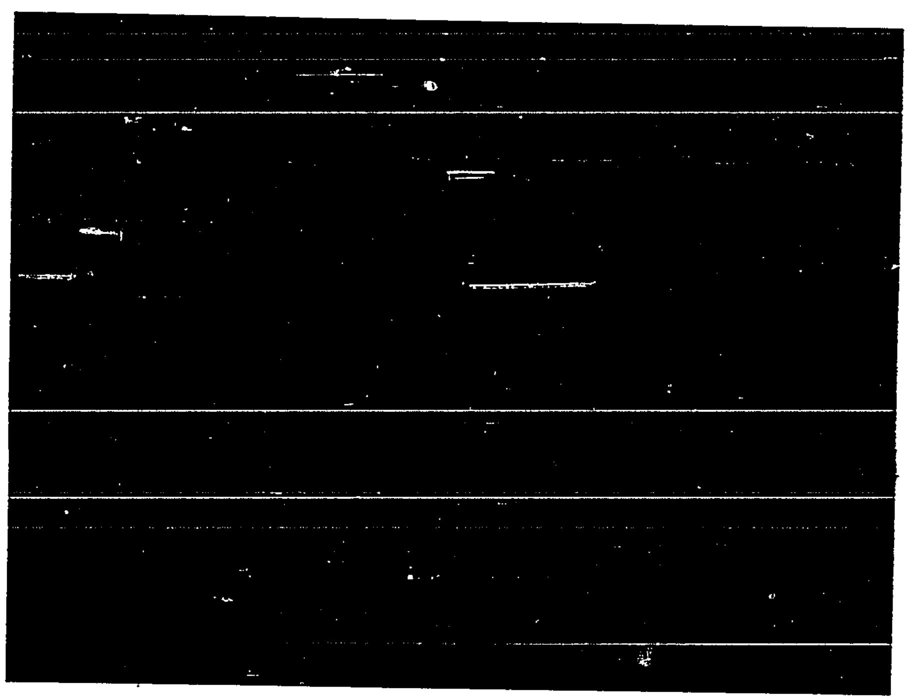


Figure 4-24. Prehistoric roads (in red) on the North mesa against a background of TIMS data.

Arguably, it makes good sense to take a path of least resistance as one transports items into the Canyon. Although this notion may reflect a western cultural bias, it still stands to reason that the most efficient way to move items through human labor is that which expends the least caloric effort. An experiment was conducted using a respirometer (Morenon 1977b:3) to measure energy expenditure under varying conditions in Chaco Canyon. Using varying degrees of slope and weight factors, Morenon concluded that the roads saved significant energy whether one was transporting goods or merely traveling. While I agree with Morenon that the roads would save energy in the transportation of goods, I disagree with him based on my field experience that the roads saved significant energy for mere travel. Morenon concluded:

> Thus, one cannot assume that prehistoric roads implied that the transportation of goods was the underlying reason for their construction. A highly mobile population could benefit from the construction of roads even if these roads were not generally used for transporting goods (Morenon 1977b:4).

Morenon also determined that the transportation of heavy items would minimize slope while the use of a road for traveling purposes would minimize distance. His evaluation of the road network was that it was used for travel and the conveyance of light items.

Efficient Constructional Effort

This brings us to the second hypothesis which states that if the roads have an economic function then they will incorporate greater constructional effort in making travel easier at difficult places, i.e. areas of steep slope, than in areas of flat or level relief. This is not the case in Chaco Canyon. In the transportation of heavy items it is more efficient to minimize slope, even at the expense of sacrificing distance and making a longer route. Although this is certainly the case for contemporary roads it is not for the prehistoric roads. If Chaco Canyon served as a center for redistribution it would be expected that heavy items would be moved throughout the roadway system and that the factor of slope would be minimized.

The evidence does not support the premise that heavy items were moved along the roads. When the roads reach the canyon's edge one finds stairways rather than ramps. If one is carrying heavy or cumbersome objects, a ramp would have saved substantial energy expenditure. The roads make no attempt to avoid areas of loose sediments or incorporate areas of hard surface which would have served to secure footing and minimize energy expenditure. Nor do the roads attempt to minimize slopes by either circum-navigating around them or through efficient leveling across them. On the contrary, the greatest constructional effort takes place on flat, level areas, such as when the roads approach a great house, than it does in the middle of the desert where steep topographic relief is encountered (Roney, personal communication 1989).

A puzzling characteristic of the roadways is their consistent 9 meter width. This is not an economically effective component to incorporate into the roadway design by a group of people who did not have the wheel nor beasts of burden. Although a similar road width appears to have aided in the movement of armies along the Maya sacbes (Trombold, n.d.), this explanation does not hold for Chaco Canyon. In short, the energy expended to maintain the consistent road width in Chaco Canyon does not appear to be necessary in the economic transportation of goods. As shall be shown later, there appears to be very little transportation of goods along the roads in the first place, making the purpose for the consistent width more obscure.

Topographic Obstacles

The third hypothesis stated that if the roads have an economic function then they will by-pass and avoid areas of high topographic relief. By-passing pinnacles and steep uplifts would save energy and time whether or not the roads were used for traveling or for the transportation of goods. The remotely sensed data and ground reconnaissance, however, demonstrate that the roads are occasionally directed at these high topographic features rather than avoiding them. Analyzing the TIMS imagery on the computer reveals that the roads sometime make dog-leg turns to reach these features rather than continuing in a straight line to the next apparent point on the road. In short, they are sacrificing the direct linear course of the roads to include topographic obstacles. This involves a greater expenditure in time, distance, and construction; factors that are not economically profitable.

Storage and Redistribution

The fourth hypothesis stated that if the roads have an economic function, then they will provide linkage to Chaco Canyon for the storage and redistribution of goods. As stated previously, most investigations of the Chacoan roadway system centered around economic interpretations with one of the primary interpretations being that Chaco Canyon was a center for redistribution. Although various models for redistribution have been proposed, the basic tenets are similar in that they are all economically oriented. Judge et al. (1981) described a system for complete redistribution with materials cycling through Chaco Canyon. In their view the San Juan Basin was an uninhabited desert during the 11th and 12th centuries and the road system crossed areas that were uninhabited by the Anasazi to reach the basin rim. Here, better soils and greater rainfall allowed for population growth. The unpredictable, localized rainfall around the basin could have resulted in a productive agricultural year at one spot with a bad year occurring at another spot. Surplus food would have been brought into Chaco Canyon, stored in great houses, and eventually distributed to communities experiencing a low-rainfall season.

This theory of redistribution seems plausible when one looks at the mapping results of the remotely sensed data and sees a pattern of radiating roads leading to the basin periphery. The archeological evidence also supports this position in light of the large-room suites, the road-related suites, and the trash mounds. In addition, the vast number of rooms in the great houses, the over-engineered construction of the great houses, the presence of farming terraces, and the known roadway pattern, suggested a substantial population living in Chaco Canyon proper; possibly with year-round occupation. New evidence, however, undermines this impression of Chaco Canyon.

Research and excavation at Pueblo Alto (Windes 1987) demonstrated that resources there were not adequate to support a population of more than 100 individuals. Despite local roads which could have been used for water procurement, terrace farming, and localized exchange, occupation must always have been locally unsuitable. Of the 85 rooms originally constructed at Pueblo Alto, only 5 were used for habitation (Lekson et al. 1988:104). The location of Pueblo Alto on a mesa top where there are few natural resources to attract settlement might suggest that habitation was in the great houses at the canyon bottom.

Surprisingly, however, similar patterns of low population and limited resident occupancy were also found at these canyon bottom sites. As Lekson et al. state:

> ...we found only five household suites at Pueblo Bonito, five at Pueblo del Arroyo and no more than

> 11 at Una Vida. All had apparently been constructed between 920 and 1095 (a period that coincided with Pueblo Alto). We estimate that in each of these Great Houses the household suites many have been home to no more than 100 people, a far cry from the 5,000 or more projected by earlier archeologists (Lekson et al. 1988:104-105).

Since the roads on the north mesa converge at a small gate at Pueblo Alto, it would be reasonable to expect the inhabitants to have control of the storage suites of the structure. Curiously, these suites are completely inaccessible from inside the great house. In addition, the doors open only from the exterior of the building suggesting that the rooms are road-related features and that the residents had limited control over them (Lekson et al. 1988:105). The same situation is found at Pueblo Bonito, Penasco Blanco, and Chetro Ketl, all of which were built around A.D. 1040. This architecture is inconsistent with a redistribution system where control over goods would appear to be essential in their inventory, monitoring, and dissemination to other locations.

The fact that the roadway system extends far beyond the basin reduces the possibility that Chaco Canyon was a center of redistribution (Lekson et al. 1988:109). Exotic trade items such as macaw feathers and copper bells from Mexico (Reyman 1971), turquoise from Santa Fe, and Pacific coast shells occur more frequently at Chaco Canyon than other known Anasazi sites. The number of known periperhal Bonito-style structures has grown from 20 to over 150 in the last few years dramatically expanding Chaco's territorial limits. This vast domain would not be efficient in the redistribution system proposed by Judge. As he and other researchers have concluded:

> The Chacoan system, as we now define it, is from eight to 10 times larger than we had previously recognized, and the scale of our studies has become irreversibly much larger... Now, given the dramatic increase in the scale of the Chacoan system, we must reevaluate our hypothesis. Although we are certain that Chaco Canyon was very different from the isolated proto-urban community it is often portrayed as being, we are less certain of how it fits into the world beyond the San Juan Basin. We know that it was the heart of a vast regional system and a community of unprecedented complexity; we also have reason to believe it was much more than a communal center for the San Juan Basin (Lekson et al. 1988:109).

RELIGIOUS FUNCTION

Rather than searching for a satisfactory economic interpretation for the prehistoric roadways, it is time to reconsider the possibility that they are the "ceremonial highways" of Judd. The religious and symbolic functions of other roadways in the New World generally defy rigorous analysis. Nevertheless, there are areas throughout the new world where cultural and natural features upon the landscape have been endowed with abstract or religious connotations. Maya roads (sacbes) may have been aligned to the rising and setting of specific constellations. Roads in association with the Mexican centers of Xochicalco and La Quemada had both political and ritual symbolism (Trombold, in press). I observed the same situation during my fieldwork in Peru for the roads emanating from the Inca capital city of Cuzco. The abstract connotations associated with landscape features for the above areas are supported from ethnohistorical data; this is not the case for Chaco Canyon.

An intensive ethnological study for the roads has never been completed for the Pueblo cultures neighboring Chaco Canyon. Beyal's statement to Judd (1954:346) that the Chaco roads "were not really roads, although they looked like them," suggests another interpretation, possibly a religious one. At a minimum, Beyal's statement should make us aware that we should not always perceive roads as always being utilitarian; that, in short, we must not transfer our concept of modern-day roads into the prehistoric past.

<u>Ritual Activity</u>

The first hypothesis stated that if the roads served a religious purpose then they will connect to a major center of ritual activity where they will be associated with religious features such as shrines, great houses, kivas, or areas of ceremonial ceramic breakage. To test this hypothesis it will be necessary to examine the archeological data, and to a lesser degree the ethnographic data. From this synthesis it may be possible to determine whether or not the prehistoric population viewed Chaco Canyon as a "central place" which had the prestige of a great ritual center with links to major areas outside the Canyon.

Although the roadways on the north mesa of Chaco Canyon converge at Pueblo Alto, its initial role may have been to interface with a shrine communication system (Hayes and Windes 1975; Toll and McKenna 1983). Alto's location high on the mesa renders excellent visibility to distant shrines, outliers, and topographic peaks. Road segments around Pueblo Alto may have originally been marked by stone animal figures which could have been used to mark shrines. Atop the stairs marking the final approach to Alto from the South, Holsinger reported "a shrine, around the rude carved figure of some animal"

(Holsinger 1901:68). Windes was able to find a masonry feature 9 meters from this point and speculated that it might be the shrine that Holsinger observed (Windes 1987:105). Mrs. Wetherill confirmed the existence of the stone figure to Gordon Vivian (1948), although in a different location. O.C. Havens, photographer for Neil Judd, photographed a stone figure which he simply remembers having been found in the vicinity of Pueblo Alto (Havens, in conservation with Randy Morrison and John Stein, 1983-- from Windes:1987:105). Confusion arises because another carved-stone animal head on a cylindrical body was reportedly found in 1925 at Tsin Kletzin (Judd 1954:295), but may be the same one reported by Havens at Pueblo Alto. This figure is currently stored at the Chaco Canyon headquarters (Windes 1982:22). Mrs. Wetherill also recalled another stone figure that was located to the northeast of Chetro Ketl. Other shrines may have existed in the area. Waters (1963:43) states that a Hopi informant found shrines along the Alto roads and around the canyon although they were without carved stone figures. Windes (1987:109) concludes that "Despite confusion over location, it seems probable that carved-stone animal figures marked one or more of the roads in the central canyon complex."

Many other features outside the canyon also suggest the location of shrines and their association with the roadways. At the northern terminus of the North Road, for instance, elevated small shrines are found near the staircase that descends into the Kutz Canyon. Five structures that resemble historic Pueblo shrines are also found north of Pierre's Complex. Many structures found in Chaco share the common characteristics of historic shrines in that they are small, remote, and elevated. Even the horseshoe-shaped herradura, which is consistently located on major topographic breaks where there is extended visibility in both directions along the roadway, may have served more as a religious shrine than a functional economic purpose. Although no known carved figures have been found at the herraduras, the features are associated with ceramic scatters in the roadway within 50 meters of the herradura. No middens or other material associations such as lithics, manos, or metates have been found in connection with the herraduras (BLM 1987).

SIGNALLING, COMMUNICATION, AND RITUAL

The topographic location of herraduras and other shrine-like features has initiated an interest in the subject of signalling stations (Hayes and Windes

1975:143-156; Drager 1976; Lister and Lister 1981; Robertson 1981; Powers et al. 1983). In the religious ceremonies of some contemporary puebloes in the Southwest, the beginning of religious activities are determined by an observer in a structure outside the pueblo who sends a signal (sometimes by fire) to the pueblo for the ceremonies to begin (Reyman 1971). Usually the observer is located in a position to view a phenomenon such as a sunrise which is not visible from the pueblo itself. When the sun rises for the winter solstice, a signal fire is sent from Corn Mountain to alert the town of Zuni, and this same practice is done at Acoma to signal the summer solstice (Parsons 1939:373; White 1932:95). One of the earliest references to this activity is recorded by Cushing between 1882-1883 for the equinox at Zuni:

> Each morning, too, just at dawn, the Sun Priest, followed by the Master Priest of the Bow, went along the eastern trail to the ruined city of Ma-tsa-ki, by the riverside, where, awaited at a distance by his companion, he slowly approached a square open tower and seated himself just inside upon a rude, ancient stone chair, and before a pillar sculptured with the face of the sun, the sacred hand, the morning star, and the new moon. There he awaited with prayer and sacred song the rising of the sun. Not many such pilgrimages are made ere the "Suns look at each other," and the shadows of the solar monolith, the monument of Thunder Mountain, and the pillar of the gardens of Zuni, "lie along the same trail." Then the priest blesses, thanks, and exhorts his father, while the warrior guardian responds as he cuts the last notch in his pine-wood calendar, and both hasten back to call from the house-tops the glad tidings of the return of spring. Nor may the Sun Priest

> err in his watch of Time's flight; for many are the houses in Zuni with scores on their walls or ancient plates imbedded therein, while opposite, a convenient window or small port-hole lets in the light of the rising sun, which shines but two mornings in the three hundred and sixty-five on the same place (Cushing 1967:40).

It should be noted from Cushing's account that there is a ceremonial relationship between a shrine, a carved figure, a topographic feature (Thunder Mountain), a pilgrimage, and an astronomical event (equinox). In addition, the event occurs simultaneously with the training of runners in the kivas who eventually compete in a twenty-five mile event (Cushing 1967:40).

During the 1970's the Chaco Center conducted a series of experiments to determine if shrine-like structures were located in such a manner as to preserve line-of-sight view. A series of "flare-up" tests were used throughout the Canyon:

> Flare-ups involved individuals lighting railroad flares at Shrine locations throughout the San Juan Basin at a pre-ordained time (during the night), and recording exactly what was visible from what. The results of the flare-ups demonstrated conclusively that the Shrines were, in fact, situated on the landscape in a position which resulted in the maintenance of line-of-sight between other Shrines and major great houses (BLM 1983:9-23).

There is scant archeological evidence, however, to warrant herraduras and shrine-like structures as being used for signalling stations. In most cases there is little or no evidence for repeated burning. Large firepits do occur at places such as the East Wall at Pueblo Alto, El Faro at Pierre's Ruin, and the Poco Site (BLM 1983:9-24) which could have been used in a fire-signal communication system. The archeological absence of repeated burning at herraduras and other shrine-like structures, however, does not dismiss their potential role in a communication system. Signalling could have been conducted from these structures in the form of torches (like the flare experiments), mirrors, or runners; all of which are used in historic and contemporary Pueblo ceremonies. As is the case for modern pueblos, these signals could have been used to initiate religious activity in prehistoric Chaco Canyon.

The straight course of the Chacoan roads and the location of herraduras along them are similar to the Ceque system in Peru which I studied under the direction of Dr. Tom Zuidema in 1977. The herraduras are reminiscent of the "huacas" (shrines) of the Ceque system. The Ceque system was a series of 41 straight lines emanating from the city of Cuzco and crossing the steep terrain of the Andes mountains. This system was recorded by chroniclers on the Pizarro expedition of A.D.

1536. Along the lines there were a total of 328 "huacas" or shrines. The lines themselves are generally not visible on the ground but were determined by navigating between two huacas. The Ceque system was used for recording superimposed cycles of ritual events (Zuidema 1977). As Zuidema states:

> The meaning of the ceque system can be explained best by way of the feast of the Capac hucha, when children were sacrificed in Cuzco during the two solstitial feasts...At that time, the ritual and calendrical value and rank of all the huacas in the empire, of every village, town, province, were reassessed. The representatives of these sent presents and children to the Inca in Cuzco. Some were sacrificed there while others were sent back and sacrificed at home. These capac hucha (messengers) followed a straight line (ceque) on their way home and did not go by way of the roads (Zuidema 1977:231).

As a research assistant with Zuidema, I noticed that many of the huacas were located at places where there was an excellent line-of-site. From our discussions with the local population near a huaca it became apparent that the huacas apparently had no economic function, purely a religious one. This interpretation was confirmed through the research of Tony Morrison who studied contemporary Incaic cultures and found that lines and shrines continue to be a part of ritual activity:

> I learnt that six sacred places led to the church, the seventh in the line, starting from a silu on a hill some miles distant. Next was a holy place at one corner of the village (there were four of

> these places, each used on specific occasions); then the pile of stones, next an adobe-built shrine in front of the church; next the place of the sacrifice, and finally a bloodstained brick-made square...the mis'quala or place for an offering. The Indians made offerings and prayers at each place as they respectfully made their way to the church. It was, on a smaller scale, similar to Father Cobo's seventeenth-century description of the holy stopping-places on the ceques of Cuzco. Although the order of the shrines was probably coloured by some ideas introduced in the sixteenth century, the ritual was most likely a curious mixture of old and new beliefs that still exists in many parts of the Andes (Morrison 1978:185-186).

In his discussion of the lines at Nasca, Morrison states:

> Straightness or directness was clearly of prime concern to the creators of the paths. The shortest distance between two wak'as (huacas) had to be a straight line, but it was not always the easiest route. The paths were intended to be straight-- Gerald Hawkins estimated they have a deviation of no more than four yards in a mile-- and if, as seems most likely, the paths were pre-Spanish then the concept of straightness has to be an ancient one...The wak'as almost certainly represented spirits of ancestors...Maria Reiche has said that a temple does not exist on the desert, but long ago she suggested that the stone piles and cleared areas could have been sacred spots (Morrison 1978:187-188).

Morrison analyzed the lines from a technical, surveyor's standpoint; yet, he wondered if there was not a spiritual concern in mind as the builders struggled to reach the mountain tops in the desert:

> Once, in the Andes, near Lake Titicaca, I asked an Indian about a route through the mountains. He gave me careful instructions that I was not to leave the path, as evil spirits hid everywhere. Though his concern might have stemmed from recent teaching, I believe it was old. The concept of

> special paths or routes to a divine place is not confined to one religion, and in Nasca the straightness of the paths is clearly demonstrable (Morrison 1978:193).

Returning to Chaco Canyon we find that only limited ethnographic work has been done to place the features of Chaco Canyon in Navajo or Pueblo legends. The Navajo believe that the Anasazi structures are reminders of internal strife which they believe destroyed the "fourth world" (Fransted 1979). The ruins marked natural aspects of the landscape and represented balance and harmony. To the Navajo, these places are considered to be spiritually unsafe places (Fransted 1979). Williamson described the relationship of shrines and ceremonial activity at Hopi:

> At Hopi, in addition to the sun shrines that exist near the pueblos, it is customary to erect shrines at the spot on the horizon at which the sun seems to rise or set at specific times. Though these are sometimes five to fifteen miles away, the shrines are tended by runners from the pueblos and prayer sticks are "planted" in each on the day at which the sun rises or sets over the shrine. In conjunction with the sighting place, the shrines constitute a group of sacred places and a long set of straight lines that are highly reminiscent of Incan huacas and ceques, though I do not suggest that one set of ideas derives from the other. They are, however, conceptually related and demonstrate how similar ideas may spring up in widely separated locations. The young Hopi initiates run in as straight a line as possible to the shrines and back in order to plant their prayer sticks. They follow, as it were, literally, the straight road of a beam of sunlight (Williamson 1984:110).

Pilgrimages are conducted at Zuni by religious leaders who go to a lake which is considered the "village of the gods" where the spirits of dead Zunis abide (Hart 1985). Fires are lit along this journey and archeological evidence indicates that the route has been used for several centuries. Kelley (1984) describes a Zuni pilgrimage that occurs along straight roads with shrine-like sites. Another pilgrimage, conducted by a Keresan group, visited features and shrines as it crossed Chaco Canyon on its journey north to the San Juan Mountains which was the land of the ancestral spirits (Ellis and Hammack 1968:32). Although shrines and features in Chaco Canyon continue to survive in the ceremonial activity of contemporary Puebloan and Navajo cultures, they have received fragmentary documentation.

In summary, it is proposed that the Chacoan roads are associated with shrines which could have been used in ceremonial ritual. Although supportive archeological and ethnographical information is scant, the thread of evidence does indicate that at one time there were at least a few carved-stone figures in association with some segments of the roadways. Also, consistent ceramic scatter as well as repeated absence of other material associations at the herraduras suggest a ritualistic rather than economic function. Finally, the physical layout of straight roads and possible shrine constructions is similar to the Ceque system in Peru whose interpretation has been aided by ethnohistorical information. The fact that herraduras are located between great houses, and that the great houses like the herraduras are manifestations of roadway construction, suggest that we examine the great houses and their associated features more closely.

POPULATION ESTIMATES AND ARCHITECTURAL ASSOCIATIONS

Great Houses

The most significant aspect of the great houses has already been discussed, namely that they did not contain the large number of inhabitants that were originally projected. In addition, a large work force was not necessary for the construction of the great houses. It is estimated that a 30 man crew, working between two to four months a year, could have completed a major construction project within 10 years (Lekson et al. 1988:102). As mentioned previously, a peculiar aspect of the great houses is that the small resident population did not have control over the storage facilities; rather, they were accessible from the road. If the great houses were used primarily for habitation quarters, one would expect the residents to have control over the storage rooms.

Skeletal Remains

Another confusing issue in Chacoan archeology has been the limited discovery of skeletal remains other than the presence of a few "high status" burials (Akins and Schelberg 1984). Where did the occupants bury their dead? The cemeteries or burial grounds have never been found, perhaps confirming the limited population proposed by Lekson et al. (1988) and by Windes who states:

> ...much of what was found at Pueblo Alto suggested behavior not rooted in long-term, permanent residence...The small, resident population estimated for the site in the A.D. 1000s is more in accordance with available local resources than a site (and a canyon) crammed with Anasazi residents (Windes 1987:423).

If the great houses were not the loci of large numbers of inhabitants, what was their purpose? Are the great houses occupied year-round or seasonally? To answer these questions we must examine two features associated with the great houses: earthworks and large ceremonial kivas (with the exception of Pueblo Alto).

Earthworks

As the roads approach a great house they are often flanked by massive linear mounds which the BLM characterized as earthworks (BLM 1987). Throughout most of the previous archeological literature these features have been referred to as trash mounds or middens, (see, eg., Marshall et al. 1979). There are several distinctive characteristics which separate the Chacoan earthworks from conventional trash mounds. For instance, the earthworks may contain constructional features such as retaining walls like those found in front of Pueblo Bonito (Judd 1964). There is also an absence or disproportionately low amount of carbon material such as ash, bone, or charcoal that is normally found in a midden. There is a similar lack of rock material. Conversely, there is a large quantity of fine-grained sediment matrix, suggesting that the earthwork sediments came from excavations that neared or penetrated bedrock (BLM 1987:15).

From the surface, the earthworks look like trash mounds since there are large quantities of ceramics on top of them; yet ceramic material is often the only component in the earthwork. What is more, the BLM (1987:15) notes that "Most characteristics indicate that a large volume of materials composing the earthworks are deliberately excavated and emplaced" as opposed to the haphazard refuse found in middens. The debris in the earthworks is layered and appears to have been deposited intermittently as opposed to daily. Since the earthworks are devoid of normal midden materials they seem to reflect human activity that is not related to daily subsistence and occupation. This is further supported since earthworks or trash mounds are not found at all great houses.

The recent excavation of the trash mound at Pueblo Alto revealed some intriguing information regarding the 204,000 artifacts found there. As Lekson et al. state:

> How could the small permanent population in the household suites have produced such a disproportionate number of artifacts? We estimated that over a 60-year period more than 150,000 pottery vessels alone were discarded in this one trash mound. If our estimate of the number of permanent residents at Pueblo Alto is correct, that amounts to 2,500 vessels per year or 25 pots per person per year! (Lekson et al. 1988:105).

Windes summarized from his excavations at Pueblo Alto:

> The discrepancy between the small population size and the large volume of the refuse in the Alto trash mound, along with the cultural material and the mound stratigraphy, can be explained as a result of intermittent activities, probably in the form of large, periodic influxes of people not in "permanent" residence at the site (Windes

1987:423-424).

Although the function of the earthworks is not known at this time, in almost every instance they are located along the roads accessing Anasazi sites and great houses (BLM 1987). It may be that the earthworks are remains of past ceremonial events which were held at special times of the year. In this way the earthworks may reflect the seasonal gathering of large numbers of people who saw Chaco as a "Central Place" in their ceremonial worship. In this regard Judge (1984) notes that the great houses experienced periodic intensive consumption of food while Toll (1984) comments about the possible large scale activity of ceremonial ceramic breakage. As shall be shown in the next chapter, this large scale ceremonial breakage is similar to that conducted at the Arenal study area in Costa Rica.

Great Kivas

Another direct association with the great houses is the great kiva. Generally, the great kiva is found within the floor plan of the great house. However, if the great kiva is found outside the great house there is usually a formalized road leading to it. The great kiva is an elaboration of the kiva, a circular subterranean structure a few meters in diameter that was the center of religious and social activity. The underground nature of the kiva reminds contemporary Puebloans of their original emergence from within the earth into this world. Within the kiva a hole in the ground, or "sipapu" may have been a symbolic reminder to the Anasazi of their journey from the underworld as was their climb up a kiva ladder through purifying smoke onto the surface. The emergence myths figure prominently into Pueblo cosmology as evidenced at Acoma:

> When they built the kiva, they first put up beams of four different trees. These were the trees that were planted in the underworld for the people to climb up on. In the north, under the foundation they placed yellow turquoise; in the west, blue turquoise; in the south, red; and in the east, white turquoise. Prayer sticks are placed at each place so the foundation will be strong and will never give way. The walls represent the sky, the beams of the roof (made of wood of the first four trees) represent the Milky Way. The sky looks like a circle, hence the round shape of the kiva (Stirling 1942:19).

There are at least 38 kivas at Pueblo Bonito as well as two great kivas. Over 18 great kivas are known in Chaco, the largest being Casa Rinconada (Figure 4-25) which has a complex of associated astronomical features

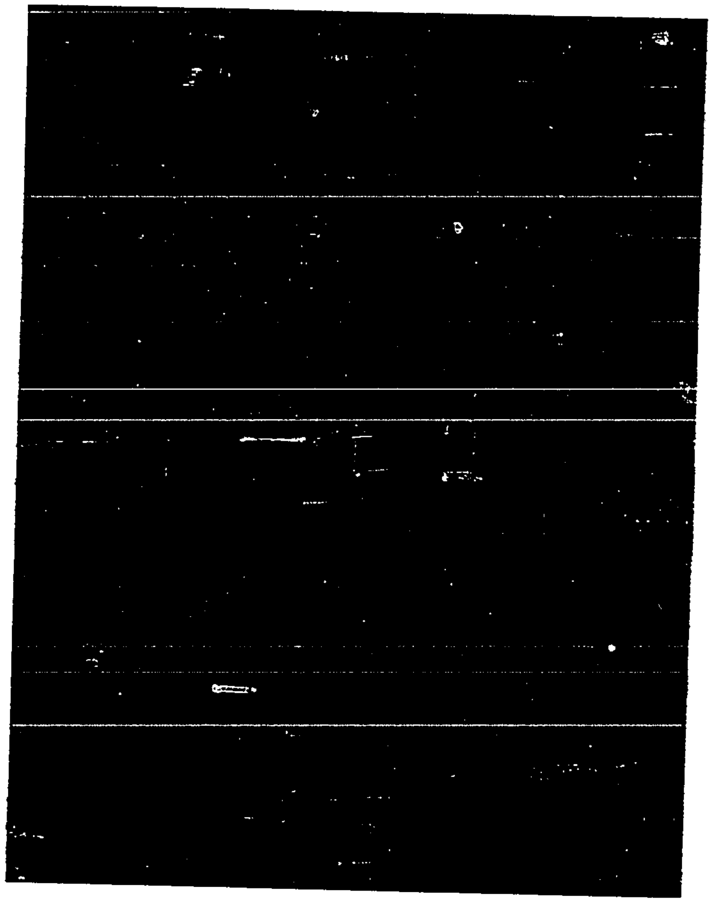


Figure 4-25. An example of a great kiva can be seen here at Casa Rinconada. Above the Canyon in the background can be seen the ruins of New Alto to the left and Pueblo Alto to the right.

(Williamson 1984:136-137). These great kivas range from 15 to 20 meters in diameter with recessed niches in the wall, and, like the great houses, generally contain Bonito-style architecture. Certainly, the great kivas figured prominently into Anasazi ceremonial worship and are probably related to the ceremonial ceramic breakage in the earthworks. Another curious component of the great houses and great kivas are the existence of a unique style of cylindrical vases which may have been used solely for ritual use (Roney, personal communication).

Ceremonial Ceramic Breakage

Like the ceramics within the earthworks, the ceramic breakage found away from the great houses along the prehistoric roads may be ceremonial in nature. These features are found only along the roads. John Roney (personal communication, 1989) reports that these features are generally 20 meters wide and up to 400 meters long. As mentioned previously, although these features have been detected in the remotely sensed imagery, no other road characteristics are found in association with them from ground level. The ceramics along the North Road have a larger percentage of non-utility ware than ceramics found at Chacoan Sites (Toll

1984) and Kincaid et al. (1983) estimate that only 10% of the ceramics found along the road are from the San Juan River communities. Mesa Verde wares from the north and Chuska wares from the west are the dominant intrusive group (Kincaid et al. 1983:9-76). Ceremonial breakage of ceramics is often associated with rituals relating to the dead (Parsons 1939:72-77). The ceramic scatters along Chacoan roads may have a ceremonial analogy in the Tewa rituals where a bowl is ritualistically broken at death away from the pueblo to sever a person's connection with the pueblo (Ortiz 1969). White records (1973:137) that officials from Keresan and Tanoan pueblos take offerings that represent a person's soul and place them in topographic features away from the pueblo.

Linear Grooves

Other possible shrine-like features found in Chaco Canyon are the long linear grooves which have been cut into the bedrock, apparently at the road's border. An example of this feature can be seen along a road leading from Chetro Ketl to Pueblo Alto (Figure 4-26). This groove is in association with the shrine reported by Holsinger:

> ...an ancient road-way, which can be traced from Chetro Ketl stairway to Alto ruins. This road-way

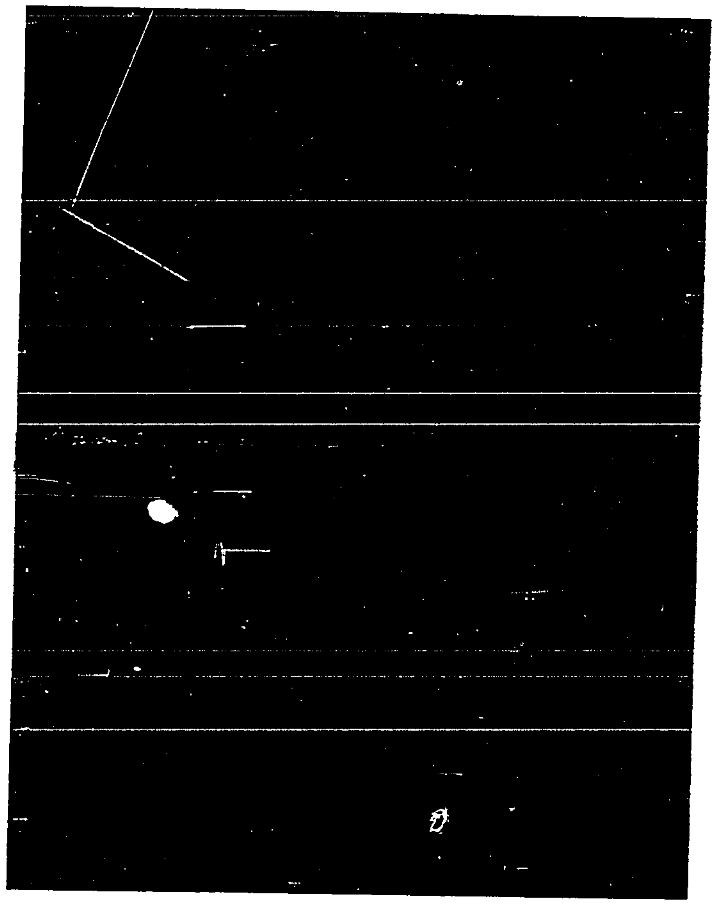


Figure 4-26. Long linear grove etched into the rock surface on the road border between Chetro Ketl and Pueblo Alto.

> was 20 feet wide and walled up to a grade with loose rock and soil. It commenced near the top of the stairway referred to and followed a narrow shelving or terrace of the rock, westward, parallelling the canyon. It followed this ledge for about half a mile to a point where there are indistinct remains of a broad flight of steps, twenty-one in number. At the top of this stairway there appears to have been a shrine, around the rude carved figure of some animal, now mutilated beyond recognition. It is near this point where the first traces of the groove is found and it follows this road-way to a point where it crosses a wash and enters the sand covered mesa where both disappear (Holsinger 1901).

Parsons (1939:339) notes that in Pueblo ritual these features are used in curing ceremonies and that contact with these grooves can heal a number of physical and psychological maladies.

Chaco Canyon appears to have been an area of major religious activity as evidenced by shrines, ceramic breakage in the earthworks, cylindrical vases, great house functions, great kivas, and ceramic scatter along roadway orientations . The local resources appear to have been insufficient to have sustained a large population and some of the residency seems to have been seasonal rather than year-round. Rather than an economic center, Chaco Canyon may have become an important ritual center (C. Breternitz 1982; Judge 1983). In this context, the roads would have served to connect distant communities and ensure widespread participation.

CENTRAL PLACE

Chaco Canyon may have been perceived as being a "central place" to the Anasazi. Ethnological data regarding roadways is often scant although there is a wealth of material regarding emergence, migration, and central place. Center place figures prominently in Puebloan mythology. From the underground worlds the Pueblo emerge into the present world. Parsons (1939) notes that roads are used to travel to the middle place, the place of emergence. The roads are also conceived as the routes along which the spirits of the dead travel (White 1942:177). In Pueblo cosmology the people wander to the four points of the compass before finding the Middle Place; the place where all roads connect. "Much more than merely a geographical notion, the Center is the proper place for them to be, the place in which they will prosper and thrive as a people--the place where their heart resides (Williamson 1984:65).

The physical landscape figures prominently in the emergence myths of Pueblo tradition. Mountain peaks, valleys, springs, caves, lakes, and canyons are visited by the Pueblo as they re-enact the history of emergence and creation (Ladd 1983; Stephen 1936; Stirling 1942;

Ellis and Hammack 1968). From what is known from the remote sensing analysis and ground verification to date, the North Road runs to a canyon, the Ashislepah Road ends at group of cisterns and possible lake, and the South Road terminates at the prominent feature of Hosta Butte.

RITUAL CONCEPTS

The second hypothesis to be tested stated that if the roadways served a religious function, then they will incorporate elevated areas of topographic relief into their course such as pinnacles, mesa tops, or other observational areas and will be associated with ritualistic concepts such as directional symbolism, orientation, and astronomy. From the remote sensing analysis and ground truth verification it is apparent that these features, such as Pierre's Ruin and Hosta Butte, are being incorporated in the roadway pattern. Hosta Butte is a prominent projection to the south of Chaco Canyon. Pierre's Ruin is composed of a number of structures that are situated atop pinnacles and ridges (Powers et al. 1983). Like the Pueblos in Chaco Canyon, Pierre's Ruin contains a large number of rooms which were not used for habitation. From an economic and efficiency standpoint it makes better sense to avoid elevated features. Even if Morenon is correct that a mobile population could benefit from the roads even if they were not using them to transport goods, it would still be more efficient to by-pass topographic features even if the roads are used primarily for traveling.

To the casual observer, prehistoric roadway systems may appear to be more linear than they are in actuality:

> The Inca construction engineers followed a simple rule in laying out their roads: they ignored all obstacles and ran their lines over the shortest route, straight across the face of the land...They made no concession to steep rock walls; when they encountered one, they either tunneled right through it or cut steps and went over the top...(Von Hagen 1952:35).

A closer examination of the Inca roads, however, reveals that they incorporate slight changes in direction as they move from one feature to another. This phenomenon has also been determined in the case of the Chacoan roads as they negotiate across the landscape; a condition different that the original "straight as an arrow" roads recorded in early road research.

Topographic Features

The role of topographic features in contemporary Pueblo ritual has been documented well (Cushing 1967; Ortiz 1969; McCluskey 1977). As Williamson observes:

> The boundaries of the Pueblo World are circumscribed literally by the surrounding mesas and mountains that can be seen from the Center. They also serve as figurative or psychological boundaries of Pueblo life. Everything and everyone outside those boundaries is other. Inside the boundaries, ties of blood, clan, and fraternity link them to their world (Williamson 1984:67).

And as Horgan comments regarding the backgrounds of southwestern cultures:

> Everything in the landscape was sacred, whether the forms of nature, or those made by people--altars, shrines, and the very towns, which were like earth arisen into wall, terrace, light, and shadow, enclosing and expressing organized human life (Horgan 1971:37).

The sacredness rendered elevated topographic features by the Anasazi can documented. An example of this is the "sun dagger" atop Fajada Butte, which rises 450 feet above the east end of the Canyon floor. This feature can be reached through a series of stairs and ledges which climb up from the canyon floor. The sun-dagger feature consists of a pecked spiral pattern on a ledge behind three upright stone slabs. The dagger-like patterns created by this arrangement are used to mark the winter and summer solstice as well as the equinoxes. It is unique in that it marks these positions at noon rather than sunrise or sunset positions along the horizon (Sofaer et al. 1979).

Astronomy

Astronomy figures prominently in contemporary and historic Puebloan ceremonies and is incorporated into the architecture of the Anasazi (Reyman 1971; Williamson 1984; Brandt and Williamson 1979; Sofaer et al. 1979; Fewkes 1892; McCluskey 1977). It is known from historic Pueblo practice that the exact determination of the winter solstice and often the summer solstice and equinoxes is crucial to the ceremonial and agricultural interests of the society (Ellis 1975; Parsons 1939; Cushing 1967). At Hopi, for instance, there is a calendar system that uses natural features along the horizon. When the sun reaches the appropriate place along the landscape, the Hopi know it is safe to plant certain crops, burn-off fields, and clear the irrigation ditches (Forde 1931; McCluskey 1977). As documented by Cushing (1967) and Williamson (1984), a combination of architectural features, natural landmarks, and astronomy are used in ceremonial activity.

Directional Symbolism

From astronomical observation one can determine orientation and direction; factors which are apparent in both Pueblo ritual and Anasazi architecture. The orientation of the great kivas at Pueblo Bonito and Casa Rinconada are on a north-south axis. Casa Rinconada contains features which could have been used for astronomical observation but equally important is its alignment:

> In investigating Casa Rinconada for astronomical alignments, we quickly came to the realization that its structure was remarkably symmetric. Even unaided, the eye can easily pick out one major axis of symmetry--the line between the north and south doors. Most of these features on either side of this line would fit counterpart features on the opposite side of the kiva. But what is certainly more remarkable is that the line of symmetry is also a true north-south line!... Later, after making a detailed transit map of the kiva's interior, we concluded that the designers and builders of Casa Rinconada had taken unusual pains to construct a geometrically precise building unlike any other building in the Southwest (Williamson 1984:135-136).

Reyman (1971:253) notes that, contrary to the pattern of small kivas, great kivas are generally entered from the north side. At Zuni there are six kivas; each one is associated with one of the six directions and a priest who represents that direction (Reyman 1971:134).

In Pueblo society the cardinal directions are associated with colors, animals, and mountains. Dozier states:

> The cardinal direction associations...are made in all the pueblos, but some pueblos have additional associations. Parsons considers Zuni as most thoroughgoing in this respect; even the various animal species have been subdivided by color and direction (Parsons 1939:365). The Tewa, however, must surely vie with Zuni in the number and complexity of the phenomena associated with directions. Thus, the Tewa have cardinal corn maidens, cardinal birds, cardinal snakes, cardinal shells, cardinal trees, cardinal mountains, cardinal sacred lakes, and cardinal "houses" (Dozier 1970:207).

The north direction is perhaps the most primary direction in Puebloan society. At Acoma, for instance, altars are placed on the north (Parsons 1939:362). Most Pueblo tradition states that their source of origin is from the north (Roberts 1930:156; Ellis 1967:43; Dozier 1970:204). The importance of the north direction permeates Pueblo society: the Keresans believe that north is where Iyatiku resides at the sipapu (White 1942:177); ceramic breakage in honor of the deceased occurs on a road to the north (Ortiz 1969:54); the people of Jemez believe that north is the ancestral homeland (Weslowski 1981:123); and at Zuni it is the primary direction regarding ceremony and religious leadership (Reyman 1971:134-135).

The North Road, itself, may be a cosgmographic expression of the Anasazi (Sofaer et al. 1986). The road appears to connect one canyon to another canyon and does not have any evidence for the transportation of economic goods (Stein 1983:8-7). Shrines, ceramic scatters, and parallel segments occur throughout its course. No major settlements, other than the enigmatic pinnacle complex at Pierre's Ruin, are encountered along its trajectory. Its northern orientation is maintained even in areas where immediate views to the north and south are obstructed by the undulating plano. It slightly shifts angles along its course to incorporate elevated topographic features into its alignment:

> It is interesting to note that the road's slight angle change at Pierre's complex, which shifts its bearing from north to 2 degrees east of north, directs it straight from the cone at Pierre's Complex, El Faro, to the large Upper Twin Angels mound. These symmetrically-shaped pinnacles, while not very high, are the most distinctive prominences in the vicinity of the road corridor as it crosses the rolling northern terrain (Sofaer et al. 1986).

Astronomical Associations with Roadways

As a student with Jonathan E. Reyman in 1975 and 1976, I participated in the recording of features which had potential astronomical significance in Anasazi architecture, none of which were associated with the roadways. Through the years, however, astronomical sites have been located in Chaco Canyon which do have direct association to the roadways. Williamson (1984:87) and O'Flyn have found what they believe to be a shrine near the road at Penasco Blanco which was used to observe the winter solstice. Penasco Blanco also has a pictograph of a hand, sun, and crescent moon (similar to that reported by Cushing at Zuni) which is felt to be a representation of Crab Nebula explosion in Taurus in A.D. 1054. A pictograph is also located a few inches away which most interpret as being a sun symbol. I feel, however, that it is a representation of a comet with its tail and marks the appearance of Halley's Comet in A.D. 1066, when it appeared brightest to earth. O'Flyn also found a painted white sun symbol adjacent to an ancient road near Wijiji at the east end of the Canyon. From this site the sun can be observed at the winter solstice to rise behind a sandstone pillar which projects up from the Canyon floor (Williamson 1984:88-89).

Parallel Segments

Remote sensing analysis, as a part of this study, has located a number of parallel road segments in addition to those which have been previously mapped. Some of these are found along elevated portions (such as ridges) of the landscape. Although the function for these parallel segments is unknown, they may have had religious connotations. As previously discussed, even dual pairs (4) have been found along the roadway system. This dualism may be reflective of religious ceremonies conducted by Anasazi moitey systems.

Moieties

Dual divisions (moiety systems) are commonly found in Pueblo society and archeological evidence suggests their existence in Anasazi architecture. Dozier (1970:192-193) states that all Pueblos have moieties except Zuni and Hopi. Parsons sees evidence of a previous moiety system in the calendrical distributions at Zuni and Oraibi (Parsons 1939:62). Cushing notes a dual division of the summer and winter peoples in Zuni mythology (Cushing 1896:386). At Zia, dual division is associated with two kivas and the basis of membership is determined by residence and direction:

> Those who live north of an imaginary east-and-west line, drawn through the village between the north and south plazas, belong to the Wren kiva; those who live south of this line belong to the Turquoise (White 1962:183).

Like Zia, dual division is formed from north and south units at Taos and Picuris. The Tewa also have a north-south division and have made dual division a central feature of their ceremonial organization; dividing the population into summer and winter people (Ortiz 1965).

The incorporation of cardinal directions into a possible moiety structure is seen at Pueblo Bonito (Figure 4-27). The southwest wall is aligned due east-west. The central plaza is divided by a wall that is on a due north-south orientation, basically dividing Pueblo Bonito in-half. The two great kivas are located on opposite sides of this north-south wall, reminiscent of the situation at Zia. The largest of these kivas is itself on a north-south orientation paralleling the division wall as evidenced by the entrance, wall and floor features of the kiva (Hadingham 1984:150). The fact that Pueblo Bonito may have been a moiety is further enhanced by the research of Travis Hudson (1963). Hudson

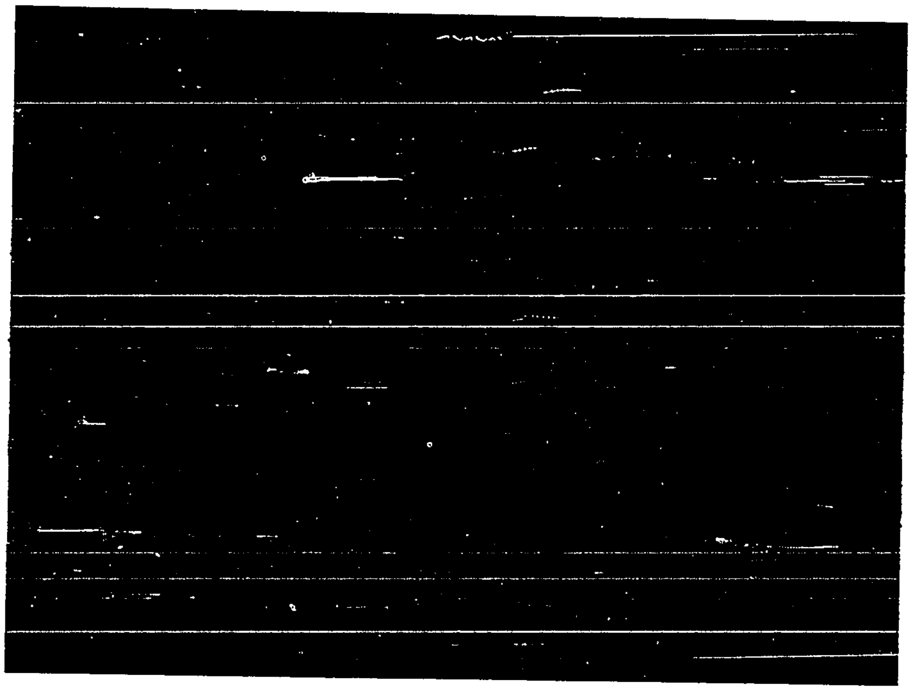


Figure 4-27. Pueblo Bonito showing a dividing wall down the middle with a great kiva on each side. This Anasazi structure may represent a moiety system.

was interested in the units of measurement that had been employed in Anasazi construction. At Pueblo Bonito, Hudson learned that two separate units were used at the same time. The boundary for the two sets of units was the north-south dividing wall. On the west the builders used a unit of about 20 inches; the builders to the east used a unit of about 29 inches (1963:27). The division of the structure with its own great kiva, orientation, and units of measurement suggest that during the 11th century Pueblo Bonito may have been divided into a moiety. Like many of the Pueblos along the Rio Grande valley, the possible moiety structure at Bonito may have been essential to the organization of practical and spiritual affairs. Like the Tanoan legend discussed below, moiety ceremonialism may have been incorporated into the parallel segments of the roadways.

Duality extends into Pueblo myth and ceremony in the form of pairing and binary oppositions (Levi-Strauss 1955,1963; Parsons 1939:101-102). Pueblo legends describe "two" war gods, or multiples of two and Ortiz provides examples of paired concepts among the Tewa of Summer and Winter as well as binary opposition or contrast (Ortiz 1965:390). Parallel roads have been described in Pueblo mythology (Parsons 1925:137-138). An interesting example, discussed in the cosmographic expression of the Great North Road (Sofaer et al. 1989), comes from a Tanoan legend:

> True to the underlying message of the origin myth...the Tewa do begin and end life as one people. The term they use for the life cycle is poeh, or "path", after the two different migration paths the moieties followed after emergence. Thus, at the beginning of life there is a single path for all Tewa. ...it divides into the parallel paths and continues in that way until the end of life. At death the paths rejoin again and become one, just as the moieties rejoined in the myth of origin (Ortiz 1969:57)

The archeological and astronomical evidence has demonstrated that topographic features along the roadways are associated with ritual activity. Elevated features are associated with herraduras, kivas, tower kivas, shrines, rock art, ceramic scatters, and fire-pits. Anasazi architecture associated with these topographic features, like other architecture in the Canyon, expresses celestial activities which occurred in the 10th and 11th centuries. It is proposed that the roads incorporated these topographic features, not only because of the excellent visibility they afforded, but also because they represented sacred places in Anasazi cosmology and at times, like contemporary Pueblo practices, were used for celestial observation and ritual.

SUMMARY\CONCLUSIONS

The discovery of prehistoric roads in Chaco Canyon initiated a number of scientific investigations regarding their origin, function, and time of construction. Although there had been reference to roadways around the Canyon by previous researchers, the extent of the road system was not appreciated until it was seen in aerial photography by investigators in the early 1970's. At that time it became readily apparent that remote sensing would be an important tool in mapping the limits of the roadway system. New techniques were successfully employed in data acquisition to enhance these features in the photography. This study has incorporated advanced multispectral data analysis into the Chaco roads research in an attempt to detect roadway segments that are not visible through conventional photographic techniques. The use of multispectral airborne scanners has added to the growing inventory of roadway patterns and holds great potential for future research in the San Juan Basin.

The roads themselves are formalized in that they show evidence of planning and purposeful construction. In other parts of North America trails resulted from the repeated use of an efficient route. But the Chaco roads of the Anasazi were not efficient routes; they made inefficient use of human resources and the natural landscape in order to maintain a straight course and generally consistent width. Economic interpretations that viewed Chaco Canyon as a center of redistribution have been modified as our knowledge of the San Juan Basin has increased. The roadway system is larger than was ever anticipated and the artifactual evidence indicates that Chaco Canyon was a place of limited resources and low population. There was a purpose, perhaps multiple purposes, for Chaco Canyon but we are uncertain of what it was.

Constructed in the 11th and 12th centuries, the roads are associated with great houses, earthworks, great kivas, shrines, and areas of high topographic relief. Although the roads near the Canyon may have been multi-functional, those that extend across the San Juan Basin show little evidence for the transportation of materials and goods. The material that is found along the roads near the canyon indicates that the material is coming in from around the periphery of the Canyon rather than exiting from within it. This is demonstrated by the low percentage of utility wares and the high percentage of intrusive wares along the roads.

The roads are economically inefficient. They do not connect areas of greater population to the Canyon, rather, they seem to connect to mountains, lakes, and canyons. Although many speculate that the roads connect to outlier sites, the evidence to date only verifies this along the North and South roads. Even in the case of the North road this is debatable, for while it crosses Pierre's ruin and ends at Kutz Canyon, there has been no documented evidence that it bends toward Salmon Ruins or Aztec. Nor do the Anasazi place the biggest labor investment in roadway construction where it would have seen the greatest return. Instead of minimizing slope and avoiding topographic obstacles the labor investment is put in the flat, open areas, particularly near the great houses. In fact, the roads seem to be an extension of great house architecture.

The roads appear to be associated with ritual activity. They are found in conjunction with architecture, features, and activities that appear ceremonially motivated. Shrines are found along their course as they connect to great kivas, tower kivas, and elevated features. Ceramic scatters along their route and the large earthworks near the great houses suggest ceremonial breakage. The roads are associated with cosmographic and astronomical relationships such as due north orientation and features that mark solstitial positions. Ethnographic analogies between the contemporary Pueblo and the Anasazi can be found to support a religious function for the roads, but the obscurity of the data demonstrates the limits of our knowledge in this area. Future ethnographic research may prove to be the most profitable course in determining the function of the Chacoan roadway system, particularly since it appears to be ceremonially inspired.

By mapping the prehistoric roads through the efficiency of remote sensing we have uncovered a system that is larger than originally anticipated. The combination of aerial photography and multispectral imagery has increased our knowledge of a system that simply cannot be mapped or understood from ground level. The thermal portion of the electromagnetic spectrum has been particularly useful in mapping roadway segments that are not visible in the other bandwidths or in the aerial photography. This success is tempered by the fact that new instruments and techniques will be necessary for ground verification in the future, since the imagery is recording information that is invisible to the human eye. Although the use of multispectral imagery in this study has expanded our knowledge of the Chacoan roads, more research will be required in the future in order to have greater control of the data and thereby map additional road segments with improved reliability.

When the Chacoan roads were first discovered Chaco Canyon was seen as a permanent center with a large population and a complex polity. The formalized roads and the engineering achievements suggested an organized society that emanated control across the San Juan Basin. But recent evidence documents that Chaco Canyon was a place of intermittent activities with a small permanent population and seasonal influxes of people who only stayed for a short time during the year. Since the Canyon itself has few natural resources, the Anasazi may have seen it as a "central place", a mecca of sacred significance. The resources and goods that entered the Canyon were a result of ceremonial participation.

Economic, social, and political activities were components of this ceremonial center. People gathered periodically to renew social and economic obligations, renew acquaintances, and re-affirm system organization. Here they learned and exchanged information not only about traditional beliefs and heritage but also about astronomy, mathematics, and engineering. The over-engineered roads were an expression of the system. They were impressive accomplishments that facilitated widespread movement and participation in religious activities. They connected the people along the periphery of the San Juan Basin and beyond to sacred places upon the landscape and ultimately to the very center itself.

After two decades of research very little is known about the Chaco Canyon phenomenon. Through the years the information base has been enlarged and the hypotheses have been revised. In order to understand the Chacoan roadway system it must first be mapped. In order to make conclusive statements regarding its function we must first know the limits of the system and the complexities within it. In this respect remote sensing has been a valuable tool in the past and will be even more important in the future.

CHAPTER 5

COSTA RICA

INTRODUCTION

This chapter has investigated prehistoric social integration and human adaptation in the tropical rainforest of northwestern Costa Rica. This area has experienced a series of volcanic eruptions from Volcan Arenal which have preserved remnants of settlements from about 4000 years ago up to the time of Spanish Conquest. There are two major objectives of this research. The first objective was to determine whether lineaments seen in remotely sensed imagery are manifestations of prehistoric pathways or are the effects of natural processes. The second objective was to determine if the application of Geographic Information System technology can assist in verifying the cultural stability expressed over the centuries through the archeological remains. Several types of remotely sensed imagery and photography were investigated to determine their utility in mapping prehistoric pathway locations. A GIS was developed to characterize the similarities and/or differences of prehistoric site locations through time. The Arenal populations have left their record upon the prehistoric landscape. Their activities have survived as faint expressions in the contemporary surface cover. Through a combination of remotely sensed imagery and the construction of a GIS over the study area, new insights have been gained regarding human adaptation in a tropical rainforest environment.

ENVIRONMENTAL SETTING

Costa Rica lies between 9 and 11 degrees north latitude and is located within the latitudinal tropical zone (Figure 5-1). The Arenal study area is located in northwestern Costa Rica in the province of Guanacaste. This province can be divided into three physiographic zones: the Pacific coast, the interior plains, and the mountains along the east. The landscape of the Arenal area is dominated by a volcanic ridge which runs in a northwest to southeast direction along the continental divide. The mountainous area along this ridge is called the Cordillera de Tilaran. The height of the continental divide in this region ranges from a few hundred to 3000 meters above sea level. Volcan Arenal is situated along this ridge. It has erupted at least nine times in the past 4000 years, with the last eruption occurring in

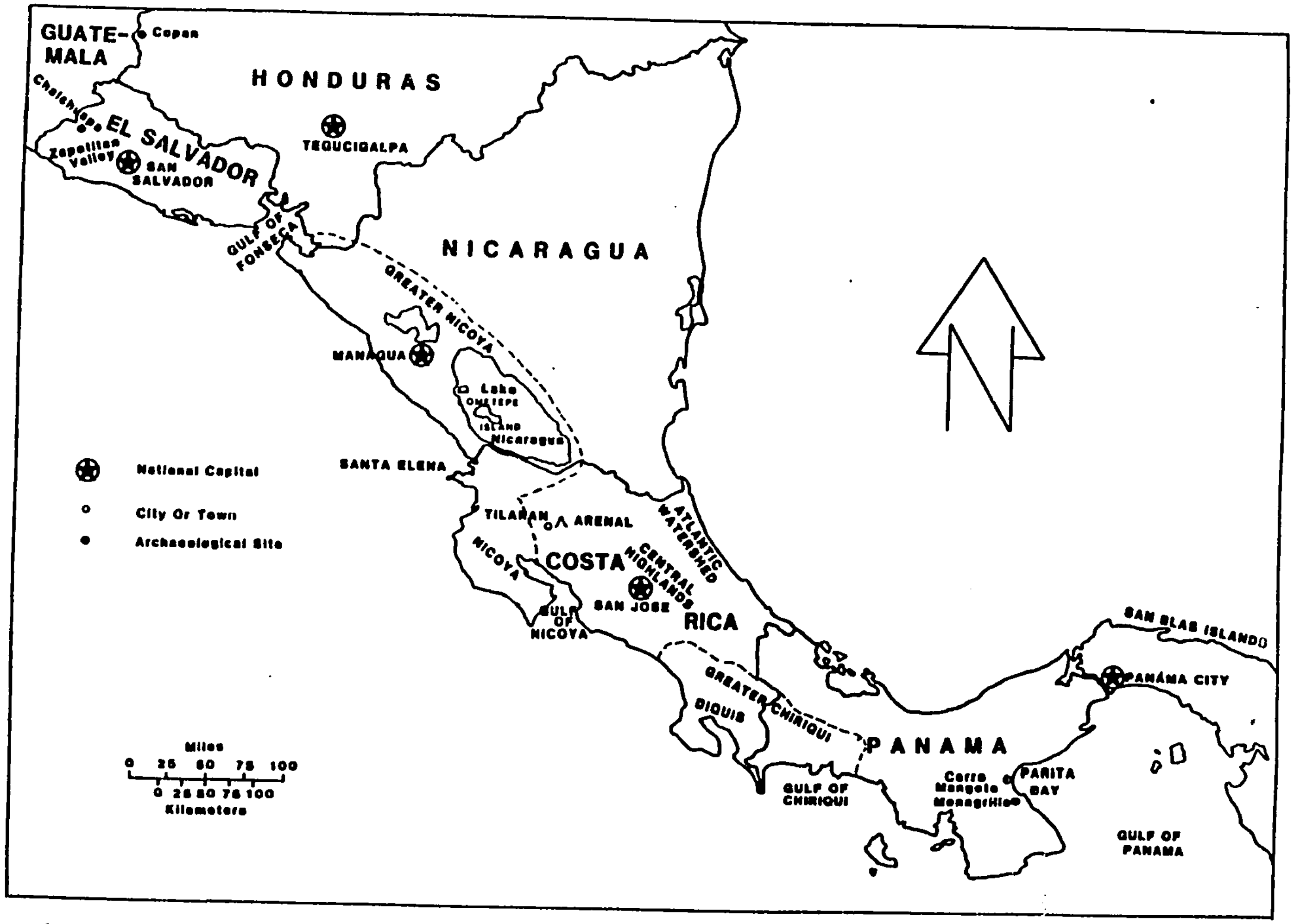


Figure 5-1. Map of Costa Rica and neighboring countries in Central America.

1968. Volcanic activity from Arenal is characterized by a cycle of 200-400 years of dormancy interrupted by violent catastrophic eruptions (Melson 1982).

As with most areas in the tropics, seasonality in this area is expressed through precipitation variation rather than through temperature variation (MacArthur 1972). The mean temperature of coolest month, January, varies only about 2 degrees C from the warmest month, May (Sheets n.d.). The daily (diurnal) range, which is about 8 degrees C, exceeds the mean annual temperature range of the region. Rather than temperature fluctuations, seasonality is determined by precipitation variation which breaks the year into "wet" and "dry" seasons.

Rainfall

The Arenal area has a humid tropical climate with rain occurring in every month. Rainfall data from the Instituto Costarricense de Electricidad (I.C.E.) and the Instituto Meterologico, show that mean rainfall amounts in the area range from 6000mm to the east of Lake Arenal to under 2000mm on the western side of the Lake. Within this area Volcan Arenal receives 4500mm of rainfall and the town of Tilaran receives 2250mm. February, March, and April are considered the driest months although 100mm of rain falls even in these months.

Life Zones

Bioclimatic variation in the region is best described by the Holdridge (1966) tropical "life zone ecology." The Holdridge system analyzes the temperature, elevation, and precipitation in an area and computes how these factors affect vegetation. The four life zones that exist within the Arenal study area: 1) the tropical wet forest, 2) the wet tropical forest-- premontane transition, 3) the premontane wet forest, and 4) the tropical moist forest-- premontane transition. The reader is referred to Holdridge (1966) and Sheets (n.d.) for a detailed description of these life zones. For purposes of this discussion, however, these life zones indicate that there is great botanical and biological diversity in this area as opposed to a notion of a uniform, consistent tropical rainforest. In fact, the Cordillera de Tilaran is considered one of the richest forest areas in Costa Rica (Tosi 1980), with many edible fruits, nuts, berries, and animals.

Flora and Fauna

Native flora in the area providing edible food include ceiba, palms, ramon, papaya, jicaro, zapote, jocote, nance, guanabana, cashew, sapodilla, and pineapple. Several tree species are useful for construction and tools. Tosi (1980) lists the minimum species counts for the area at: 500 plants, 400 birds, 150 amphibians or reptiles, 100 mammals, and 25 fish. The selective clearing and intentional planting of wild species can increase the support capacity of the rainforest. This activity requires little increase in labor and has a minimal impact on soils. The cleared areas are open to plant successionals which can be consumed directly by human occupants or can provide forage for animals. Subsequently, exploitable animal biomass can increase in an area through burning and clearing as long as adaptation remains extensive and human population density remains low and dispersed (Sheets n.d.). Many of the 100 mammal species such as deer, rabbit, armadillo, and coyotes could have benefited from abandoned slash-and-burn plots.

Soils

Most of the soils in the area were formed by weathering volcanic ash. Ninety-three percent of these soils were formed from volcanic ash with the remainder formed from basalts (Tosi 1980). In general, these soils are fertile and porous although they have low concentrations of phosphorus, potassium, zinc, and manganese (Tosi 1980) which would have inhibited agricultural potential. The tropical soils below the volcanic ash deposits contains high clay and aluminum-iron oxides and have relatively low fertility and are called the Aguacate Formation. The fertile soils formed from the weathered ash, however, can be used for intensive cultivation. Vegetation on these fertile soils can have a high biomass and can be rich in species diversity. Soil saturation in the wetter area on the eastern side of the study area, however, is less conducive for seed-crop cultivation than the drier, western side. Soil acidity also follows the moisture gradient with pH levels ranging from 4 on the eastern side to 6 on the west.

Living in an active volcanic area has advantages and disadvantages. A sudden volcanic eruption can deposit ash upon the landscape destroying natural vegetation. Yet the weathered ash, in addition to the fertile soils it produces, can form clays for pottery making as well as iron oxides which can be used for a wide range of pigments. Stone material such as basalts and andesites can be used for tools. In general, the long term gain that results from living in a volcanically active area outweighs the short term risk. The benefits of living in a volcanically active area have been documented for prehistoric populations in El Salvador (Sheets 1983;1981). Hazardous risk factors occur in contemporary society as evidenced by California residents who live along the active San Andreas Fault. The decision to live in an area that is susceptible to cataclysmic events such as earthquakes, floods, hurricanes, and volcanic eruptions is routinely made by many people today who feel that the potential danger is offset by the immediate advantages offered by the location.

Wind Effects

The Arenal region is unusual in that it has a year-round predominant wind direction from the northeast

(West 1964). This pattern extends back into prehistory as demonstrated by the deeper and more numerous ashfall deposits located on the western side of Volcan Arenal. The area is extremely windy with mean annual windspeeds along the lake at 23 km/hr and 14.5 km/hr at Tilaran (Sheets n.d.). Winds are greater from November through April with January being the windiest month. The winds negatively affect modern-day construction, agriculture, and landuse and presumably had the same effect in prehistory. An example of this can be seen in the cultivation of maize, a shallow root crop which would have been susceptible to wind destruction.

Landforms

The Arenal study area contains many different types of landforms such as alluvial flats, gentle slopes, valleys, hills, steep slopes, and recent volcanic features. Tectonic and seismic activity as well as erosion have played major roles in shaping these landforms. Topography was a major consideration by prehistoric populations in their selection of habitation sites, pathways, and cemeteries. Habitation sites preferred flat areas with year-round access to potable water. Prehistoric paths followed relatively straight routes that ran over steep slopes and preferred to stay on ridge tops rather than valley bottoms. Cemetery sites are located on steep hills or ridges with excellent views across the landscape. Volcanic features, such as deposits of a flat-fracturing volcanic stone called laja, were quarried and used to line and cover the funerary pits in the cemeteries.

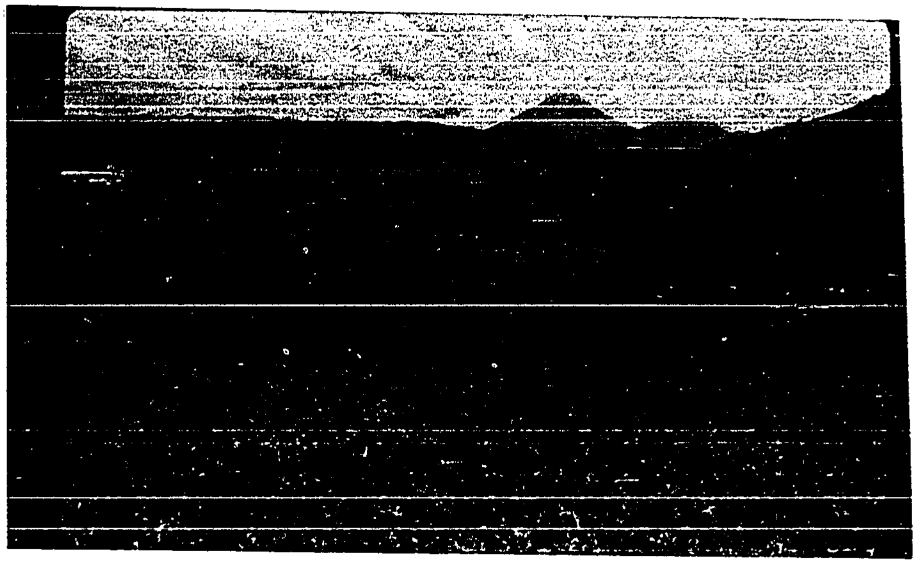
Lake Arenal

Historically, Lake Arenal was a swampy lake that was an important feature in the daily lives of the prehistoric occupants who lived along its shoreline. In 1980 a hydroelectric project by the Instituto Costarricense de Electricidad (ICE) resulted in the construction of a dam across the Rio Arenal, just to the west of Volcan Arenal. The dam and facilities enlarged the lake surface (Figure 5-2) and elevated the water surface of Lake Arenal from 512 m to 545 m. Although there has been an argument for a large prehistoric Lake Arenal (Tosi 1980), recent evidence (Aguilar 1984; Sheets n.d.) suggest that the prehistoric lake was similar to that existing in historic times prior to the ICE project.

Volcan Arenal

The most recent eruption of Volcan Arenal occurred on July 29, 1968, devastating 12 square kilometers and killing about 80 people. The volcano (Figure 5-3), with a symmetrical cone at 1633 m, continues to emit lava and some tephra. Small tremors from the volcano are still felt in the area today. Despite the damage and destruction it caused, the 1968 eruption was minor compared to the volume of ashfall that fell in the previous 9 eruptions (Melson and Sheets n.d.; Melson 1978; Saenz and Melson 1976). The earliest eruption of Arenal occurred about 1000 B.C. with successive eruptions laying down ashfall layers on top of each other.

The ashfalls from these eruptions emptying in the Silencio area vary between 5 to 20 cm. The ash layers themselves are distinct features that can be individually identified during excavation by their granular composition, thickness, and relationship to the other layers (Figure 5-4). The soils that have formed on top of each ashfall are also characteristic and often can be identified. The ash layers and their associated soils are located on top of an orange, clay-laden tropical soil (Aguacate Formation). Archeological evidence indicates



Figures 5-2. Looking east across Lake Arenal to Volcan Arenal in the background.

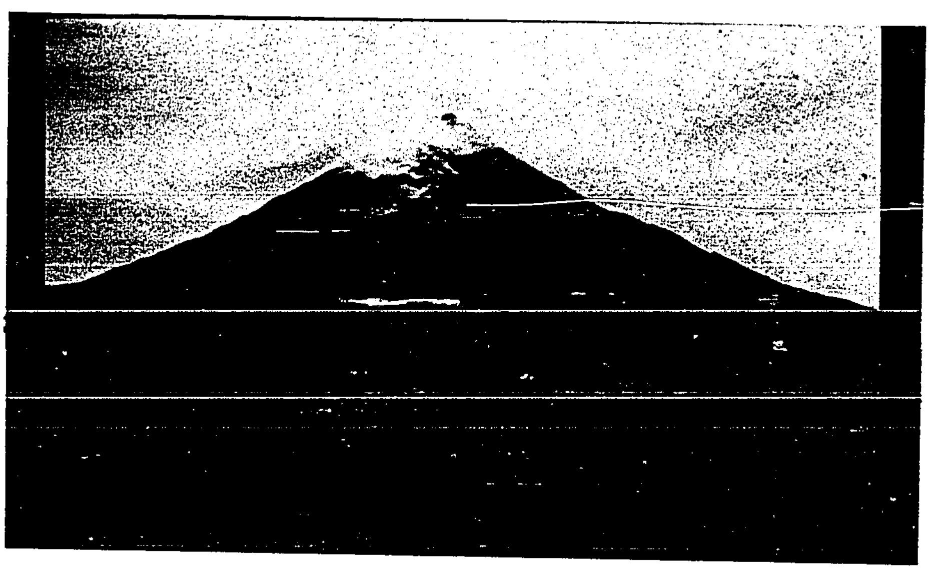


Figure 5-3. Volcan Arenal.

that PaleoIndian and Archaic cultures had adapted to the tropical soils prior to the deposition of any fertile volcanic ashfall. The population densities of these cultures, however, were apparently quite low (Sheets n.d.).

Present vs. Past Climates

Palynological research of the past 12,000 years (Bartlett and Barghoorn 1973) suggest that the present climate is similar to that of the prehistoric past. A drier and possibly cooler climate ended about 2000 B.C. and gave way to the present conditions. For the purpose of this research, these current conditions will be considered to be comparable to past conditions when discussing archeological sites. Recent deforestation and agricultural development have altered the landcover in the region during the last three decades. Despite these recent land surface changes, it is anticipated that remote sensing analysis will be helpful in the detection of prehistoric impacts upon the landscape and useful in understanding the conditions surrounding human adaptation in the prehistoric environment.

PREVIOUS ARCHEOLOGICAL RESEARCH

Archeological research in northwestern Costa Rica has been conducted since the turn of the century with artifact oriented research (Hartman 1907; Lothrop 1926), being replaced with more systematic and process oriented research (Willey 1971; Stone 1977; Ferrero 1981; Snarskis 1981; Lange 1984; Lange and Abel-Vidor 1980). In general, northern Costa Rica has been divided into two distinct cultural traditions and ecological environments: the Greater Nicoya and the Atlantic Watershed. The Arenal study area lies between these two areas and has experienced influences from both areas, although the Greater Nicoya influence appears to have been more prominent (Sheets n.d.).

Archeological research in the Arenal cordillera area has been rather recent. Beginning in 1969, four projects have been conducted in the Arenal region. The first was a brief project by George Metcalf (n.d.) who did not complete his analysis of the ceramic and lithic material that was recovered from a site north of Volcan Arenal. The second was a survey project along Lake Arenal in 1974 by Tom Murray. The results of this survey have also not been published. The third was a survey and excavation project by Carlos Aguilar in 1977 prior to the rising water level of Lake Arenal that resulted from dam construction for the hydroelectric project. Aguilar (1984) published the results of the project, which are significant at the El Tajo site in view of the excellent preservation of vegetative materials in addition to the ceramic, skeletal, and lithic information.

The fourth project to operate in the area is called the "Proyecto Prehistorico Arenal" under the direction of Payson Sheets. The project was funded by the National Science Foundation (NSF) and the National Geographic Society in 1983, with fieldwork commencing in 1984. The project entailed an interdisciplinary research design to study tropical settlement and adaptation in a hazardous volcanic environment. Based upon the preliminary research results of this project, a cooperative agreement between NASA and NSF was made in 1985 to combine remote sensing analysis with archeological research in a tropical forest. Field research continued until 1987. The early results of the "Proyecto Prehistorico Arenal" are published in VINCULOS, Vol. 10, the Journal of the Museo Nacional of Costa Rica. The remote sensing/GIS analysis that will be discussed later in this chapter is an outcome of the NASA-NSF cooperative research agreement.

PHASES OF CULTURAL OCCUPATION

The earliest, although non contextual, evidence of human occupation in the area is a Clovis Point that was found along the shore of Lake Arenal at site G-164 (Sheets et al. n.d.). The point was made from locally-available chalcedony and indicates PaleoIndian habitation of the area at approximately 10,500 B.C. PaleoIndian adaptation was presumably based on hunting and gathering and the discovery of a Clovis point in the area suggests that the assumption that PaleoIndians adapted better to drier, grassland plains than to humid rainforests may be in error. This assumption is further questioned by the fact that an abundance of PaleoIndian artifacts were found in the forest region of Turrialba (Snarskis 1979) and only a few PaleoIndian artifacts were found in the dry Santa Marta region of Panama (Cooke 1984).

The Arenal area is characterized by a high level of cultural continuity and stability, especially in settlement patterns, subsistence, and technology. Many of the basic elements of technology that were established by 4000 B.C. survived intact to the Spanish Conquest. Remarkably, most of the villages that were established by

2000 B.C. were still occupied in the phase prior to Spanish conquest with similar adaptations. Changes in lithic and ceramic typology were slight. Apparently, the Arenal area never experienced rapid population increases nor was there ever a dependency upon a single staple. Despite the large number of resources that were available to the Arenal occupants, the fact remains that these resources were not unlimited and the effects of overpopulation would have left a significant impact upon the landscape. Overpopulation is a major factor that is currently contributing to the rapid destruction of tropical forests and the lifestyles of the indigenous populations. As Wynne-Edwards observes:

> ...have the strongest reasons for concluding...that population density must at all costs be prevented from rising to the level where food shortage begins to take a toll of the numbers--an effect that could not be felt until long after the optimum density had been exceeded. It would be bound to result in chronic over-exploitation and a spiral of diminishing returns (Wynne-Edwards 1962:11).

The Arenal area also demonstrates that villages preserved economic self-sufficiency rather than becoming dependent upon long-distance trade networks and centralized economies (Sheets n.d.) The cultural stability of the Arenal region is even more remarkable when one considers that it was maintained throughout a sequence of volcanic eruptions and earthquakes. By contrast, villages to the north in El Salvador, which did not maintain the self-sufficiency of the Arenal populations, recovered far more slowly and did not retain the same technological level of previous generations (Sheets 1983).

The preferred location for villages in the Arenal area was on flat surfaces near permanent streams. Most of the sites are located along the south shore of present Lake Arenal at the base of upland regions. This location provided inhabitants access to a variety of ecological zones and resources. Macrobotanical analyses reveal that the Arenal populations utilized a mixed subsistence strategy that included seed crops, tree crops, root crops, and wild fruits, seeds, and berries (Sheets et al. n.d.). This diverse subsistence strategy survived throughout all phases of Arenal's cultural history.

Fortuna Phase (4000 - 2000 B.C.)

The Fortuna Phase has been defined from archeological materials and features found at a location along the shore of Lake Arenal. This site has yielded calibrated radiocarbon dates that range from 3700 to 3000

B.C. Surface finds, excavated materials, and an excavated campsite have provided the criteria for determining this phase, although the exact limits of the phase are not known for certain. There is a thousand year gap between the end of the Fortuna Phase and the beginning of the Tronadora Phase which cannot be identified from the available archeological evidence. Presumably the transition from a hunting and gathering lifestyle to sedentary villages occurred during this gap.

An informal percussion core-flake industry was established during the Fortuna Phase which continued up to the time of the Spanish Conquest. In similar fashion, the stone cooking technology of the Fortuna Phase also persisted for over 6,000 years. Stones were heated and then dropped into liquid foods to transfer heat. Surprisingly, this technique continued even after the use of ceramics were well established by 2000 B.C. (Sheets et al. n.d.).

Tronadora Phase (2000 - 500 B.C.)

Sedentary occupation began by 2000 B.C. as evidenced by the Tronadora Vieja site (G-163). Houses were about 8 meters in diameter and were constructed of pole and thatch with a tamped earth floor. Ceramics of the Tronadora Phase were extremely well made and elaborately decorated by incision and painting (Hoopes 1984, 1985, 1987). The ceramic sequence for the Arenal area is based on the analysis of over 12,000 diagnostic sherds (Hoopes 1987). Tronadora Phase ceramics were originally made in the Cordillera prior to Arenal's first eruption and therefore do not contain the volcanic ash temper used in later ceramic sequences. Ceramic analyses indicate that the earliest ceramic-producing Costa Rican societies were located in the moister tropical forests 1000 years prior to adaptation in the tropical dry forests.

Pottery found on the island in Lake Arenal (site G-166) demonstrates that watercraft were available during the Tronadora Phase. Burials during this Phase were located within habitation sites in small, simple pits dug down into the clay soil. These pits were located between houses within the village and generally did not contain any evidence of ritualistic offerings.

The Tronadora Phase was a transition phase that marked the emergence of sedentary life, the making of pottery, and the cultivation of plants. The transition was apparently a gradual and uneventful one, as many aspects of society remained unaltered. Settlement patterns remained the same for many of the Tronadora sites had earlier Archaic occupations before them. Lithic technology and stone cooking technology also remained intact. What is not known is exactly how the transition occurred. It appears that the ceramic technology of the period was an internal development of the local population rather than an external invasion by neighboring pottery-producing peoples. The source of the sophisticated Tronadora ceramic industry, however, remains unknown.

Arenal Phase (500 B.C. - A.D. 500)

The Arenal Phase is the local expression of the established Zoned Bichrome period in Lower Central America (Lange 1984). During this period prehistoric population levels reached their peak as based on the number of Arenal Phase sites, the profusion of ceramics, and the establishment of cemeteries. The cemeteries are located on prominent ridges near the villages and are distinguished by an abundance of round river rocks. These rocks were used to line the graves in a rectangular pattern (Figure 5-5) after they had been filled and were also smashed into place over the tops of the pits. Ceramic vessels, manos, and metates were subsequently smashed on top of these rocks indicating ritual activity.

Domestic housing patterns remained the same with circular floorplans and pole and thatch construction. Large cooking hearths were placed in the ground outside the houses. Ceramic analyses indicate a strong connection to the Greater Nicoya area to the west although a lesser connection with the Atlantic area continued throughout the phase. It is estimated that the Arenal Phase had as much as ten times the population of the preceding Tronadora Phase (Sheets n.d.).

Silencio Phase (A.D. 600 - 1300)

This phase is marked by a noticeable population decline, the advent of polychrome pottery, and by the location of cemeteries on very prominent ridges far from the villages (Figure 5-6). Although there was a decrease

Figure 5-4. Ash layers from Volcan Arenal.

Figure 5-5. Tomb construction showing how rectangular pits were lined with stone.

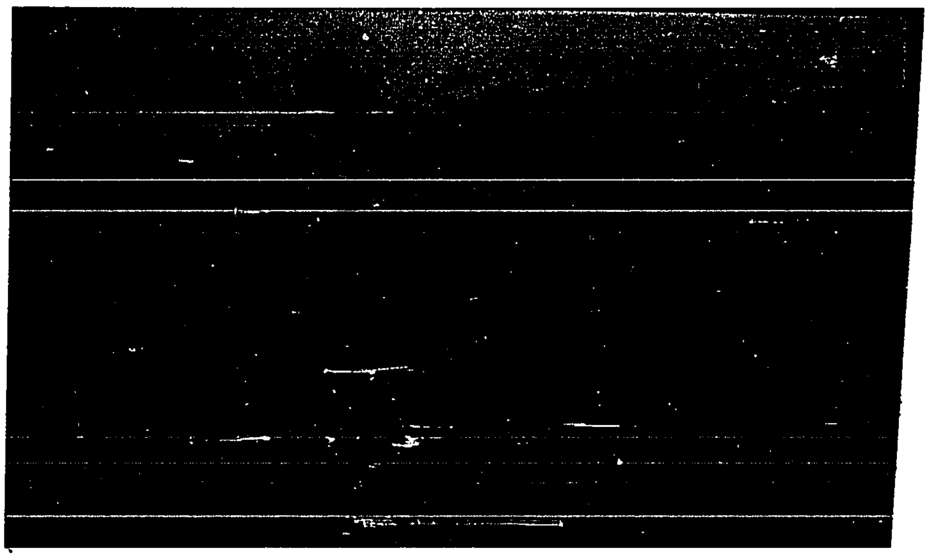


Figure 5-6. Looking east toward the Silencio Cemetery (G-150) which is located on top of the Continental Divide in the background.

in the number of occupied villages, there was not a decrease in the size of the sites still occupied. While ceramics are generally localized, they show strong evidence with the Greater Nicoya cultures although some affiliations with the Atlantic still continue. Burials at the cemeteries were placed in rectangular stone cist tombs. The stone used to line these tombs is a locally available volcanic material called "laja." The grave construction techniques are similar to those used at Guayabo de Turrialba and other sites in central Costa Rica (Snarkis 1984). During the Silencio Phase there is a pronounced elaboration of grave good items that included miniature polychrome vessels, metates, and gold pendants.

Although polychrome pottery appears during this phase, the previous tradition of incised pottery also is maintained:

> Decoration in fine-line motifs, which often extend to the upper surfaces of flat vessel rims, include geometric, hatchured friezes and gulloche patterns, occasionally infilled with white pigment. Vessel forms include jars and open bowls with T-shaped rim profiles which carry polychrome, bichrome (red-on-cream), and incised monochrome decoration (Sheets n.d.).

The same balance of invention and tradition is seen in the manos and metates. The metates change from oval grinding surfaces and long tripod legs to rectangular shapes with short, thick legs. The Silencio phase metates are elaborately decorated with zoomorphic figures and abstract geometric designs. The manos, however, continue unaltered from the previous phase.

The Silencio Phase is the culmination of a chronological trend that saw increasing distance between villages and cemeteries as well as greater embellishment in tomb construction and burial items. This phase also saw a significant population decline as evidenced by the lesser number of occupied sites. The sites occupied at this time, however, remain as large as those that existed during the Arenal phase. Two ash layers (Units 40 and 41) were deposited during this phase which assist in the dating of the period.

Tilaran Phase (A.D. 1200 - 1500)

Population decline continued during this phase with distribution shifting from a few large sites to a complex of numerous, small dispersed villages. Cultural affiliation shifted from the Greater Nicoya toward the Atlantic area and southward. The elaborate polychrome ceramics of the Greater Nicoya were replaced by a dull, monochrome, utilitarian ware (Hoopes 1984). With the exception of a few sherds that may represent trade items, the polychrome decoration prevalent in the previous phase disappears. With the shift toward low quality ceramics it is speculated that there was a parallel shift away from elaborate funerary practices. However, no cemeteries specific to the Tilaran Phase are known to document this.

SUBSISTENCE

From the archeological evidence it appears that the local Arenal societies were able to maintain a sedentary existence without resorting to full-scale dependence upon a specific cultigen. The benefit from this adaptive strategy is that the rich tropical forest environment was not destroyed by intensive slash and burn activities. Maize was first domesticated during the Tronadora Phase and continued up to the time of Spanish Conquest as evidenced by carbonized macrofossils (Sheets et al. n.d.). An analysis of stable carbon isotopes in human bone indicates that a maximum of only 12 per cent of the diet could have been based on maize (Friedman and Gleason 1984). This finding is supported by the fact that there are low ratios of manos and metates to ceramic and lithic artifacts when compared to agriculturally based economies elsewhere in Mesoamerica. The manos and metates generally show little evidence of wear. The fact that they are more highly decorated than their counterparts in other parts of Mesoamerica and that they were not extensively used suggest that their function was primarily symbolic.

Domesticated beans were also found to complement the wide range of edible tropical forest products. The avoidance of a maize staple, typical of Maya and Inca adaptations, and the maintenance of low population levels may have contributed to the stability documented by the archeological data. By enjoying a diverse subsistence base, the Arenal peoples avoided the hazards of deforestation, soil loss, erosion, and disease that accompanies full scale agriculture in a tropical forest region. These hazards continue in contemporary societies (Nations 1988). The stability enjoyed by the Arenal populations is reflected in their ability to quickly recover from the volcanic eruptions of Arenal. In general, they were able to re-establish themselves to the environment in accord with the natural recovery processes. When comparing two volcanically affected societies, Sheets states:

> The simpler Costa Rican societies seem to have been more resilient than the more complex Salvadoran societies when impacted by explosive volcanic eruptions. Prehistoric Salvadoran

> societies were more vulnerable to sudden eruptions, evidently because they relied more heavily on the "built" environment, they relied more on a domesticated staple crop, they had a more complex economy relying on commodities transported greater distances and involving redistribution, and the settlements were vertically organized into tiers which represent social, political, and economic centralization (Sheets 1983).

Sheets (n.d.) also notes that in both El Salvador and Panama the impacts of major volcanic eruptions were sufficient to create phase boundaries as defined by the variation in archeological materials before and after the events. In contrast, not one of the ten volcanic eruptions in the Arenal area effected a significant cultural change.

The counterpart for the lack of dependence upon a staple crop such as maize or beans is the fact that there is less time and less organization for the construction of monumental structures such as formalized roads, temples, or pyramids. Despite its environmental degradation (Harris 1973), seed crop agriculture allows for greater intensification of production which expedites population increases and expansionism. The maize-based economies of the Aztec and Inca are testimonies to this fact. The successful adaptive strategies of the Arenal people can best be appreciated by the fact that they were successfully in place before and after the Maya and Inca civilizations. Erroneous perceptions of human adaptation in the tropical rainforest remain prevalent, even in the professional literature. The following passage comes from An Introduction to Anthropology: Ethnology:

> Primates are adapted to tropical forest environments, and man's ancestors must have come from such regions, but he has since done better elsewhere. The tropical forests do not supply good food resources except for societies which have developed advanced agricultural techniques.... Preagricultural societies do not fare very well in such environments, nor do agricultural societies with simple technologies (Barnouw 1971).

In addition, the temptation to equate architectural achievement with adaptive success is a dangerous one that has pervaded western thought both in the past and present. As Ferrero states:

> The adaptive systems of the indigenous populations of Costa Rica were not as striking as those of Mexico and Peru. Perhaps the first impression the conquerors had was of a low level of culture, with root-crop swidden agriculture and small dispersed villages of pole-and-thatch houses. The Spaniards did not immediately comprehend the wealth and variety of sophisticated craftsmanship in wood, stone, and metals, nor the socio-political and religious complexity that had shaped an apparently simple way of life (Ferrero 1981:93-94).

ETHNOGRAPHIC ANALOGIES

Many ethnographies have been written about tropical forest cultures such as the Mbuti pygmy

(Turnbull 1962), the Yanamamo (Chagnon 1968,1974), and the Desana (Reichel-Dolmatoff 1971). Dillon's (1984) research on the Cuna and Posey's (1983) research on the Kayapo, however, provide an insight into tropical forest environments that appear comparable to that experienced by the prehistoric Arenal populations.

Cuna towns and villages provide a number of ethnographic analogies to pre-Columbian settlement. The Cuna live in island villages and mainland sites along the Caribbean coast of Panama. Contemporary village settlement patterns, construction techniques, house styles, and burial practices make use of similar materials and resources that were available to the prehistoric populations living in the Arenal regions. Dillon's ethnographic research among the Cuna, particularly in reference to burial practices, offers some potential interpretations for the archeological data of Arenal. For instance, beginning at the Arenal Phase, why are the dead being buried in cemetery sites upon topographic ridges that overlook village locations? Dillon states:

> All of the cemeteries visited were located on ridgelines, in well drained clay instead of the waterlogged humus and mud of the flatlands near the coast. The cemeteries are thus elevated high above the villages that they take their inhabitants from, and mainland and island towns are normally visible from the burial grounds. When

> relatives of the deceased were asked why the cemeteries were located so far from the mainland and island villages, it was stated that the dead were "more content to be away from town", and that they were not bothered with noise, smoke, children, and so forth.... The living, apparently, are also much happier with the dead at some distance and while a strictly practical reason exists for this with island villages (there is not enough room for the living, much less for the dead as well), this is not the case with the mainland towns (Dillon 1984:60).

As shall be discussed later, the prehistoric paths in Arenal lead to cemetery sites as well as to other natural and cultural features in the environment. Dillon states:

> The Cuna...do not avoid their cemeteries or place them off limits to visitors, but instead consider them to be an important part of their environment, just as the need to continuously honor their dead motivates much of the behavior that takes place in and around the burial grounds (Dillon 1984:60).

Other ethnographic analogies of the Cuna will be used later in the discussion of the prehistoric path network.

An important question regarding the Arenal occupants is how they adapted to their environment. The Kayapo of Brazil live in a rainforest environment that reflects adaptation to a large number of tropical resources. A similar extensive resource base was available to the Arenal occupants and through a description of the Kayapo we can gain an insight into human adaptation in the Arenal area. The following description of the Kayapo is based upon Posey's (1983) article "Indigenous Ecological Knowledge and Development in the Amazon."

The Kayapo inhabit nine permanent villages in a 2-million hectare area in the tropical rainforest of central Brazil. They are an egalitarian society who, like many rainforest cultures, perceive their environment in terms of ecological zones. The forest, mountains, and grasslands represent the primary zones which are in turn subdivided into a complex of categories based on soils, vegetation, and other environmental criteria. The most important niches in the environment are the transitional zones. Like the prehistoric village locations in the Arenal area, the Kayapo choose village sites in the transitional zones in order to maximize the resources from the adjacent zones.

The complete inventory of wild plant species that are incorporated into the Kayapo diet numbers in the hundreds. The Kayapo use over 250 wild plant species for fruit alone. A large number of cultigens such as maize, beans, squash, cotton, sweet potatoes, papaya, and pineapples compliment the natural vegetational resources.

Both wild and domesticated plants are used for medicinal purposes.

Unlike the Desana who travel through the Amazonian environment on water corridors and do not have a system of overland trails (Reichel-Dolmatoff 1971:3), the Kayapo have an intricate system of footpaths that extend for thousands of kilometers throughout the surrounding rainforest. This pathway system links villages with garden areas, hunting areas, and natural resource areas that result from openings in the forest canopy. These natural resource areas provide edible food and are also used for the planting of additional species. Like the Yanamamo in Brazil and the Mbuti in central Africa, the Kayapo carry very little food with them on their hunting excursions, relying rather on these pockets of natural resources which are incorporated into the path network.

REMOTE SENSING

As stated previously, the remote sensing research conducted in this project was an outcome of the Conference on Remote Sensing and Archeology held at the Stennis Space Center in 1985. As a result of this Conference, a cooperative agreement was made between

NASA, the National Science Foundation (NSF), and the University of Colorado to incorporate remote sensing analysis into the NSF funded project in Costa Rica. Under this open-ended, multi-year cooperative agreement, NASA has provided four overflights of optical and digital remote sensing. These flights occurred in 1984, 1985, 1987, and 1988. Color and color infrared photography were acquired from airborne missions and previous black and white photography was purchased from the Instituto Geografico Nacional in San Jose. In addition, L-band radar were obtained, laser profiler (LIDAR) data were provided, and TIMS data were acquired over select areas within the study area. These airborne-acquired data compliment MSS and TM data over the study area. A GIS has also been developed that includes ancillary information such as topography, soils, and landforms. The purpose of the GIS is to characterize prehistoric sites for use in comparative analysis.

In addition to the airborne scanner data that were gathered for this project MSS and TM data were also acquired. Most of the satellite images over the Arenal study area are cloud-covered and only a few, cloud-free images over the region have been acquired since 1972. The TM image (Figure 5-7) shows that the Arenal study area is at the transition between the moist Atlantic

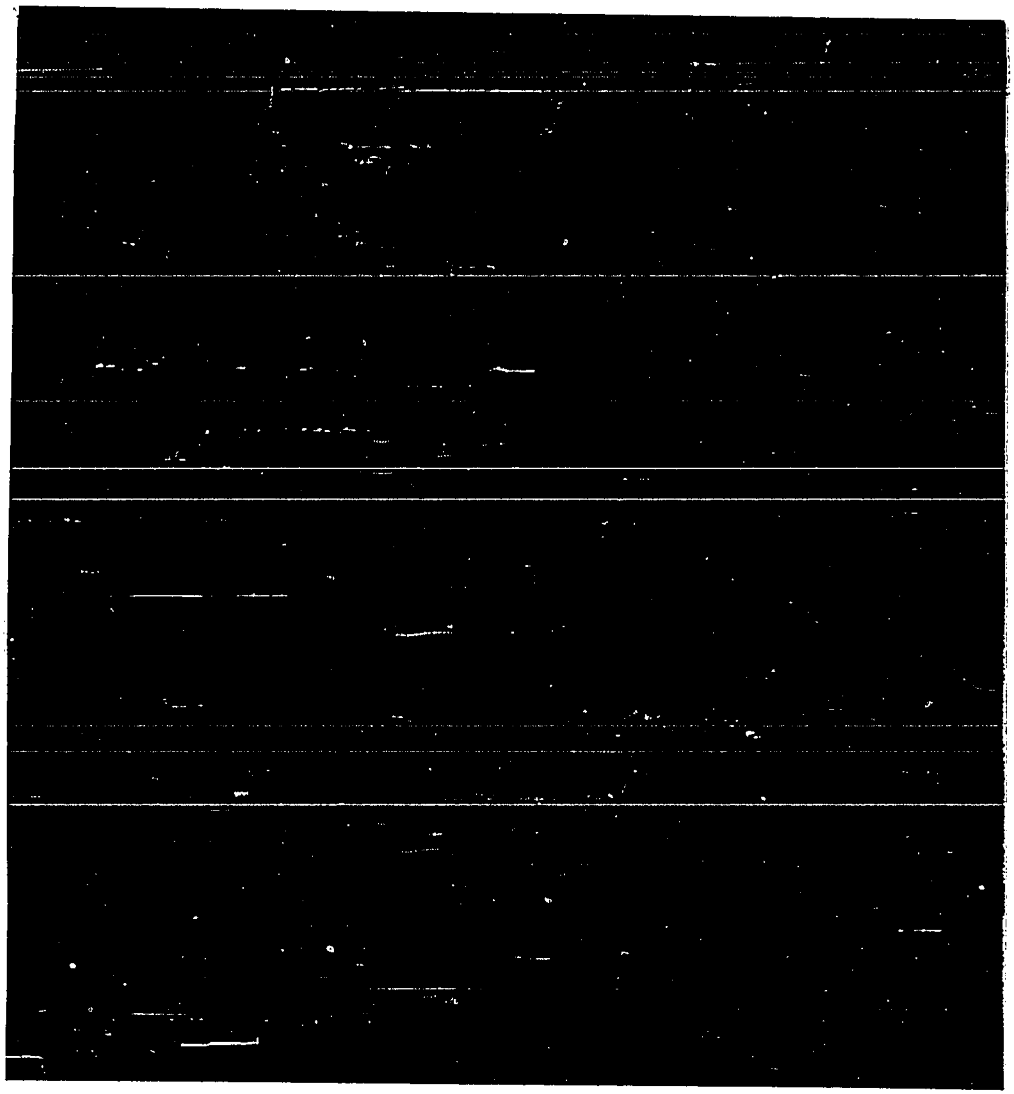


Figure 5-7. Thematic Mapper (TM) satellite image showing the transition between the moist Atlantic region and the dry Pacific coast. Lake Arenal can be seen in the center of the image.

region and the dry Pacific coast. In this image the environmental gradients are distinguishable as a result of the vegetational changes upon the landscape. This project did not intensively investigate the use of satellite data for archeological feature detection. Mueller (n.d.), however, has submitted a proposal to NSF to detect prehistoric Arenal settlement patterns that result from environmental variations observable in TM imagery.

The Arenal area of Costa Rica was selected by NASA to test the feasibility of using remotely sensed information for archeological research in a tropical forest environment. Although archeological remote sensing research had been successful in the arid environments of Chaco Canyon and the Sudanese desert (Adams, Brown, and Culbert 1981), as well as the semi-humid conditions at Poverty Point (Sever and Wiseman 1985), little was known about the use of remote sensing instruments for archeological research in a tropical rainforest.

A rainforest presents major challenges to archeological remote sensing research. Heavy cloud cover and recurrent rainfall impede data acquisition. The high biomass of the Arenal rainforest results in a surface cover that is rich in tall forest stands (Figure 5-8) or heavily-grassed pasture lands created through relatively recent clearing. The ten volcanic eruptions of Arenal have buried archeological features through time, inhibiting surface detection. Prehistoric population density was low in the Arenal region resulting in slight impacts upon the environment. As stated previously, the egalitarian nature of Arenal society precluded the construction of massive features such as cities, roadways, and ridged-field systems that typify the Maya to the north and the Inca to the south. Finally, ground verification is hindered since it is difficult to correlate and locate subtle remotely sensed features in the imagery with surface manifestations in open grasslands and thick forests.

PREHISTORIC FOOTPATHS (BACKGROUND)

A prominent outcome of the remote sensing analysis has been the detection of a system of prehistoric footpaths in the Arenal area. While examining color infrared photographs that were acquired simultaneously with the laser profiler mission in 1985, a linear feature was seen leading westward from the G-150 site. This site was a Silencio Phase cemetery that was situated high on the continental divide. The line made an obtuse angular bend around a repository of laja stone used in the cemetery, divided in two, went straight to a ridgetop, met with another cache of laja, and continued westward.

Because of the unusual orientation of the feature, a decision was made to investigate. While visiting the site the next day, the linear feature was found to be a subtle linear depression, similar to the many gulleys and erosional depressions that typified the surrounding mountainous landscape. The linear depression appeared to be about 7 meters wide as it descended westward from the cemetery and bifurcated before it crossed the stream below. From the cemetery, two parallel linear features could barely be seen ascending the opposing slope after they had crossed the stream.

After the original line segment was seen in the CIR, three shallow trenches were dug to determine the nature of the linear segments. A trench was placed across the lineament coming directly from the cemetery, and on each of the segments directly below the bifurcation (Figure 5-9). The excavations showed that the features had existed prior to A.D. 1500 because they were buried by the tephra of Unit 20 which dates to that time. Excavation and examination of the layers revealed

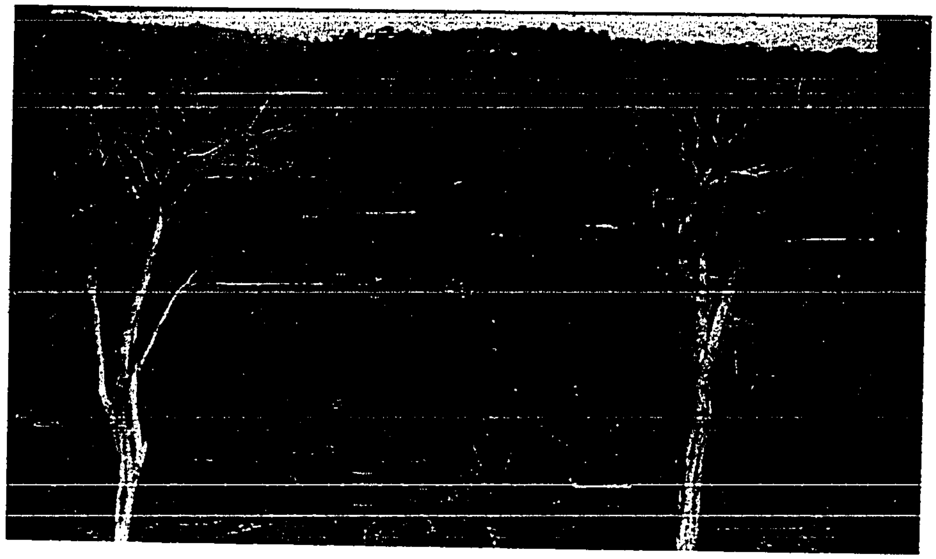


Figure 5-8. Ground photo showing the dense vegetation and canopy of the Arenal rainforest.

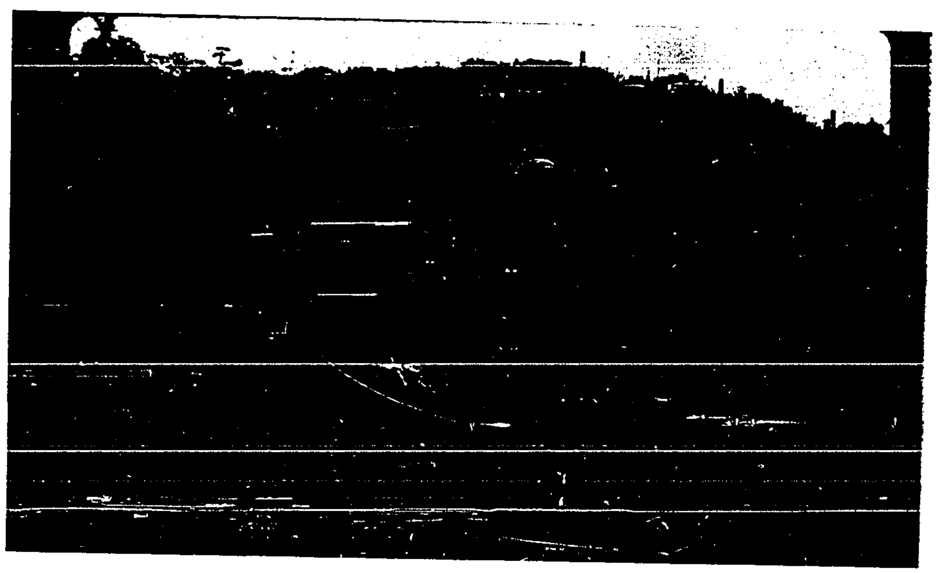


Figure 5-9. Location of Trench 3 below the Silencio Cemetery showing how difficult it sometimes is to see evidence of prehistoric paths from ground level.

that the linear feature was not a prehistoric road, as had been originally anticipated, but an ancient footpath. The infrared photograph had revealed a footpath over 1,000 years old which had formed and then been buried through a complex of erosional and geological processes. To the knowledge of the Arenal research team, this was the oldest footpath ever found through remote sensing and field excavation.

Previous field experience in locating prehistoric roads in Chaco Canyon and in the Mideast had aided in recognizing the pathway both in the photography and from the ground. The ability to discriminate cultural lineaments from ground level is somewhat comparable to seeing horizons in a soil profile. Like soil horizons, the pathways are not readily apparent, but through experience they become easily recognized. This is illustrated by the fact that local residents who had lived, worked, and even hunted in the region had never recognized the prehistoric pathways before, but within a few weeks were finding pathway segments on their own and were reporting them to the research team.

HYPOTHESIS TESTING FOR PREHISTORIC FOOTPATHS

As a result of this discovery, a research strategy was designed to map linear anomalies in the remote sensing imagery, and to confirm or reject the assumption through excavation that these lineaments were pathways. The first hypothesis to be tested is that:

> if the linear patterns in the remotely sensed data are prehistoric footpaths, then they will demonstrate relationships that are of a cultural origin. Specifically, the paths will demonstrate a linkage system between resources, villages, and other cultural areas. They will connect sites with each other, with springs, cemeteries, manufacturing areas, storage areas, and natural resources.
>
> Conversely, if the linear patterns are attributable to natural processes, they will not demonstrate any cultural relationships. Specifically, they will be reflective of the ongoing geological or erosional processes that occur in the area today.

It was anticipated that linear anomalies that were of a cultural origin would demonstrate characteristics that were different than those that occur naturally. For instance, they would negotiate the terrain by meandering around topographic obstacles or they would ascend topographic obstacles to reach cultural areas such as the Silencio cemetery. It was also anticipated that the degree of erosion along the footpath would be proportional to its prehistoric use, where factors such as slope, elevation, and rainfall could be kept constant. Based on the three initial trenches that were made to verify the footpath leading out from the cemetery, it was thought that the footpaths could be verified through stratigraphic and possibly, archeological evidence. From the circumstantial evidence elicited from the remote sensing data and the irrefutable evidence produced through field excavation, an effective technique was developed for the verification of prehistoric footpaths. As shall be shown, excavation was an important component in this process, for several of the cultural features turned out to be historic paths and roads.

THE ROLE OF FOOTPATHS IN ARCHEOLOGICAL RESEARCH

Footpaths, like other transportation systems, may be able to provide an insight into a culture's religious, economic, political, and social organization. Like prehistoric roadways in other parts of the world, footpaths might be used to learn of a culture's system of transportation and communication. If a footpath system can be mapped in an area, it should be able to demonstrate the interaction between villages and resources as well as provide clues to ritual activity. Perhaps most importantly, footpaths might be instrumental in determining and synthesizing regional human behavior as opposed to site-specific behavior alone.

DATA ANALYSIS

Linear segments and patterns were apparent in the black and white, color, and color infrared photography. The lineations, however, were only seen in the open grassland areas and were not seen in the forested areas. The most useful imagery was the color infrared photography (Figure 5-10). The reason it was superior to the black and white and color photography is because of the CIR's ability to record information in the infrared portion of the spectrum. As shall be shown later, the composition of the soils and subsoils in the pathways are different than the adjacent soils.

In the aerial photography, particularly the CIR, the paths often show up as positive crop marks. This is due to erosional fill in the path which contributes to richer plant growth. In the field, some of the paths can be seen as linear depressions. The depression becomes more visible in proportion to the degree of slope. On flat areas the paths are often not visible from ground level. On slopes, however, the paths can be seen by the

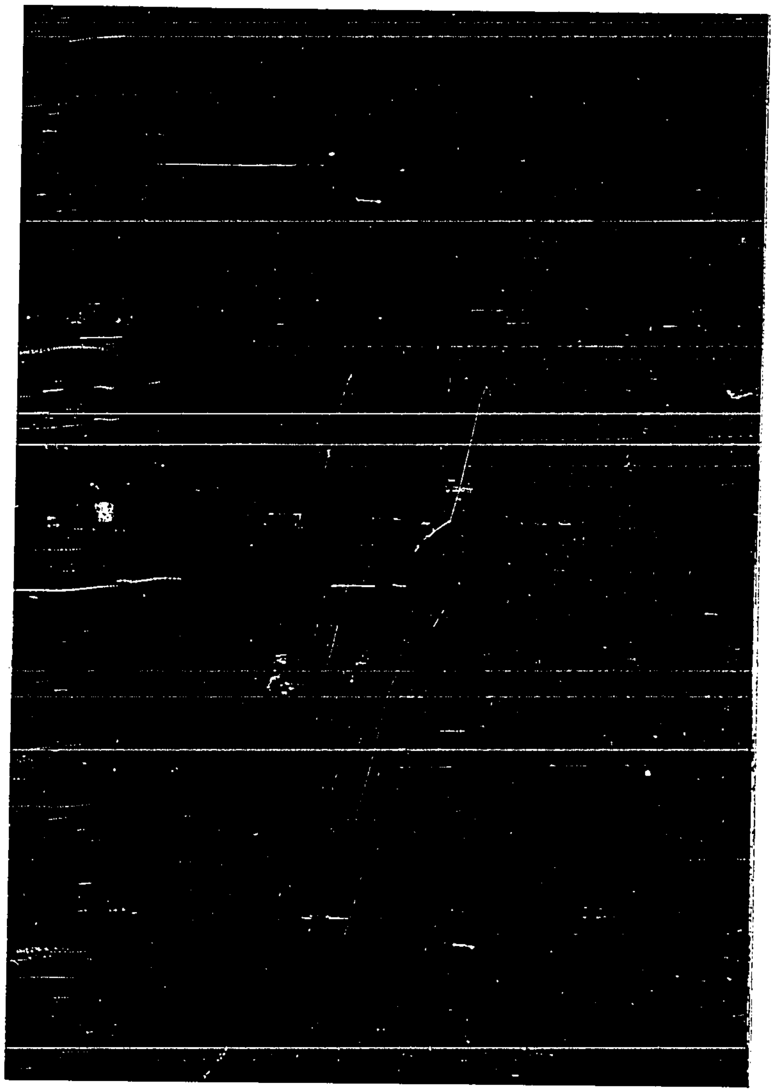


Figure 5-10. CIR photograph showing the bifurcation of the footpath leading west from the Silencio Cemetery.

depressions with the deeper depressions resulting from steeper slopes.

No significant erosional activity occurred along the paths after they were abandoned. The little activity that has taken place is largely due to infilling and stabilization. Paths that are located on slopes over 8 degrees or more had incised themselves to two meters or more below the surface at the time of use. Although the original path was only a foot or more wide, the erosional effects and subsequent ashfall layers on top of the path can extend 10 meters or more across it. Thus, the surface information that is being expressed by the buried path is theoretically within range of the digital remote sensing instruments. Technically, remote sensing is not detecting buried paths a foot wide but rather recording the 10 meter wide surface manifestation of subsurface phenomena.

Lidar data were acquired by a NASA aircraft at 400 meters above terrain in 1984. Nine by nine inch frame CIR photography and 35mm color photography were acquired in conjunction with this mission. Originally, it was anticipated that the lidar data would provide microtopograhic evidence for the location of pathways. The lidar's ability to penetrate forest canopy as well as its sensitivity to topographic relief was the principal reason for its selection. The application of lidar technology to this investigation, however, revealed that it also recorded a large number of natural dips and depressions in the terrain. As a result, it is difficult to determine if the depressions are prehistoric footpaths, historic roadways, natural depressions, or drainages. The large number of these features revealed that the use of lidar technology would be an inefficient technique for pathway discovery because of all the positions that would need to be verified from ground level.

Radar data was also investigated because of its ability to detect linear patterns in the surface cover that result from topographic variations as well as its cloud penetration capability. In 1984, an L-band, 24cm, 1.225 GHYz radar system flown aboard a NASA aircraft gathered microwave data with four polarizations at 30 and 10 meter resolutions. The radar recorded numerous lineaments in the Arenal region, but it could not be determined if these lineaments were due to natural or cultural origins or were the result of noise in the data. Radar records a large amount of information and the ability to reduce the data into a meaningful interpretation is still a problem for applications such as archeological feature detection (Brown 1989).

A number of mean and median statistical filters were employed to smooth the data and reduce the number of lineaments, but this approach still proved ineffective for reducing the number of lineaments (Figure 5-11). New techniques that were developed for reducing speckle noise (Wu and Sader 1987) were also attempted, but were equally unsuccessful. Determining the nature of the numerous linear features in radar data is complicated by the fact that the radar is recording information invisible to the human eye and by the difficulty of finding the features on the ground in the dense rainforest vegetation. A comparison of radar data with TIMS data indicates that the radar is recording the prehistoric pathways, but it is also recording such a large number of additional lineaments that, at this time, it is an inefficient technique for the mapping of prehistoric paths on its own.

Two flightlines of Thermal Infrared Multispectral Scanner (TIMS) data were gathered by the NASA Learjet at 5 meter resolution over the study area. One flight line was an east-west orientation that went over the Silencio cemetery (G-150); the other was a northwest to southeast flight line that ran along the southern edge of Lake

Arenal. CIR photography was simultaneously acquired at 60% overlap. The TIMS imagery (Figure 5-12) clearly shows some known segments of footpaths as well as other linear features outside the area of known footpaths. The TIMS compliments the CIR in that the TIMS is recording footpaths in the forested areas while the simultaneously acquired CIR photography is recording the footpaths in the open, grassland areas. In general, the TIMS did not record footpaths that were located in the open grasslands. This may be due to the time of acquisition which was near solar noon. Based on previous calculations, the TIMS would be more useful when acquired within an hour of sunrise. Several days of heavy cloud cover in the mornings prevented this and the decision was finally made to acquire the data at the first opportunity since the NASA aircraft was scheduled to return to the United States.

The thermal response of a land surface is dependent upon complex interactions between many physical and vegetational factors. In agricultural areas and grassland, the amount of vegetation cover, its composition, and soil moisture all influence the thermal response (Carlson 1986). In the case of Arenal, the footpaths had reached thermal equilibrium with the surrounding landscape and consequently were not visible

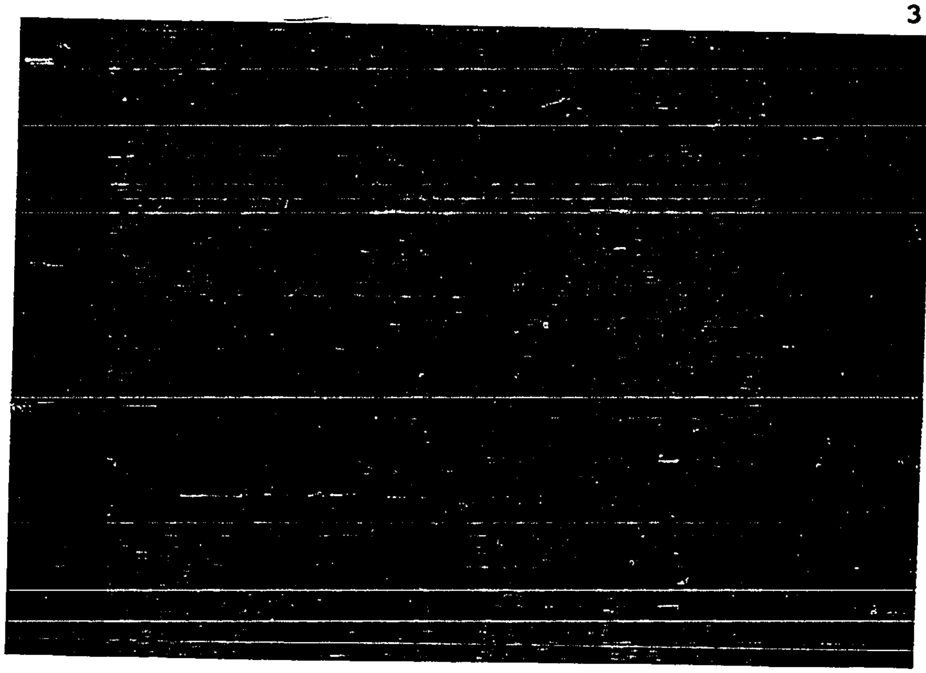


Figure 5-11. Filtered radar data showing a number of linear and curvilinear features. Radar data was an ineffective technique for the mapping of prehistoric paths.

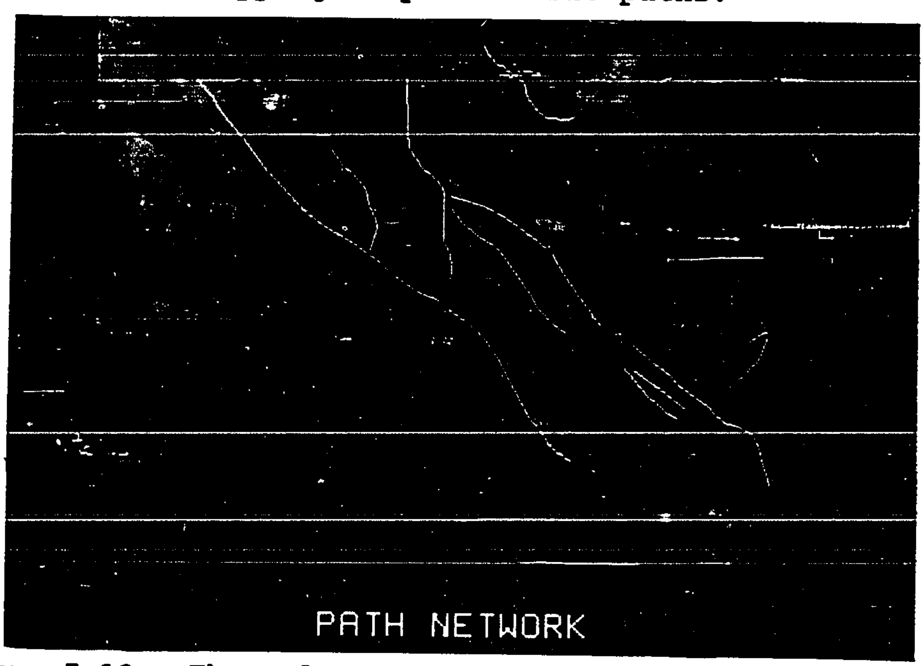


Figure 5-12. Thermal Infrared Multispectral (TIMS) data showing potential locations of prehistoric footpaths in the forest canopy. The linear features have been accentuated in the image to emphasize their locations.

in the TIMS. Differences in forest structure present a complex range of surfaces such as forest canopy type, depth, and architecture. In addition, ground slope can become an important factor in the flow of radiant energy fluxes (Luvall and Holbo 1989:2). Due to a combination of forest dynamics, erosional factors, and the location of the pathways up and down the mountainous slopes, the TIMS was able to map the pathway locations based on thermal inertia differences.

FOOTPATH VERIFICATION

Field reconnaissance and excavation was conducted to determine whether the linear features identified in the remotely sensed imagery were prehistoric footpaths, historic cultural features, or erosional features. In the case of the prehistoric paths, field analysis indicated that the paths had formed as a result of natural erosional processes that were initiated by human activity. In the same manner that paths are formed today, human traffic in the past began the erosional process by walking over the surface, destroying the vegetation, compacting the soil, and creating a channel for water run-off. These factors accelerated the erosional process along the pathway.

Detection of the lineaments in the remotely sensed data, ground survey along the path routes, and the placement of trenches across the paths to reveal wall profiles, have all combined to verify whether the features are prehistoric footpaths, erosional features, or recent cultural manifestations. Many of the linear features were either contemporary or historic and were eventually discounted through either photographic interpretation or excavation.

Using a combination of photographic and digital imagery, a system of prehistoric pathways has been mapped and verified through field reconnaissance and excavation. Several factors help to distinguish the paths from natural erosional features. These factors include topographic location, relationship with known prehistoric sites and resources, artifacts found within the pathway, and the nature of the erosional/depositional material in the path.

Ground survey was conducted to verify the location of the footpaths. A total of thirty-eight trenches were dug along the path network in order to verify or discount the linear features as being prehistoric footpaths (Figure 5-13). In the open, grassland areas the paths

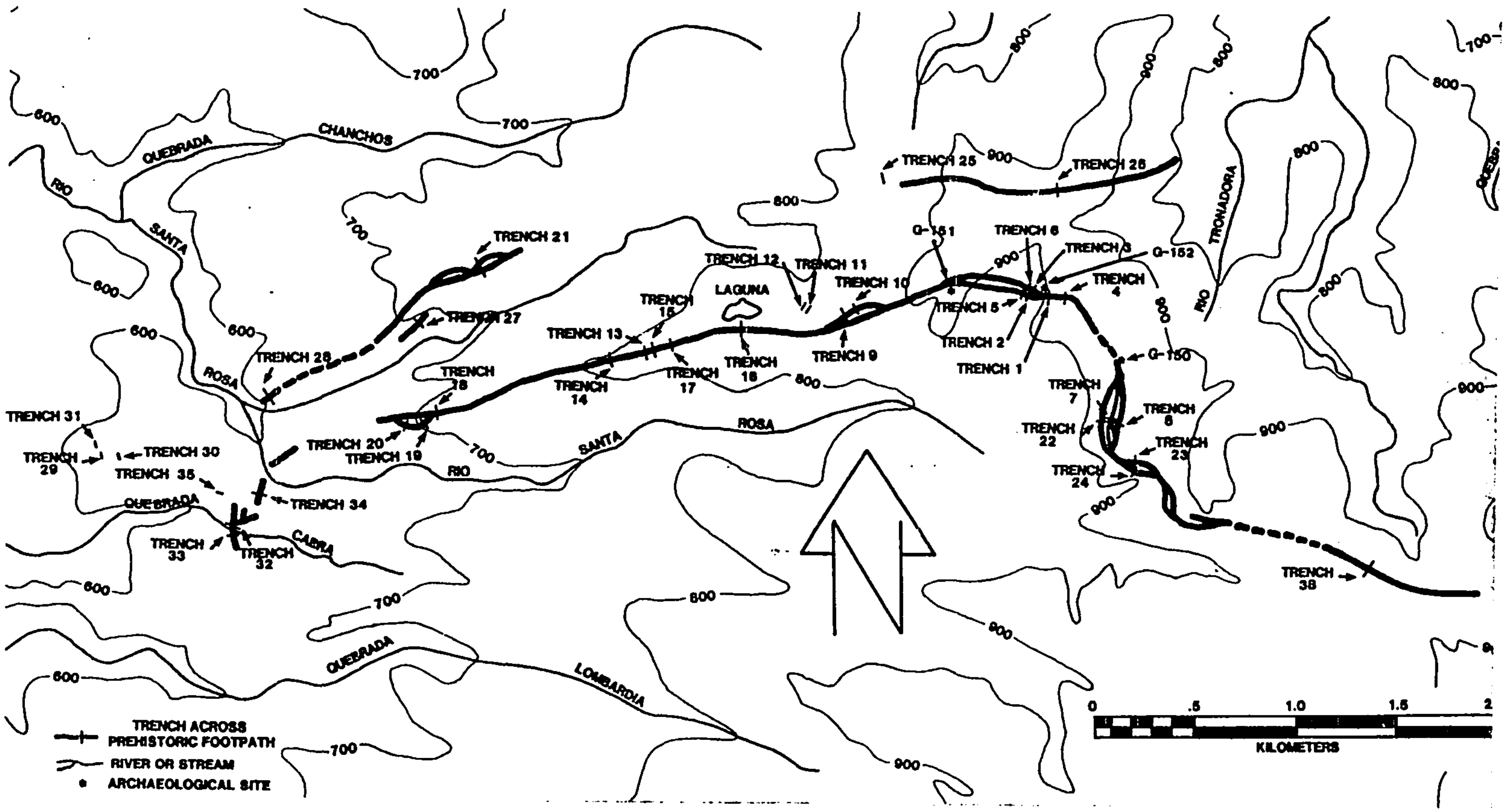


Figure 5-13. Diagram of trench placement along the prehistoric path network.

were best visible on steep slopes and seldom visible in the flat areas. In the forested areas, the paths could not be distinguished because of the thick, mat of vegetation.

One of the farthest segments of the path leading from the Silencio cemetery was seen as a result of shadow effects and was eventually verified. This is reminiscent of the Wetherills who saw the Chacoan roads during sunset at the turn of the century. Figures 5-14 and 5-15 demonstrate this phenomenon. Figure 5-14 is taken looking westward across the landscape just south of Tilaran in the early morning. The path cannot be seen crossing the hillside in this photograph. In Figure 5-15, however, which is taken at sunset from the same place, the path can be seen climbing up the hillside. This observational technique was helpful because there is no evidence of the path from ground level above it. The placement of a trench along this feature verified it as being a prehistoric path.

The paths tend to remain relatively straight and are generally located along ridgetops rather than meandering around and avoiding topographic obstacles. At first, this linearity was unexpected for even contemporary cattle trails show that animals are

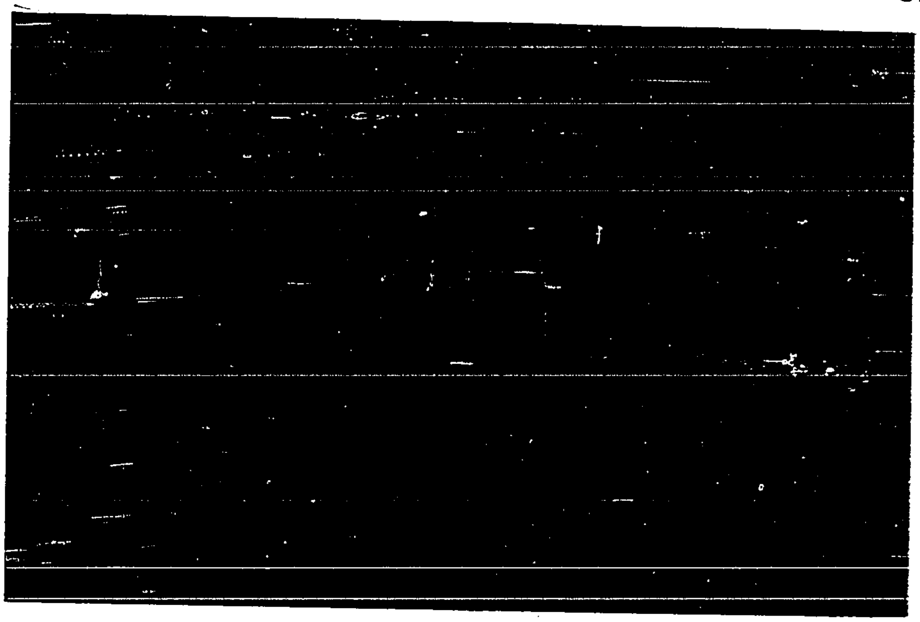


Figure 5-14. Photograph taken looking west at sunrise. The feature of interest is a hill at the center-left of the photograph. No evidence of a path can be seen on the hillside. Compare with Figure 5-15.

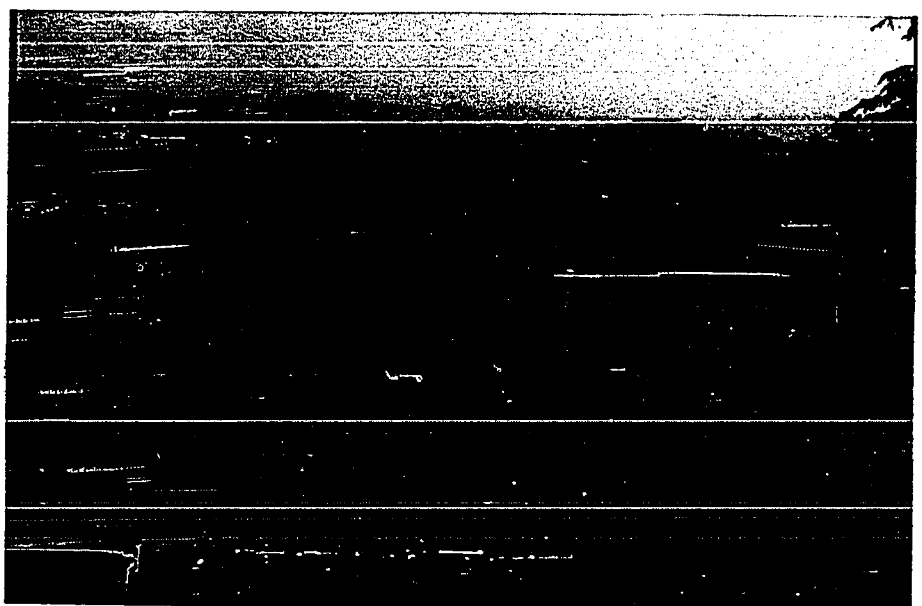


Figure 5-15. Photograph taken looking west from the same point as Figure 5-14 at sunset. Note that the prehistoric path can be seen leading up the hillside. This feature is visible at sunset due to the shadow effects of the sun.

contouring around slopes, thereby, creating paths of gradual ascent and descent through the hillside. The cattle trails also erode in proportion to the degree of slope, with the steeper slopes showing the greatest erosion. As shall be discussed later, the same process appears to have occurred in the prehistoric past with the Arenal footpaths.

The linearity of the footpaths is a distinguishing characteristic which separates them from contemporary and historic features in the remotely sensed imagery. The Arenal Phase people would route their path directly over hills and valleys rather than curve around them. Hills have their paths travelling over their crests and valleys have paths that descend to their low points and directly up the opposite side rather than following the contour of the valley. This pattern contrasts with Inca paths and contemporary Quechuan paths in the arid Peruvian Andes which often follow valley lowlands and by-pass steep topographic obstacles, which I witnessed during my fieldwork in 1977.

As opposed to the roadways in Chaco Canyon, however, there is a functional explanation for this linear pattern. In this wet, rainforest environment, the location of paths along the ridge lines provides better drainage than lower routes. As a result the footing is better in the elevated areas for the wet soil and clay in the low-lying areas creates a slippery surface. Several seasons of field survey in this area have verified the practical use of the ridgetops in negotiating the wet, mountainous terrain.

Another feature of the paths that is characteristic of a cultural process rather than a natural process is the existence of occasional parallel segments. These features are visible in the CIR photography and have been verified from ground survey. Unconfirmed parallel segments are also seen in the TIMS imagery. As originally seen on the path leaving the Silencio (G-150) cemetery and at other locations along the path network, parallel pathway segments occur for various distances. As opposed to Chaco Canyon, there is again a functional explanation for this phenomenon. After human inhabitants had eroded the path to the lowest layer, which was composed of clay, the surface was simply too slippery to conduct traffic. Consequently, a new path was used that was parallel to the original path. This new path was located only a few feet away from the original path (Figure 5-16). A similar pattern can be seen today along paths and trails in contemporary parks and reserves.

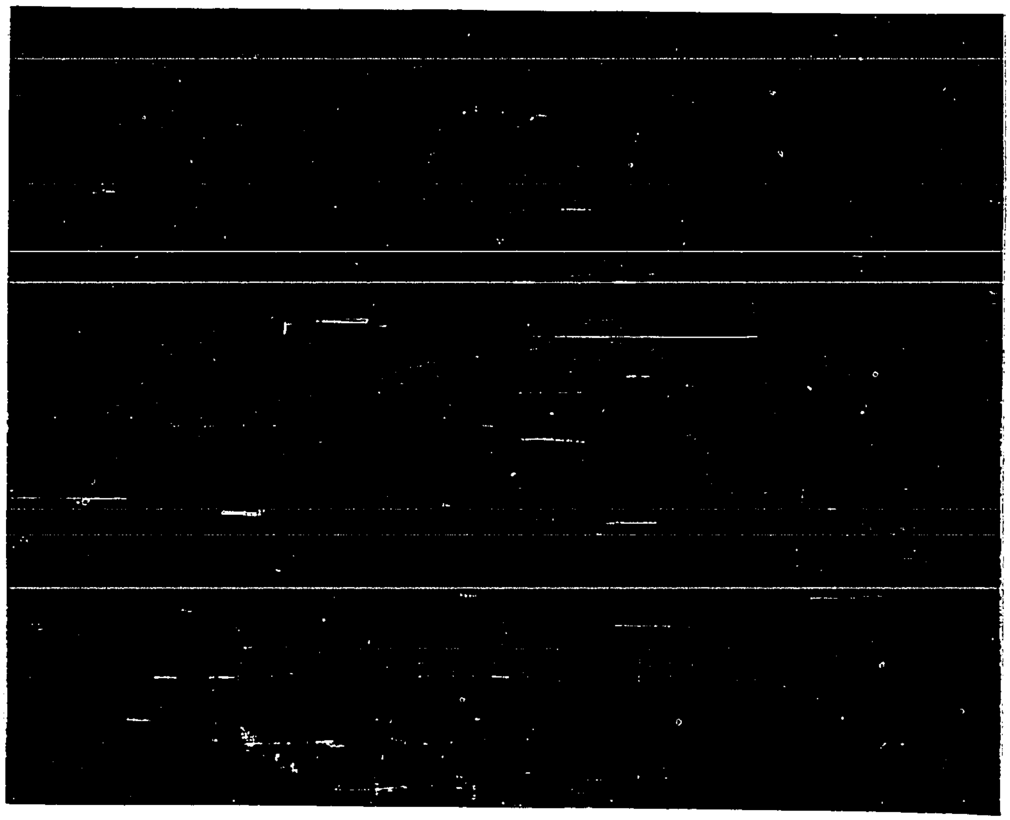


Figure 5-16. Computer-generated image showing prehistoric footpaths on top of topographic data. The loops and parallel segments have been exaggerated in this image to show their locations.

Another cultural pathway pattern involves the use of looping trails that occur in association with the original linear path. These looping segments are found at places where the original path was not worn down to the slippery, clay layer. Here, the new path loops up the slope adjacent to the original footpath. Generally, these looping paths are found on very steep slopes and it is obvious that they are sacrificing shorter distance for decreasing grade. In all instances, the looping paths received less traffic than their adjacent, linear counterparts. The functional use of the looping paths may have been for the transportation of heavy loads, or possibly for use by older or infirm inhabitants.

Straight linear courses, parallel segments, and looping adjacent paths are manifestations of cultural activity. The existence of a depression running across a ridgetop was an indicator of a footpath for normal erosional processes would have created a drainage that ran perpendicular to the ridgetop. Collectively, these factors were able to distinguish the cultural lineaments from the natural features both in the remotely sensed imagery and subsequently from ground level. However, remote sensing analysis alone was not sufficient for the accurate mapping of prehistoric footpaths. The following example illustrates the need for excavation.

The need for excavation to verify prehistoric paths can be seen by comparing Figures 5-17 and 5-18. From the surface, both paths appear similar as indicated by a shallow depression. The linear course and width of both features appear similar in the CIR photography. Examination of the stratigraphy, however, shows a dramatic variation. Figure 5-17 shows a Silencio Phase path lying beneath several volcanic depositions. Figure 5-18, however, shows a historic road associated with Unit 20 which Melson (n.d.) dates to the 15th century AD. As can be seen, this road lays upon several undisturbed layers. Informants in the area verified that the feature was in fact a historic wagon road used in the early decades of this century. The importance of stratigraphy in the verification of prehistoric footpaths will be discussed below.

Path location can also be distinguished by its association with prehistoric sites and resources. As stated previously, one of the first recognized path segments was seen connecting a cemetery atop the continental divide (G-150) with a repository of laja stone (G-152) used in cemetery construction. Another path was seen connecting the cemetery with a nearby

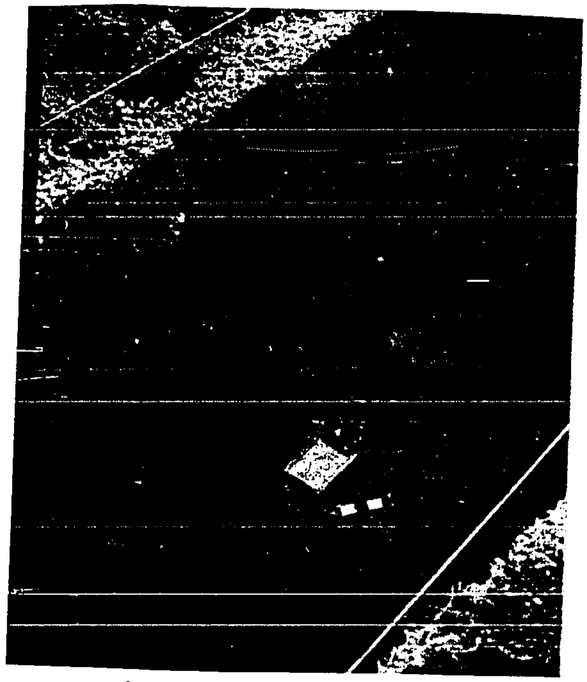


Figure 5-17. Profile of a prehistoric path showing the erosional effect through the strata depositions.

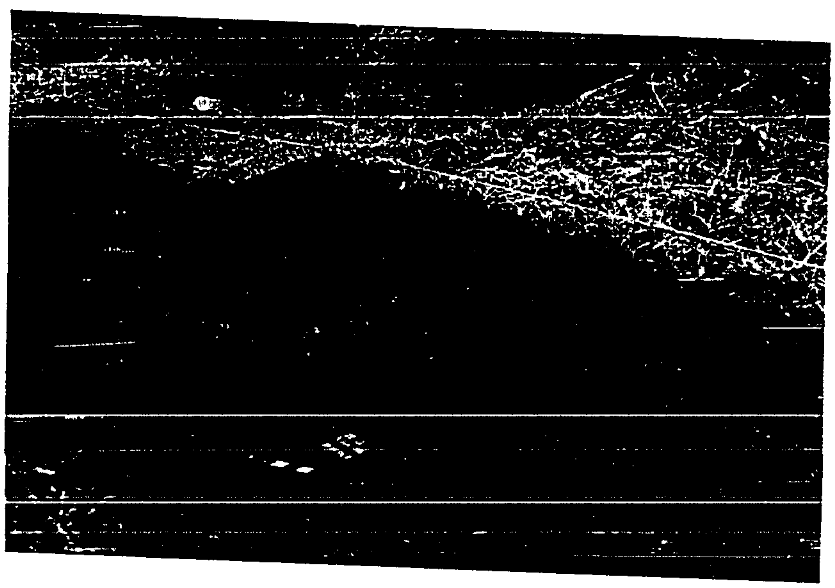


Figure 5-18. Profile of a historic roadway showing the undisturbed strata below it. The depression that can be seen at the surface is similar to the depressions that are indicative of prehistoric footpaths.

spring. Finally, one path was seen connecting another cemetery site (G-180) with a village site (G-184). By contrast, natural erosional features do not generally link cultural features such as sites, cemeteries, resources, and springs.

Prehistoric artifacts directly associated with the paths are also evidence of their cultural affiliation. The trenches that were dug across and beyond the edges of the path reveal ceramic and lithic associations. The stratigraphic evidence shows that the artifacts are located upon the original path surface, even if several meters of fill have buried the original surface through time. Even whole pots have been found upon the original surfaces of the path network. It should also be mentioned that there is a considerable absence of artifacts in the stratigraphy above the original path surface, demonstrating that the paths apparently were not used in subsequent phases.

The volcanic stratigraphy deposited by Volcan Arenal is also useful evidence in identifying the linear features as prehistoric footpaths. The sequence of deposits which have created the stratigraphic record in the area have been chronologically dated by Melson (n.d.). Soils have formed from the tephra deposits resulting in an alternating arrangement of dark soils between light tephra layers. The relationship between an original path surface, time period, and associated artifacts can be derived from the stratigraphic record.

The stratigraphy can also be used to chronologically date the time when the footpaths were in use. The earliest date for the use of a footpath can be determined by the uppermost tephra layer showing erosion. The latest date for path use is simply derived from the first uneroded tephra layer lying on top of the footpath.

FOOTPATH FORMATION

As a result of the excavations that have been made into the footpaths, the processes involved in their formation have been identified. Generally, it is not possible to distinguish paths in areas which have slopes of two degrees or less. Most of the area, however, has slopes steeper than this with some path slopes being recorded at 40 degrees. The fact that tephra is missing from footpath profiles and not from the adjacent profiles demonstrates that these features result from different rates of erosion, with water runoff being the primary erosional agent.

After compaction of the surface soil by human traffic, the path became a conduit by which to carry off the frequent rainfall. This erosional process was accelerated over normal drainage patterns due to the fact that the paths were linear and went up and down slopes rather than curving up and around them. Excavation shows that the original path surface was only 30 to 70 centimeters wide. As the path eroded downward into the under-lying layers, the sides became steeper increasing erosional dynamics. As a result, the banks of the path were eroded away even though they were not carrying any traffic. Wall profiles show that the narrow path itself maintains a U-shaped depression. The rapid erosion of the banks along the path, however, show a broadening V-shape which gradually becomes 10 meters wide or wider at the present surface.

After the path was abandoned, further erosion and depositional processes occurred along the path and banks. The next volcanic eruption stabilized the path by depositing a layer of tephra across it. This basically sealed the path in time and provided an approximate time-frame for the use of the path. Soil formation and developing vegetation from the tephra layer apparently assisted in stabilizing the erosional effects. Ensuing volcanic eruptions continued to fill the pathway trench.

As a result, the filled pathway appears as a slight depression on shallow slopes and is not visible in the flat areas.

I have observed a similar erosional process along segments of a historic road in Southern Mississippi. On his way to what would later become the Battle of New Orleans, Andrew Jackson built an unpaved road to transport his troops. Over the course of nearly two centuries, this road has eroded into a massive V-shaped ditch that is sometimes 30 feet wide and 5 to 10 feet deep. The feature continues to erode because unlike the footpaths in Arenal, no materials are being deposited into it.

The erosional process involves a number of variables. These factors include use, slope, moisture, soil composition, and time. The greater amount of use (human traffic) eroded a path deeper. Slope is a predominant factor since the steeper the slope the more severe the erosion. Moisture affects the erosional process to a major degree. The 6000mm of mean precipitation near Volcan Arenal erodes the landscape faster than the 1300mm of annual rainfall occurring to the west. The type of soil is also a factor for erosion. Different ashfall layers contain different compositional elements and the soils that form from them are somewhat different. As a result, some of the soils are more resilient to erosion than others due to their matrix and consolidation. Finally, the time a footpath was in use by a prehistoric population is directly related to the degree of erosion it experienced.

PATHWAY USE

One of the objectives of this research was to determine the degree of footpath use. Original field observations of the excavated footpaths demonstrated that some paths were used more than others as indicated by erosion. The observations indicated, for instance, that the footpaths near the Silencio Cemetery (G-150) experienced more traffic than the paths laying several kilometers to the west. Archeological evidence of the Silencio Cemetery had indicated extensive activity and long-term stays at the cemetery. Certainly, this activity would have increased the wear and tear on the footpaths. In his discussion of footpaths among the Cuna, Dillon states:

> Some trails leading from the coastline to fields in the interior pass through cemeteries, and most conscientious Cuna visit the graves of their important ancestors at least once a year. Others, perhaps more dedicated to the memory of the deceased, will

> visit the tombs on a weekly basis, and yet a third group, which consists of an age-set of elderly widows, visits the graves of their dead husbands every day, commuting from their homes on the islands at daybreak and returning at dusk. These older women set up hammocks in the burial houses, carry on conversations with their dead spouses, cook, sew and perform other daily tasks in the cemeteries, and, of course, tend to meet with each other so as to exchange gossip (Dillon 1984:60).

Other evidence of intense pathway use was found near the cemetery. The excavation of the footpath below the cemetery at the point where it bifurcates had revealed that one footpath had existed prior to the other. In addition, footpaths leading directly from the same cemetery to a natural spring (Figure 5-19) also demonstrated various degrees of traffic use. As a result of these observations, an approach was investigated that would quantify the factors involved in pathway use. If this approach proved successful, it would be possible to determine the degree of use throughout the entire pathway network.

Quantitative manipulations were performed that incorporated the variables used in footpath use. These variables were originally determined by Sheets (Sever, McKee, and Sheets n.d.) The amount of erosion of a footpath is directly proportional to the amount of annual

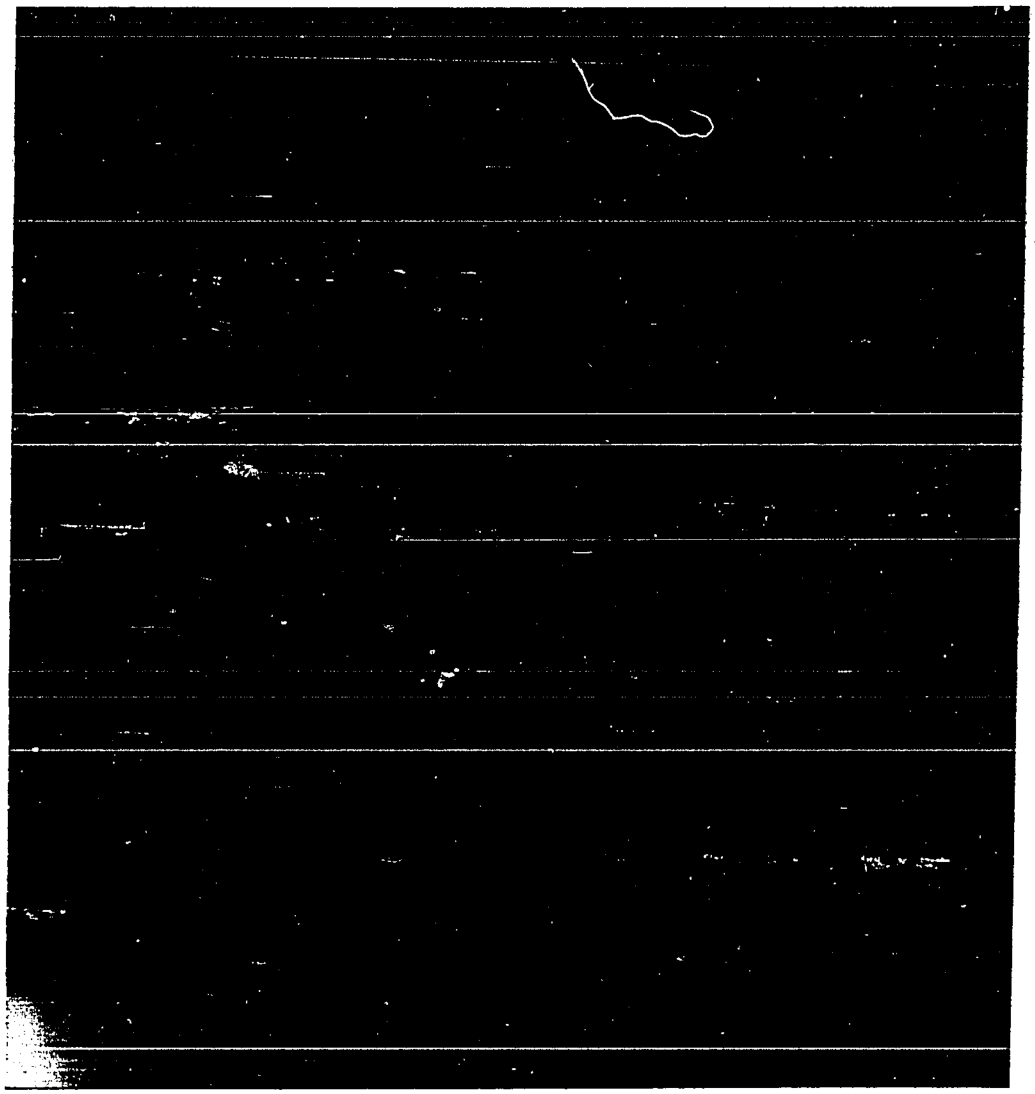


Figure 5-19. CIR photograph showing three footpaths connecting the Silencio Cemetery beneath the forest canopy in the upper left with a natural spring beneath the forest canopy in the lower right.

precipitation, the amount of use at any time, to slope, and to the total time that the footpath was in use. As a result, the equation can be developed:

$$\text{Erosion} = (\text{Rainfall}) \times (\text{Use}) \times (\text{Slope}) \times (\text{Time}).$$

Erosion can be measured in terms of square meters as the area of tephra and soils that have eroded away. Rainfall can be measured in terms of mm per year. Slope can be measured in angular degree or in slope distance. Time of use is measured in centuries as indicated by the volcanic sequence layers which date the path. The unknown factor is Use, which can now be determined by:

$$\text{Use} = \frac{\text{Erosion}}{(\text{Time}) \times (\text{Slope}) \times (\text{Moisture})}.$$

Before continuing the discussion of pathway use, it is first necessary to understand some of the factors which influence erosion. As stated previously, one of these is rainfall. The temporal variation in rainfall is probably more critical to footpath erosion than the annual rainfall. The highly saturated soils of the rainy season will channel more water runoff than soils during the dry season. The intensity of a storm will also affect erosion since the direct impact of raindrops is related to soil detachment. As a result of these factors, the temporal distribution and intensity of rainfall in the Arenal area results in greater erosion than areas elsewhere.

Slope plays a major factor in the degree of erosion as witnessed directly in the field. The paths are generally not visible in the flat areas since water does not flow in level areas and erosion along the paths is not initiated. Erosion is related to slope in a linear fashion (Sheets n.d.) and as verified in the field, areas with steeper slope demonstrate greater degrees of erosion along the footpaths.

Soil composition is also related to the rate of erosion. Coarser sediments allow higher rates of water infiltration than finer sediments (Carson and Kirkby 1972). The strong cohesion between the clay particles of the Aguacate formation which rests beneath the 10 volcanic depositions makes it less susceptible to erosion than the above layers. The tephra layers themselves, however, demonstrate a variation in particle size with the heavier, larger particles having fallen near the volcano and the lighter ones to the west. As a result, greater erosion takes place near the coarser materials near the volcano than the finer ones farther away from the volcano.

It should be mentioned at this time that vegetation is a factor which helps in preventing and limiting erosion. Vegetation keeps the soil porous and allows the water to percolate more quickly through the ground. Surface vegetation increases the geometric roughness of the surface and thereby slows the flow-rate of water. In the same way it reduces the impact of rainsplash upon the soil. Finally, the root system and by-products of vegetation create a blanket which binds with the soil and further reduces the effects of erosion. While vegetation is an important variable in erosion, it is not included in the analysis since it is presumed that traffic upon the footpaths would have quickly destroyed the vegetation. As a result, the other erosional factors would have become more pronounced and are the ones which can be seen in profiles across the paths.

ANALYSIS OF FOOTPATH USE

Statistical analyses were conducted using packages such as SPSS-PC (Sever, McKee, and Sheets n.d.) to determine correlations between the variables related to footpath use. The data came from the trenches which were dug to verify pathway existence. The purpose of the test was to determine the relative roles of the different variables and consequently determine a quantified measurement that would be indicative of footpath use. A Pearson product-moment correlation coefficient matrix was determined between the variables of slope, the rainfall and the depth of remaining tephra above the Aguacate Formation at each trench location, and the degree of erosion at each trench location. Analysis results showed that the correlations were extremely low between all of the variables.

The lack of correlation suggests that the data are insufficiently controlled. A re-examination of the data shows that there are several potential sources that cannot be controlled at this time. For instance, there is no systematic way to account for localized rainfall nor was there a quantified measurement given for the various soil and tephra properties of each volcanic deposit. Vegetation may have played a major role with some species being more resilient to traffic than others, but this information simply cannot be accounted for. Finally, both the length of time that the footpath was in use and the amount of traffic it received cannot be controlled with any measurable reliability. Discussions with statisticians and programmers at the Stennis Space Center suggest that the number of trenches is too small for the various factors involved in footpath formation. In order to arrive at a statistically valid conclusion, data from many more trenches would have to be collected.

In summary, the data are not able to quantify the prehistoric use of footpaths in Costa Rica. Circumstantial evidence, however, provides an insight as to the amount of use of a pathway by the prehistoric Arenal peoples. This evidence is supported by ethnographic evidence from the Cuna and Kayapo. However, until there is a greater understanding of the environmental factors involved in footpath formation, the degree to which a footpath was used prehistorically cannot be demonstrated with any scientific reliability.

FOOTPATH FUNCTION

Although it was not possible to accurately assess the amount of use for prehistoric footpaths, it was possible to understand some of their functions and how they integrated Arenal societies with the environment. The highly eroded footpaths between the Silencio Cemetery (G-150) and a natural spring to the southwest show that they were carrying a heavy amount of traffic. As opposed to using the cemetery for burial only, the paths suggest that there was an inordinate amount of cultural activity in the area and that people were staying in the immediate area for long periods. This is supported by the fact that stone tools were manufactured, used, and discarded in the cemetery (Sever, McKee, and Sheets n.d.). Long-term visits or stays are further evidenced by the amount of forest clearing in the area, by the large amount of occupational trash left there, and by the fact that maize was being cultivated near the cemetery.

Paths leading farther away from the cemetery toward the villages were used not only to transport the dead for burial, but also to move large quantities of volcanic stone (laja). This stone was used specifically for cemetery-related construction. Two caches of laja have been excavated along the major path leading westward from the Silencio cemetery at sites G-151 and G-152 (Hoopes and Chenault n.d.). The storages of laja indicate that the material was being organized with the flatter, larger slabs being separated from the smaller, more irregular slabs. One section of G-152 contained only elongated headstones which were placed upright in a straight line. As indicated by the excavations within the cemetery, these stones were used to mark the head end of the grave, much like tombstones.

The footpaths also contributed to an understanding of the prehistoric environment. There was some question as to whether the Arenal populations lived in a tropical rainforest, or if they lived originally in a more arid environment which had been covered by the rainforest in subsequent centuries. There was also some question as to the amount of forest clearance that had been conducted in prehistoric times. Palynological research was conducted to help resolve these questions (Piperno, Clary, Mahaney et al. n.d.), but the fact that the samples come from archeological sites which are disturbed areas causes problems in the interpretation of the data. The prehistoric paths helped answer these questions for when volcanic ash layers are exposed to solar radiation, they become oxidized. Of the 38 trenches that were excavated along the path network during this project, only one showed evidence of oxidation. This trench was located between the Silencio cemetery and the spring. The layers at the village sites are also oxidized, showing that they were cleared areas. The remaining 37 trenches along the path network, however, were not oxidized and thus indicate that the prehistoric landscape was predominantly forested.

The footpaths also demonstrate that during the Silencio Phase, villages were integrated in part to religious, ceremonial behavior. During the Silencio Phase, the distance increased between villages and the population declined. It was not known if the villages became more isolated as a result of this trend. The elaborate network of paths converging on the cemetery from many directions, however, indicate that religion played an integrative role. Multiple paths extend outward from the Silencio cemetery toward the villages. People transported their dead along these paths for interment in the cemetery. The evidence from the cemeteries suggests ceremonies of long duration and elaborate burial practices, possibly related to ancestral and deity worship (Sever, Mckee, and Sheets n.d.). For instance, a gold image of a bird was found in association with one of the Silencio burials. The fact that the cemetery is shared by a number of Silencio Phase villages and that the cemetery area is where the greatest amount of traffic occurred, suggests religious activity. The relationship of the graveyard to the path network has provided an insight into Arenal society that might not have been appreciated from the artifacts alone. The religious integration that appears in the composite of the archeological and remote sensing data is similar to that reflected in the cemeteries of the modern-day Cuna. As Dillon observes:

> Cuna cemeteries mirror the political, social, and economic realities of Cuna villages, and in fact represent this concept architecturally as well as symbolically. Villages of the dead exist as a cautionary example to archaeologists working in Middle America who may not truly be seeing what is right before them. Without living informants to explain the function of the small houses grouped on the ridgelines, and without excavation, we might conclude that temporary camps were represented....by studying situations such as the Cuna villages of the dead we may come to have a better understanding of how things really were in the past, rather than how we presume they were (Dillon 1984:65).

PATHWAY SUMMARY

Hypothesis testing in the Arenal study area revealed that the linear patterns seen in remotely sensed data demonstrated characteristics which were of a cultural origin. The linear patterns were part of a prehistoric footpath network which integrated the Arenal society with the landscape. The prehistoric footpaths were verified from ground survey and through the placement of trenches. These trenches revealed the original formation processes that created the path, the time of their formation, and the erosional and depositional activities which buried and preserved them through time. Through the analysis of remotely sensed data and field verification (Figure 5-20), prehistoric paths could be distinguished from natural features.

The topographic associations, relationships with archeological features such as villages and cemeteries, associated artifacts, and stratigraphic profiles have provided supportive evidence that the linear features are prehistoric footpaths. The volcanic activity of Volcan Arenal has been helpful in dating, preserving, and understanding the processes involved in the formation of the footpaths. The approach of using several lines of evidence to confirm the hypothesis that the linear features are prehistoric footpaths is more conclusive than an approach which uses only one line of evidence. In addition, these lines of evidence correlate with the archeological and palynological evidence that has been gathered through the excavation of prehistoric villages, cemeteries, and other features.

The investigation of the ancient footpath network confirmed the position that excavation will always play a fundamental role in archeological remote sensing research. Excavation revealed that some of the suspected

Figure 5-20. Prehistoric footpath showing its erosional effect along a ridge-top.

footpaths were actually historic and not prehistoric, even though they appeared similar in the remotely sensed data and from ground level. The importance of acquiring ground truth information in conjunction with remote sensing analysis has been emphasized in the past (Sever and Wiseman 1985:72). Despite the advances in technology, this approach continues to be a mandatory procedure for current archeological remote sensing research.

Remote sensing analysis indicated that CIR photography worked better for the detection of prehistoric footpaths in open, grassland areas while the TIMS was better in the heavily forested regions. Lidar and radar imagery were capable of detecting the footpaths, but the large amount of data reduction and field verification that is required in the process renders them as inefficient techniques for prehistoric pathway detection. In the future, radar data, because of its cloud penetration and linear feature capability, may ultimately become an effective technology for archeological research after effective analytical procedures have been developed for it.

Despite the original expectations, the amount of use that a path experienced could not be quantified.

Although general observations could be made that resulted in determining primary, secondary, and tertiary routes, this information could not be presented in a measured, numeric format. Data analysis revealed a low correlation between the variables. More control of the variables involved in pathway formation must be realized before pathway use can be determined in a quantified manner.

In spite of the obstacles presented by a rainforest environment, low prehistoric population densities, volcanic deposition, and centuries of vegetational after-growth, the oldest known footpaths have been detected and confirmed in northwest Costa Rica using remote sensing analysis. Footpaths may represent one of the least investigated features in the inventory of past archeological research. The footpath network has been instrumental in understanding how the prehistoric Arenal cultures negotiated the terrain and how their integration was based on ritual or ceremonial behavior. The footpaths provide the archeologist with an insight into human transportation and communication in prehistory. Based on the research conducted in Arenal, there is a reasonable expectation of finding ancient footpath networks in other tropical regions of the New and Old Worlds.

GEOGRAPHIC INFORMATION SYSTEM

A Geographic Information System was constructed over the Arenal study area. The GIS was designed to provide a resource base that could be shared with various investigators and could be updated in response to future archeological and environmental research objectives. The GIS was developed using the ELAS software. ELAS has GIS capabilities but does not have the relational data-base capabilities available in other GIS software. As a result, ELAS does not contain the statistical and computational capabilities that exist with other GIS softwares. ELAS's GIS capabilities, however, can be used to determine data relationships and characteristics. ELAS requires a rasterized format and cannot store or retrieve vector data.

As stated previously, the archeological evidence demonstrates a stability that survives throughout most phases of occupation in the Arenal region. It is proposed that this is a reflection of a consistent adaptive strategy which would be similarly reflected in settlement patterns. The Arenal GIS will be used to assist in determining if a consistent adaptive strategy to the environment is reflected in the variables that represent site characteristics. As McKern states:

> All the traits characteristic of a given culture manifestation comprise the culture complex for that manifestation....In any comparison of this manifestation with another, made for purposes of classification, certain traits may be demonstrated as present in both complexes, and these linked traits (serve) to show cultural similarity between the two culture variants (McKern 1939:205).

The relationship between artifacts and sites has been well established in the archeological literature. Changes in human adaptation have been determined from artifact analysis that range from the hunting-gathering techniques of the Old World Pleistocene (Pfeiffer 1982) to the agricultural techniques in the New World (Willey 1974). K.C. Chang takes this one step further by proposing that archeologists shift from the artifact as the basic unit to the settlement. He states:

> The reason we shift from the artifact to settlement as the primary unit for conceptualization and operation is that we are primarily interested in past peoples living in social groups having common cultural traditions (Chang 1967:39).

Binford (1972:74-77) disagrees with Chang's suggestion arguing that the identification of a settlement depends upon the prior analysis of artifacts. Binford states that there is a relationship between artifacts and settlements and that both provide the facts for comparative study.

Research in the Arenal region had demonstrated remarkable stability through time. This stability has been documented from the lithic evidence (Sheets n.d.), the ceramic evidence (Hoopes n.d.) and the palynological evidence (Piperno, n.d.). The analysis of the soil oxidation in the paths also demonstrate that the area was heavily forested during prehistoric occupation. While there were some slight modifications to the Arenal technology, the artifacts demonstrate a general trend toward an adaptive strategy that survived for many centuries. This adaptive strategy used the multi-resources of the tropical rainforest environment and avoided the transition to a staple agricultural crop such as maize. The following hypothesis will be tested using the Arenal GIS to see if site characteristics remained similar through time.

> The hypothesis to be tested is:
>
> If the adaptive strategy to the rainforest environment was similar throughout all phases of occupation, then the archeological materials will be similar through time. Specifically, the ceramic and lithic traditions will be similar if the variables of site location are similar. These variables include elevation, slope, soil, aspect, distance to water, and life zones.
>
> Conversely, if there was a change in the adaptive strategy to the rainforest environment, then there will be a change in the archeological materials.

> Specifically, if the ceramic and lithic traditions change in order to adjust to a new adaptive strategy (i.e. hunting and gathering to agriculture), then the variables of site location will also change.

Ancillary data was digitized and input into the Arenal GIS. These data were overlayed and registered onto a classified TM scene. The final Arenal GIS data-base layers include landcover, aspect, elevation, soils, distance to water, slope, life zones, and archeological sites. These data are depicted in a tabular format in Table 5-1. The data were examined by plotting the frequencies of site characteristics for each of the four phases and displaying them in a histogram format. The four phases are the Arenal (Ar), Tronadora (Tr), Silencio (Si), and the Tilaran (Ti). The Fortuna Phase information was not included since it only included one known site. The data input procedures and the results of the frequency distributions and patterns in the data are discussed below. It should be mentioned at this time that the site characteristics that were determined from the GIS highly correlate with the field notes that were taken at each site. As shall be shown, the only exception was that of slope.

TABLE 5-1

ARENAL SITE CHARACTERISTICS

Site	Phase	Land-cover	Aspect	Elev/ Meters	Soils	Dist. Meters	Slope Degrees	Life Zone
G150	Ar Si Ti	2	W	950	RC	630	1°	NA
G151	Ar	13	SE	930	RC	810	6°	NA
G152	Si	16	SW	910	RC	700	5°	NA
G153	Ar Si Ti	7	SE	900	RC	960	8°	NA
G154	Si Ti	36	N	1000	RC	50	2°	NA
G155	Ar Ti	36	N	820	RC	40	3°	NA
G156	Ar Tr Si Ti	7	N	560	RC	100	9°	Bh-t
G157	Ar Tr Si Ti	42	N	560	RC	30	18°	Bh-t
G158	Ar Tr	14	NW	560	RC	60	17°	Bh-t
G159	Ar Si	9	NW	540	RC	270	15°	Bh-t
G160	Si Ti	12	N	560	RC	390	12°	Bh-t
G161	Ar Tr Si Ti	15	N	560	RC	150	12°	Bh-t
G162	Ar Tr	13	NE	580	RC	60	23°	Bh-t
G163	Ar Tr Ti	37	NE	550	NT	210	7°	Bh-t
G164	Ar Si	24	N	530	NT	30	7°	Bh-t
G165	Ar Tr Si Ti	22	NE	540	NT	180	12°	Bh-t
G166	Ar Tr Si Ti	24	N	560	W	Island Site		
G167	Ar Tr Si Ti	20	SE	540	TJ	120	17°	Bh-t
G168	Ar Tr Si Ti	14	E	560	TJ	240	13°	Bh-t
G169	Tr Si Ti	26	NE	650	RC	60	8°	Bmh-p
G170	Ar Tr Si	13	NE	570	TJ	270	12°	Bh-t
G171	Ar Tr	7	N	560	RC	210	17°	Bmh-p
G172	Ar Tr	10	NE	560	RC	390	18°	Bmh-p
G173	Ar Si Ti	22	E	550	RC	30	17°	Bmh-p
G174	Ar Si Ti	26	E	540	RC	120	15°	Bmh-p
G175	Ar Tr Si Ti	10	E&S	560	RC	60	12°	Bmh-p
G176	Ar Tr Si	19	SE	540	AR	200	10°	Bmh-p
G177	Ar Tr Si Ti	9	SE	550	AR	50	12°	Bmh-p
G178	Ar Tr Si	8	SW	580	TJ	180	3°	Bmh-p
G179	Ar Si Ti	13	SW	580	TJ	90	2.5	Bmh-p
G180	Ar Si Ti	9	S	580	TJ	30	2.5	Bh-t
G181	Ar Si	7	E	610	TJ	120	3.8	Bmh-p
G182	Ar Si	41	E	690	TJ	400	4.8	Bmh-p
G183	Ar	33	NE	690	RC	20	14	Bmh-p
G184	Ar Si	13	S	610	TJ	30	2°	Bmh-p
G185	Ti	33	N/A	820	TJ	N/A	N/A	N/A
G186	Ar Ti	23	S	540	RP	30	2.7	Bh-t
G187	Ar Tr Ti	17	S	530	RP	90	22°	Bmh-p
G188	Ar Ti	22	SE	550	RP	270	6°	Bmh-p
G189	Si Ti	18	SW	530	NA	270	8°	Bmh-p
G190	Ar Ti	19	S	540	RP	60	14°	Bmh-p
G191	Ar	18	SSE	530	CN	30	18°	Bmh-p
G192	Ar Ti	21	E	540	CN	60	7°	Bmh-p

NA = Not Available

Archeological Sites

A ground survey was conducted in the Arenal Area to locate prehistoric site locations. A complete survey was conducted around Lake Arenal, with most of the sites occurring on the southern side of the Lake. Survey results indicate that most of the settlement sites are located near the prehistoric level of Lake Arenal. On the contrary, cemetery (i.e. G-150) and cemetery-related sites (i.e. G-151, G-152, G-153) are located on prominent ridges away from the village settlements. Examination of the archeological evidence indicates that most of the sites were occupied throughout several cultural phases. The location of each site was digitized, labeled, and input as a layer of information into the GIS. Not included in the analysis are site G-166 which is an island site in Lake Arenal. Only partial information is available for site G-185 since it was located outside the boundaries of some of the digitized data.

<u>Landcover</u>

The landcover was determined from a classified image of Thematic Mapper (TM) data. Forty-three classes were produced from the satellite data using the ELAS modules SRCH and MAXL. The highest percentage of landcover classes were indicative of forests and dense vegetation. Analysis of the data indicates that there is a high correlation between classes that represent grasslands and site locations. Originally, it had been anticipated that there would be a relationship between present surface cover vegetation and archeological sites as demonstrated in tropical forests in Yucatan and Guatemala where ramon trees are indicative of Maya sites (Sever 1987). The results of the landcover analysis in the Arenal area, however, are more of a reflection of recent landcover changes and survey techniques than site-vegetation indicators. Deforestation and land clearing over the last two decades on the south side of Lake Arenal have severely altered the landcover surface. Thus, the pasturelands are more conducive to finding archeological sites during ground survey than those which occur under dense, tropical vegetation.

Elevation

Elevation contours were digitized from 1:50,000 scale maps produced by the National Geographic Institute in San Jose, Costa Rica. After the twenty meter contour intervals were digitized, the ELAS module YISP was used to interpolate the data using a cubic spline function. This procedure produced a smooth surface model with 10 meter contour intervals. Data analysis shows that most of the settlement sites occur at similar elevations along the extensive shore of Lake Arenal averaging between 540 and 560 meters above sea level (Figure 5-21). Cemeteries and cemetery related sites occur on much higher elevations. The highest site is the Silencio Cemetery which is located on top of the Continental Divide at 950 meters above sea level.

Slope and Aspect

Slope and aspect were determined from the topographic surface model using the TOPO series of software in ELAS. The algorithm used to produce this information is described as follows:

> This routine moves data from an input file into a rotating array such that the first and last lines are repeated. The array contains the current three lines with the center line

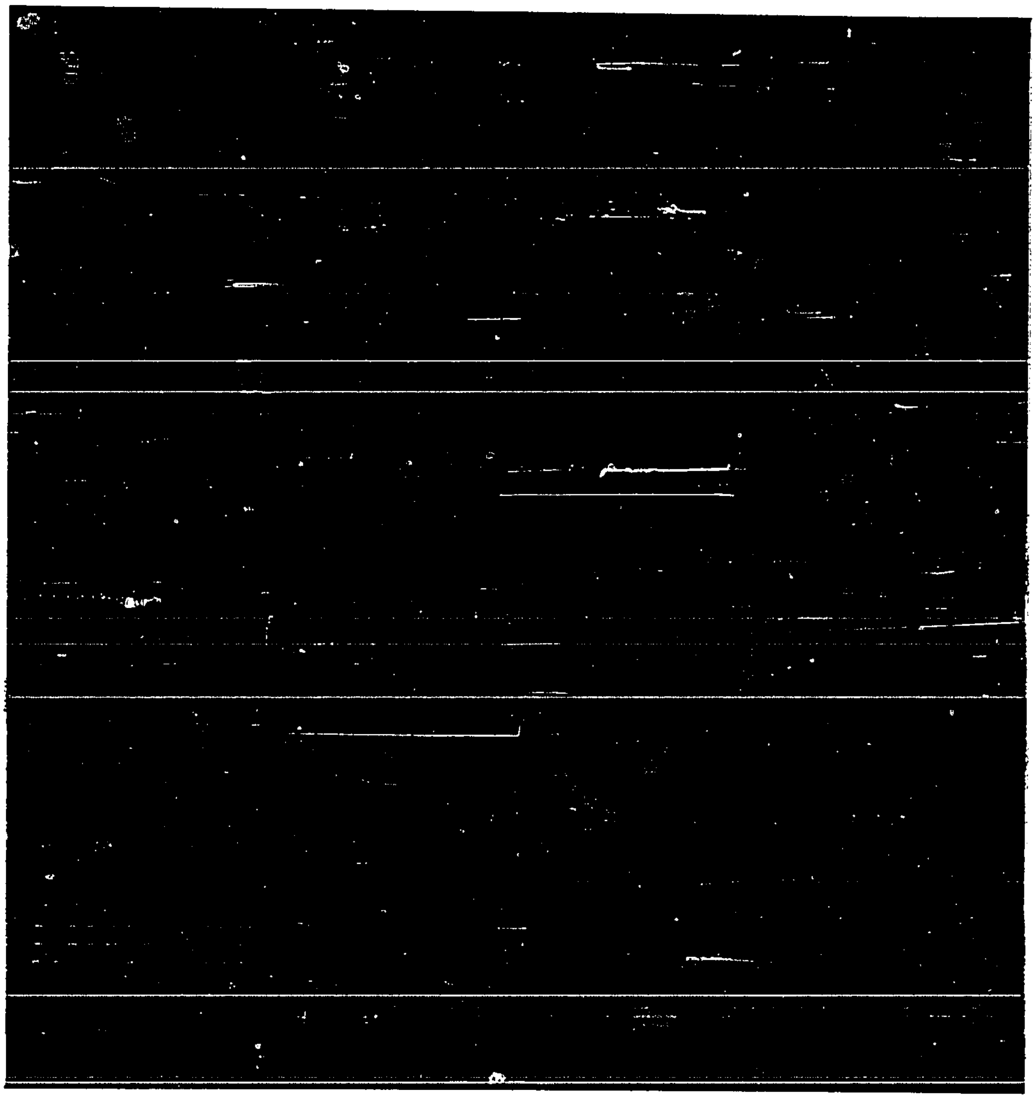


Figure 5-21. An example of sites located between the 550 and 560 meter elevation contours.

> used in a sliding 3 X 3 window approach to compute slope, aspect, and slope length. The cell adjacent to the center cell with the maximum gradient is used to compute slope, aspect, and slope length. Aspect is defined as the direction from the highest to the lowest elevation point (Junkin et al. 1981).

There was a high correlation between the aspect that was recorded in the field notes and that generated by the TOPO program. This was not the case for slope. The explanation for this appears to be that the investigator at the site is recording a specific line of sight that is related to specific archeological features that best identify the site location. Conversely, the slope estimate generated by the TOPO program is a computation for the entire area rather than a specific line of site. The slope measurements that were computed digitally showed no correlation to prehistoric sites while those slope measurements acquired in the field demonstrated that sites were generally located on flat to slight slopes.

The data demonstrate that throughout all cultural phases the sites are generally located on northern aspects, facing in the direction of the lake. Closer examination of the data, however, reveal that the aspects shift slightly from site to site, in accordance with the changing lake orientation. For example, the lake is on a north-south axis at sites G-173, G-174, and G-175, and consequently the aspects for these sites are facing east in the direction of the lake. By contrast the lake is on an east-west orientation at sites G-160, G-161, and 171, and the aspect for these sites faces north toward the lake. The transition site (G-172) is located between the two previous sets of sites with a northeast aspect. This pattern is consistent throughout almost all of the site locations.

Soils

Soils data were digitized from 1:50,000 scale maps produced by the Centro Cientifico Tropical. Digitization involved a straight reproduction from the maps in the form of closed polygons into a database layer. These soil polygons were then labeled with a digital value and rasterized. Data analysis indicates that there was no appreciable change from one soil type to another throughout the cultural phases and that soil type was not a major consideration in site selection.

Distance to Drainage

Contemporary occupants in the Arenal area have noticed that there has been a change in water flow and drainage patterns as a result of the recent landsurface alterations and lake development. In some instances, the drainages have dried up that once conducted water-flow. The contemporary drainage patterns were digitized from the hydrology map produced by the Centro Cientifico Tropical. Distance to drainage was calculated by the DIST program in ELAS. Data analysis revealed that the sites are located relatively close to drainages.

A procedure was developed, however, that would more accurately represent the drainage pattern that existed prehistorically. All potential drainage areas were identified by a combination of landcover and topographic information. Ridges in the landcover data were identified through their high infrared range and assigned a single value. All drainage areas were identified on the topographic surface model that had a minimum degree of slope and contained a 100 or more contiguous pixels. DIST was then used to compute proximity from these low-lying features and the site locations using a Euclidean distance.

The output from this procedure revealed a higher correlation between sites and distance to drainage than the contemporary drainage conditions. The correlation between sites and distance to drainage did not significantly change and was relatively high throughout all the cultural phases. The association between sites and drainages is visually illustrated in Figure 5-22 and presented in a histogram format by phase in Figure 5-23. Distance to drainage is not to be confused with distance to water for the proximity of Lake Arenal to many of the village sites could have provided fresh water to the occupants.

Life Zones

The life zones were digitized from Tosi's 1:50,000 scale life zone map produced at the Centro Cientifico Tropical. The data were digitized in polygon format and input as a layer of information into the GIS. Analysis indicates that the sites are predominantly located in two of the possible 13 life zones. These two life zones are transition zones that provide access to the resources of the neighboring life zones. The life zones for sites G-150 to G-155 were not available since they were located outside the boundaries of the life zone map.

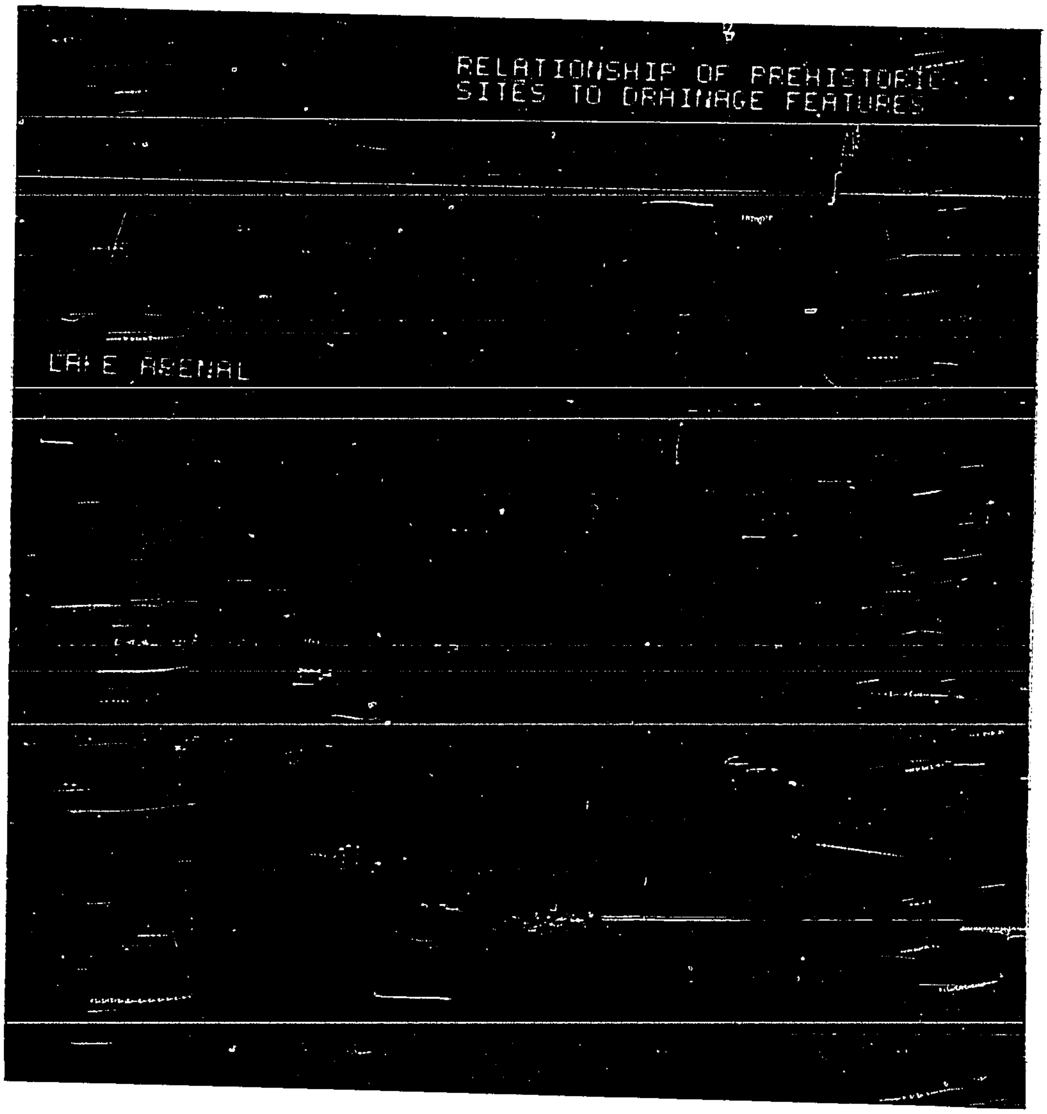


Figure 5-22. Relationship of prehistoric sites to drainage features.

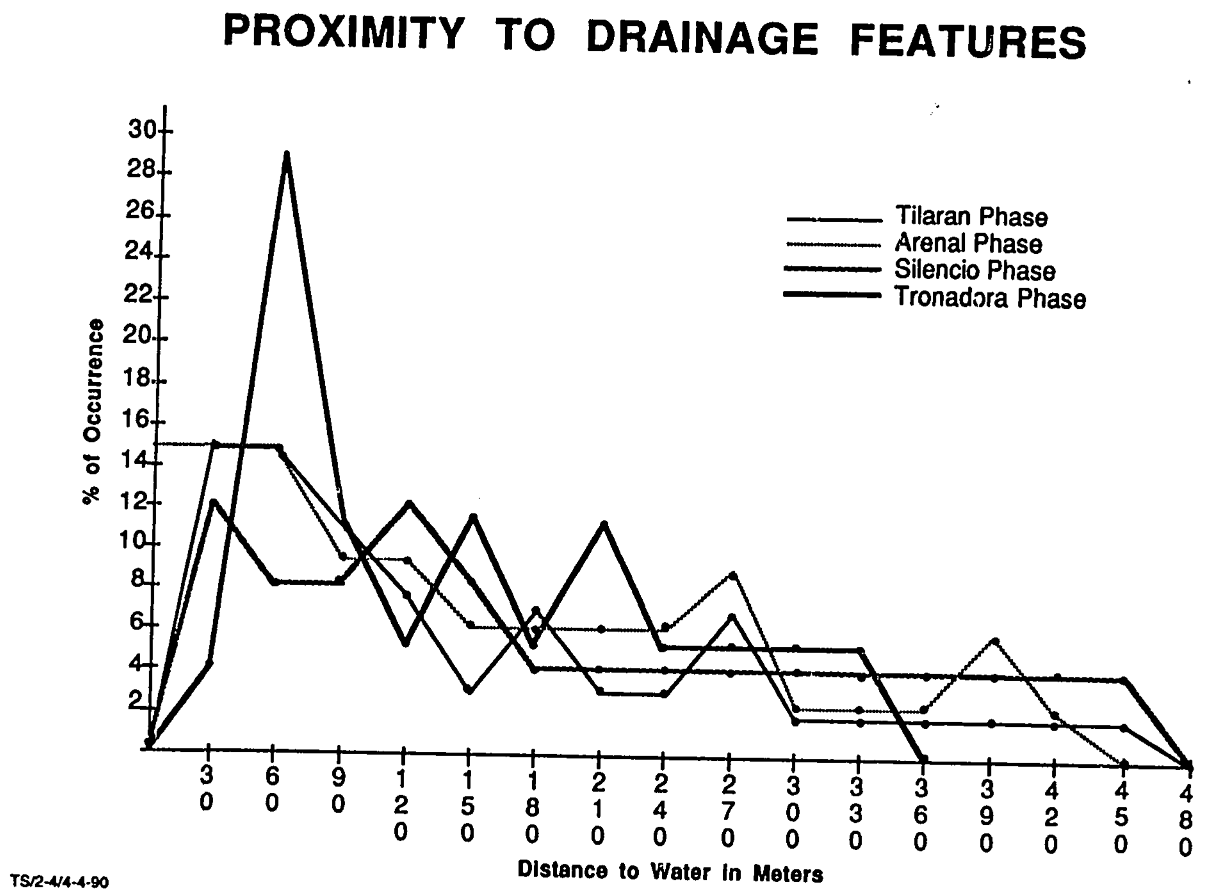


Figure 5-23. Histogram of the association between prehistoric sites and drainages.

GIS SUMMARY

This investigation has revealed that the hypothesis is true that if the adaptive strategy to the rainforest environment was similar throughout all phases of occupation, then the archeological materials will be similar through time. Analysis of the GIS data and archeological site information indicate that there were no significant changes in village site characteristics throughout all phases of cultural occupation. Village site characteristics such as elevation, life zone, distance to water, soil type, and aspect remain basically similar through time. Using ground truth slope information it was also determined that the sites are located on flat to gentle slopes throughout all cultural phases.

All of the cultural phases demonstrate that there was a tendency to locate sites on the southern edge of the lake. This preference is supported by the fact that a complete survey has been performed around the entire lake. The purpose for this southern location appears to be that this area is a transition zone that provided access to the marine resources of the lake as well as to the botanical and biological resources of the rainforest.

Most of the settlements were also located throughout all phases within two major life zones. Within these life zones the sites were located at elevations which range from 540 to 560 meters above sea level. Throughout all phases, sites were generally located on northern aspects, but these aspect orientations shifted slightly to provide a view toward Lake Arenal. As would be anticipated at most prehistoric sites in the Americas, the sites are located at relatively close distances to water. This distance provided access to potable water. The stability of site characteristics is also expressed by the fact that many site locations were occupied throughout different phases.

Like the ceramic, lithic, and pollen evidence, prehistoric site characteristics remained constant through time, suggesting the continued use of an adaptive strategy that utilized the available resources of the tropical rainforest environment. This stability is important for archeological research, for rarely is such stability seen that lasted for such millennia at other places around the world. The Arenal culture had lived for centuries within the limits of the resources that were available to them. This successful adaptive strategy to a delicate rainforest environment is a remarkable achievement in the course of human history.

CONCLUSIONS

The Arenal area in Costa Rica has experienced 10 major volcanic eruptions that have deposited ashfall layers upon the surrounding landscape. These ashfall layers have created a chronological record through time which have preserved the remains of the occupants who lived in the area throughout the volcanic sequence. Archeological survey and excavation has revealed that the Arenal area experienced five major phases of cultural occupation that ranged from the local Archaic to the time of Spanish Conquest. These phases have demonstrated a remarkable resiliency in surviving the concomitant effects of volcanic eruptions. These phases also demonstrate a unique stability in their adaptation to the resources of the tropical rainforest as evidenced by their continuing technological traditions and village site selections.

As a result of a cooperative research project between NASA, the National Science Foundation, and the University of Colorado, remote sensing analysis was incorporated into the research design of the Arenal area. This area represents one of the most difficult environments for the application of remote sensing technology. Heavy rainfall, dense vegetation, low population densities, and multiple layers of volcanic ashfall that buried archeological remains have left scant surface evidence for prehistoric activity. Despite these obstacles, remote sensing has detected a prehistoric pathway network that connected the Arenal occupants with cultural and natural features upon the landscape.

Several types of remote sensing data have been investigated to determine the optimum approach for the mapping of these prehistoric pathways. The most effective optical system was color infrared photography which was able to locate paths in the open grassland areas. The most effective digital system was the Thermal Infrared Multispectral Scanner (TIMS) which was able to locate path segments in the dense tropical forests. These linear features were verified through ground survey and excavation and revealed how the paths linked villages, resource areas, and cemeteries with one another. The paths demonstrated transportation and communication patterns in the tropical rainforest as well as the importance of ritual in prehistoric life.

The analysis of site characteristics employed a combination of GIS technology and field measurements.

The analysis revealed a consistency and stability that continued throughout all phases of Arenal prehistory. Although the settlement patterns changed in response to varying population densities through time, the site characteristics remained basically the same. This analysis demonstrated that sites were primarily located in a narrow, transitional life zone niche that provided the best access to the botanical, biological, and marine resources of the tropical rainforest. The sites face Lake Arenal and are located at similar elevations along this niche on flat to moderate slopes. The consistent village site characteristics mirror the ceramic and lithic technologies that generally remained unaltered throughout the cultural phases. Many of the sites were occupied through several phases providing supportive evidence that the Arenal populations employed an adaptive strategy that survived for several centuries.

Hypothesis testing has revealed that the linear features seen in the remotely sensed data could generally be separated from natural erosional features upon the landscape. From the ground, prehistoric paths, historic roads, and erosional drainages often look the same. The remotely sensed data indicated which linear features were connecting with cultural features upon the landscape. While cultural features can generally be separated from natural features in the imagery, excavation is required to separate historic features from prehistoric ones. Hypothesis testing has also demonstrated that the Arenal populations employed a consistent adaptive strategy throughout several phases of cultural occupation as indicated by unchanging village site characteristics and technological traditions.

A combination of archeological research, ethnographic analogy, and remote sensing analysis have contributed to an understanding of human adaptation in a tropical rainforest environment. This study has demonstrated that remote sensing research can be a valuable tool in locating information not available through traditional archeological feature detection techniques. It also has demonstrated that it can be used to support interpretations that are based on artifact analysis. In this era of rapid deforestation and destruction of tropical forests around the world, it is important that we understand how successful strategies can be employed that make use of the rainforest without destroying it. The use of remote sensing in environmental and archeological research may provide us with an insight into successful human adaptation in delicate rainforest economies at other places throughout the world.

CHAPTER 6

SUMMARY AND CONCLUSIONS

INTRODUCTION

This research project has investigated the impact of past human activity upon the prehistoric landscape. The overall goal of the investigation was to utilize remote sensing technology to generate data to assist in hypothesis testing in archeological research. New advances in remote sensing instrumentation, digital image processing, and statistical analyses have been employed to assist in the testing of the hypotheses. These remote sensing techniques provide archeologists with the ability to discover and retrieve information that is currently overlooked or unrecoverable through conventional survey and inventory techniques.

Specific objectives of this research were: 1) to demonstrate how archeological problems can be clarified with remotely sensed data; 2) to characterize those remote sensing data sources which hold potential for archeological investigations under different environmental and cultural conditions; 3) to isolate the appropriate analytical techniques for computer-implemented analysis of remotely sensed data; and 4) to demonstrate the value of remote sensing in providing information to the archeologist in a rapid, non-destructive, and cost-effective manner.

In order to achieve the overall goal and subsequent objectives of this research, two study areas were investigated that represent diverse environmental, temporal, and cultural conditions. These study areas are Chaco Canyon, New Mexico and Arenal, Costa Rica. Several hypotheses were tested in these areas that address specific questions regarding human behavior, environmental adaptation, and social integration. The results of the hypotheses that were tested in these study areas will be discussed below.

BACKGROUND

Understanding the relationships between cultural and physical systems have been investigated by many research specialists (Adams 1981; Binford 1962; Butzer 1982; Clarke 1977; Willey 1953). In order to understand the dynamics of prehistoric man-land relationships, it is important that archeologists know the conditions of the ancient landscape, the resources that were available, the settlements, the transportation and communication systems, and other features that were indicative of cultural activity. Traditional techniques that have collected this data have been expensive and time-consuming. These techniques are gradually becoming inefficient in keeping pace with the accelerating trends in land-use changes that are occurring due to urban expansion, agricultural development, and renewable and non-renewable resource production.

The strategies that have been employed by archeologists for survey and inventory vary from region to region and have resulted in non-systematic, incomparable, and non-intensive resource inventories. New techniques must be developed that can improve the traditional data gathering and analysis procedures. Remote sensing is a technique that can be employed by archeologists to meet the challenges of the 1990's. Although remote sensing is still in the developmental stage, it is a technology that is capable of providing accurate and cost-effective information for archeological research.

REMOTE SENSING

Remote sensing is the study of information using a sensor that is acquired from a distance. The data can be acquired in wavelengths that are both visible and invisible to the human eye. The information is acquired through detectors that are sensitive to various frequencies of the electromagnetic spectrum. This spectrum is a space-time continuum of electric and magnetic wavelengths that extend from gamma waves on one end to radio waves on the other end. For general purposes, the electromagnetic spectrum has been arbitrarily divided into the ultraviolet, visible, near infrared, thermal infrared, and microwave regions. The detection, recording, analysis, and interpretation of electromagnetic energy are the basis of remote sensing technology.

AERIAL PHOTOGRAPHY

Photography is an analog technique in which light sensitive film is chemically processed to produce images that are visible to the human eye. Photography is a versatile means of providing detailed images of land surface composition in an inexpensive manner. The film-types commonly used in remote sensing are black and white negative, color negative, color positive, and color infrared positive. Each of these film types have their particular attributes and processing techniques. Understanding the capabilities and limitations of each film type is essential for a researcher so that a film type can be selected that will best record particular archeological surface information. Through skillful photographic interpretation, potential archeological features recorded in the aerial photography can be distinguished from contemporary features. The potential archeological features, however, must be verified through field survey and excavation. Although several types of film were acquired over the study areas, this investigation has relied primarily upon color infrared photography for its photographic interpretation.

DIGITAL DATA

Many remotely sensed images are acquired through scanner systems that record the data in a digital, or numeric format. These data are processed electronically through the use of computer systems and result in a photographic-like image. Multispectral digital images are produced from remote sensing instruments that measure spectrally and spatially defined electromagnetic radiation. As a result, a feature on the ground surface can be recorded simultaneously in the ultraviolet, visible, infrared, or microwave portions of the spectrum. A particular range of the spectrum, or a combination of spectrum ranges (multispectral) can be employed to isolate specific features of interest on the earth's surface. The remote sensing instruments that acquire this information can be mounted on satellites, spacecraft, airplanes, balloons, and on ground-level platforms. This investigation used a combination of remote sensing information including Multispectral Scanner (MSS) and Thematic Mapper (TM) satellite data; airborne Thematic Mapper Simulator (TMS), Calibrated Airborne Multispectral Scanner (CAMS), Thermal Infrared Multispectral Scanner (TIMS), Lidar, and Radar data; and digitized ancillary map information.

Remotely sensed data are analyzed through multivariate numerical techniques and computer machine processing. The data can also be visually interpreted using conventional techniques employed in photographic interpretation. Both visual interpretation and digital analysis techniques were used in this study for remote sensing data gathered over Chaco Canyon and Costa Rica.

Digital data can also be used as input into a Geographic Information System (GIS). A GIS is designed to record, organize, analyze, and display spatial information layers that are registered to each other in a common coordinate system. Remotely sensed data as well as map information can be incorporated into a GIS. Map data can include information such as soil types, elevation, slope, aspect, rainfall, hydrology, and site locations. A GIS was constructed for the Arenal Area in Costa Rica and was used in the course of this investigation.

DIGITAL SENSOR SYSTEMS

A number of technological developments in sensor technology have occurred since the launch of Landsat, the first orbiting multispectral scanner system, in July of 1972. To date, five Landsat satellites have been launched. The first three carried the Multispectral Scanner System (MSS) which acquired data at 79 meter resolution in four spectral bandwidths. The last two Landsat satellites have added a new sensor to their MSS capability. This sensor is the Thematic Mapper (TM) and offers improved spectral and spatial resolution with its

30 meter resolution and 7 spectral bandwidths. Currently, only Landsat 5 is operational. The French satellite SPOT is also operational and records information at 20 meter resolution in three multispectral bands, and 10 meter resolution in the visible panchromatic band. Several new satellite systems have been developed worldwide and are scheduled for launch in the near future.

Many airborne scanner systems are available for remote sensing investigations. This study has used state-of-the-art airborne scanner systems that have been developed by NASA over the last decade. These systems include the TMS, TIMS, CAMS, L-band Radar, and the Airborne Oceanographic Lidar (AOL). As discussed in Chapter 3, each of these sensors have unique characteristics and were designed to record information in various bandwidths of the electromagnetic spectrum. These instruments can be used to detect subsurface features. In many case subsurface features are expressed on the surface through variations in soil moisture, plant vigor, and temperature differences even though these phenomena are not visible to the naked eye. The use of some of these data sources which can record information invisible to the human eye is illustrated below.

CIR photography records information in the infrared portion of the electromagnetic spectrum. The three dye layers in the CIR film--yellow, magenta, and cyan produce a "false color" image composed of blue, green, and red. Since the chlorophyllic layers of live vegetation reflect strongly in the infrared region, healthy vegetation appears as red. Buried features such as irrigation ditches, trenches, and refuse pits often contribute to the growth of healthy vegetation and make these features visible in the CIR photography as "positive" crop marks. Other features such as buried walls, stockades, or paved-roads, inhibit plant growth and thus the features appear as "negative" crop marks in the CIR photography in contrast to the surrounding healthier vegetation.

The TIMS records digital information in the thermal infrared portion of the spectrum and can detect buried features as a result of temperature and emissivity differences on the surface. Emissivity is the rate at which a material releases its energy and is a function of the type of material and its surface geometry. The TIMS records information in six narrow thermal bands and can achieve a sensitivity of less than a tenth of a degree Centigrade (Palluconi and Meeks 1985:5). The temperatures at the surface and subsurface are in a constant state of exchange. Thus, subsurface features can affect temperature and emissivity at the surface as a result of soil moisture, material composition, and variations in plant growth. In this way buried features can be recorded by the TIMS that are not visible either to the naked eye or to any type of aerial photography.

The CAMS is a 9 channel digital device which records information in the visible, infrared, and thermal infrared portions of the spectrum. The CAMS is not as sensitive in the thermal region as the TIMS. However, the far-ranging bandwidths of the CAMS can be used to detect subsurface features which manifest themselves on the surface in one of more of the bands.

Radar (Radio Detection and Ranging) is an active system that can be used day or night and can penetrate through clouds. Radar used microwave energy rather than light energy to image the earth's surface. Radars release short powerful bursts of energy that strike a target and are reflected back to a receiving antenna. This returned energy can be displayed as an image. The radar signal is affected by the surface roughness, angle of incidence, and the polarization of the received signal. In general, natural features tend to spead (backscatter) the energy while cultural features tend to reflect strong signals back to the antenna. In this way the linear and curvilinear features of cultural phenomena stand out against the natural terrain.

REMOTE SENSING IN ARCHEOLOGICAL RESEARCH

Simultaneous developments in the fields of photography, aviation, and archeology have contributed to the application of remote sensing techniques in archeological research. The two earliest archeological applications used cameras mounted in unmanned balloons to record the ruins near Agra, India, in 1891 and Stonehenge, England, in 1907. Several early investigators including Sir Leonard Wooley, T.E. Lawrence, and Captain S.F. Newcombe used an aircraft for archeological reconnaissance during the 1914 Sinai expedition (Garnett 1938). World War I, however, accelerated the development of sophisticated camera systems, sensitive films, and photographic techniques. Archeology was one of the first disciplines to apply this technology to scientific investigations. Many archeologists had been drafted into service by the English, French, and German armies because of their skills as pilots and photointerpreters (Deuel 1969).

Several of these archeological investigators, such as G.A. Beazeley and O.G.S. Crawford, were shot down and captured as they conducted military and archeological reconnaissance. Crawford would eventually become one of the most prominent figures in photointerpretation. John L. Myres, an Oxford archeologist, directed the Allied bombardment of the house of German archeologist, Theodor Wiengand and the surrounding structures at Didyma. Years later it was revealed that Myres had warned Wiengand prior to the attack to move his camp away from the nearby Apollo temple where Wiengand was conducting excavations (Watzinger 1944). Wiengand followed the warning and thus the archeological ruins were preserved. These examples illustrate the courage, cooperation, and vision of the many archeologists at the turn of the century, who remain the true pioneers of remote sensing/archeological research.

American interest in using aerial photography in archeology began after World War I. Although several investigators preceded him, it was Charles Lindbergh who championed the use of aerial reconnaissance for American archeologists. Working with A.V. Kidder, Lindbergh acquired photography over archeological sites in the American southwest and on the Yucatan Peninsula (Ricketson and Kidder 1930). Following the success of these investigations, there were hundreds of flights flown throughout the Americas for archeological projects. The development of color infrared film (CIR) during World War II, expanded the interest for the use of aerial photography in archeological research. An excellent example of the use of CIR is that of Kent Flannery who used it to reconstruct the microenvironments of the Tehuacan Valley (Flannery 1968).

With the launch of the first Landsat satellite in 1972, archeology entered the era of digital analysis and space technology. The "new archeology" (Binford 1964) and use of statistics (Thomas 1969) facilitated the adoption of digital remote sensing technology. At first, the spatial and spectral limitations of the MSS satellite sensor precluded significant contributions for archeological research. Archeological features such as walls, roads, canals, campsites, stockades, and refuse piles were simply too small to be recorded. The MSS, however, was capable of providing sufficient data for ethnographic research as demonstrated by Reining's (1973) study of agrarian systems of the Niger and Upper Volta, and Fanaie's (1974) research of the Dogon in Mali.

The Chaco Center was formed in the early 1970's to investigate the use of remote sensing for archeological applications. This Center was a joint project of the National Park Service and the University of New Mexico that investigated a number of remote sensing approaches and analysis techniques. The objectives of their research included optical-digital comparison, atmospheric corrections, photogrammetric mapping, ground based instrumentation, and data rectification. Although the Chaco Center is no longer in operation, it provided significant results that were important for later research projects.

Remote sensing technology developed dramatically in the 1980's as a result of NASA's research in space technology. Many of the airborne instruments were now capable of acquiring data at resolutions that could record archeological features. Parallel to this development were the new advances in image analysis. Miller (1981) located 3 extinct towns in Mississippi through vegetation species in CIR photography. Another study (Carstens et al. 1982) located prehistoric features in Kentucky. One of the most dramatic applications, however, was the detection of Maya ridged-field systems in Belize (Adams, Brown, and Culbert 1981) using airborne radar data. Although there has been recent criticism of this project (Dahlin and Pope n.d.), it provided dramatic news for archeological research and received a substantial amount of positive publicity.

The incorporation of remote sensing technology into anthropological research designs was stimulated by two conferences which brought together leading investigators to learn of the most current NASA technology. The first conference was held in 1984 at NASA's National Space Technology Laboratories (currently Stennis Space Center) in Mississippi. The conference brought together twenty-two leading archeologists who represented the major anthropological institutions. The results of the conference were published (Sever and Wiseman 1985) and contain a discussion of the capabilities of remote sensing as well as some of the major anthropological concerns regarding its application. An outcome of this conference was the selection of Payson Sheet's project in Costa Rica as a demonstration of cooperative research between NASA and the professional archeological community. Another conference was held in 1987 at the University of Colorado which discussed the cultural and ecological applications of remote sensing technology (Shankman et al. 1987). An outcome of this conference was NASA support for Dr. David Wilke's research of the pygmy in central Africa and Dr. Cliff Beherns research among the Shivaro in Peru.

CHACO CANYON

This study has investigated prehistoric roads in Chaco Canyon, New Mexico, that were built by the Anasazi in the 10th and 11th centuries A.D. The objective of the research was to determine the function of the roadway system. As shall be presented below, several hypotheses were developed and tested in order to achieve this objective. Previous and current archeological and remote sensing research has been reviewed with the resultant archeological interpretations used as input for hypothesis development. New techniques in digital airborne remote sensing analysis have been combined with photographic interpretation in order to map the prehistoric roadway network. Knowing the extent and linkages of the roadway system are a crucial component in understanding its function. Finally, ethnographic evidence has been investigated to determine if there are cultural analogies in the area that can provide an insight to the function of the prehistoric roadway system.

The prehistoric roads are generally not visible from ground level even though they can be detected as linear features in aerial imagery. The roads manifest themselves not as complete end-to-end constructions but rather as a system of brief road segments. Erosion has destroyed and buried many portions of the roadway system. Many of the road segments that were visible in photography acquired by Charles Lindbergh in 1929 photography are not visible in contemporary photography due to overgrazing practices of the 1930's and 1940's. Greater architectural effort was placed along the roads that are near the great houses and outlier communities and less effort was placed on the roads as they cross barren expanses. Since the Anasazi did not have the wheel nor beasts of burden, the purpose for the roadway's straight course and consistent 9 meter width is not known. Through the development and testing of several hypotheses, this research has arrived at the most likely function of the Anasazi roadway system.

Chaco Canyon is located in the San Juan Basin at the northwest corner of New Mexico. The Canyon is bisected by the Chaco River which is dry for most of the year. Rainfall in the area averages 6 to 15 inches per year with most of it falling in the months of July and August. Mean annual temperatures range from 47-60 degrees Fahrenheit (Bryan 1954). The Canyon is oriented east-west and is the only area in the region which contains sufficient alluvial soil for agriculture (Vivian and Mathews 1965). Although desert conditions exist today, it appears that prehistorically there was abundant timber as well as sufficient floral and faunal resources to support significant human populations (Vivian and Mathews 1965:7).

Chaco Canyon is a major scientific and archeological resource containing a relatively complete record of human occupation in an ecologically well-defined area. PaleoIndian occupation can be traced back to 10,000 B.C. The Archaic phase occurred between 5,500 B.C. and A.D. 450 (National Park Service 1980:2) and demonstrates a change from mega-fauna hunting to a subsistence of small game hunting and wild plant collection. Maize was domesticated in the area between 3400-1000 B.C. with the development of the Anasazi culture occurring between 1000 B.C. and A.D. 1. A number of different chronologies have been presented for Anasazi development by various investigators. While these chronologies vary in their dates, they do show a consistent architectural development from small pit houses to spacious, multi-storied pueblos. The highlight of this development is the "Chaco Phenomenon" which occurred between A.D. 1040 and 1200. By this time the inhabitants of Chaco Canyon appear to have gained control over the social, economic, and political system of the entire San Juan Basin.

It was during this phase that the major engineering and architectural accomplishments occurred including the nine "great houses", the "great kivas", and the roadway construction. The roads appear to be architectural manifestations of the great houses and great kivas. For unknown reasons, the monumental accomplishments of the Pueblo III phase came to an abrupt halt in the 12th century. The area appears to have been abandoned for a brief time before being repopulated by the Navajo and Apache.

CHACO ROADS

Systematic investigations of the prehistoric roads in Chaco Canyon did not begin until the early 1970's, although there have been references to the roads by Spanish chroniclers and American survey parties. S.J. Holsinger, an agent for the U.S. Government Land Office, was the first to record the existence of the roads while investigating the homesteading claims of Richard and Marietta Wetherill (Holsinger 1901:67-68). Portions of the roads were also documented by several archeologists such as Earl Morris (1915:666), J. Walter Fewkes (1917:15), and Neil Judd (1954:346). It was the energy crisis of the 1970's, however, which provided the impetus for expanded research in Chaco Canyon, including studies relating to the prehistoric roadway system.

The National Park Service, Eastern New Mexico University, and the Bureau of Land Management conducted significant research in the detection, mapping, and analysis of the Anasazi roadway system. Their remote sensing research was based on aerial photography and their photointerpretation results were substantiated through excavation. The investigation results were factored into the research designs of other archeological studies concerned with explaining the function of the Chacoan Roadway network. Several models were developed and tested with the general interpretation being that the roads were part of a redistribution system that had Chaco Canyon as the center (Judge et al. 1981). This interpretation was reversed after new data revealed that the population estimates in Chaco were much lower than previously calculated and that the known extent of the roadway network was 10 times larger than ever anticipated (Lekson et al. 1988).

ROADWAY CHARACTERISTICS

Five major roadways have been described and verified in this research using photographic interpretation and airborne digital sensor analysis. These roadways are the: Great North Road, South Road, Ah-Shi-Sle-Pah to Penasco Blanco Road, East Road, and Coyote Canyon Road. This investigation has verified a number of road segments that have been previously recorded from aerial photography and has identified and located a number of roadway segments that have not been previously mapped. Several image processing techniques were investigated in order to extract the roadway segments from the digital imagery. One of the most successful of these techniques was statistical filtering which can extract a larger number of lineaments from the imagery than is visible in the raw data (Podwysocki et al. 1975).

The prehistoric Chacoan roads have unique characteristics which help in separating them from other historic and contemporary features. The most common feature is their straight linear course which is maintained in spite of topographic obstacles (Lyons 1973; Obenauf 1980a). Other characteristics include a 9 meter width and their association with stairways, causeways, ramps, roadcuts, border constructions, cairns, herraduras, and parallel routes. This investigation has extended the associations to include great houses, kivas, earthworks, topographic features, and natural features upon the landscape.

REMOTE SENSING RESULTS

Previous photointerpretation research had indicated that vegetation was the primary factor responsible for the appearance of the roadways in the photography. Low sun angle photography was particularly successful in recording these roadway lineaments. Most of the study area, however, does not contain vegetation surface cover. As a result, several airborne digital instruments were flown over Chaco Canyon (Table 4-1) in an attempt to verify known roadway segments and detect unknown roadway segments.

Final analysis shows that the TIMS instrument recorded more prehistoric road segments than either the TMS or the CAMS. In fact, the TIMS recorded road segments that were not visible in the simultaneously acquired CIR photography. This investigation has filled in many missing gaps along known roadway routes and has located many additional linear anomalies whose characteristics suggest that they are prehistoric roads. These features, however, have not been verified by ground excavation. Many parallel segments were found in association with verified road patterns which are rarely seen from ground level and seldom seen in the aerial photography. In summary, TIMS data was more successful in locating prehistoric road segments than either aerial photography or other airborne scanner systems.

HYPOTHESES TESTING

Several hypotheses were presented whose objectives were to determine whether the Chacoan roads served primarily an economic or religious function. The majority of the past research investigations had concluded that there was an economic explanation for the roadway system. Four hypotheses were developed to test whether the roads served an economic function. The conclusions that were drawn from these hypotheses are considered below.

1. If the prehistoric roads had an economic function then they would take the "path of least resistance" as they connected one place with another, resulting in curving or meandering patterns in areas of difficult terrain.

Evaluation: Although there are a few exceptions, the Chacoan roads are characteristically straight. As opposed to avoiding topographic obstacles, the Chacoan roads seem to include them in their route. Both modern-day roads and historic roads in the area curve around not only extreme topographic obstacles, but also around areas of subtle relief. The most efficient way to transport items through human labor is that which requires the least caloric effort. Morenon (1977b) conducted a study using a respirometer and determined that the roads were used for travel and the conveyance of light items. His conclusion was that the transportation of heavy items would minimize slope while that used for traveling would minimize distance. The straight Chacoan roads do not minimize slope and from my field experience I would argue that although the roads are carrying human traffic, they are economically inefficient for the transportation of heavy loads, light loads, or for mere traveling.

2. If the prehistoric roads had an economic function then they would incorporate greater constructional effort in making travel easier at difficult places, i.e. areas of steep slope, than in areas of flat or level relief.

Evaluation: If Chaco Canyon served as a center for redistribution it would be expected that items would be moved throughout the roadway system and that slope would be minimized. From an economic perspective, ramps would have been more efficient in the transportation of goods, yet where the roads enter and exit the Canyon, stairways are generally found. The roads make no attempt to avoid loose sediments or incorporate areas of hard surface which would have provided more secure and efficient footing. The maintenance of a consistent 9 meter width serves no apparent economic function nor is there any archeological evidence that goods were being transported along the roads in the first place. Ironically, the greatest constructional effort takes place upon flat areas near the great houses rather than in areas where construction would have improved economic efficiency.

3. If the prehistoric roads had an economic function then they would have by-passed and avoided areas of high topographic relief.

Evaluation: By-passing areas of steep topographic relief such as pinnacles or steep uplifts would be more efficient for both walking and for the transportation of goods. TIMS imagery and ground reconnaissance, however, reveal that the roads are often making slight, dog-leg turns to include these elevated areas into their course, thus sacrificing the factor of straightness. This design is not economically profitable since it involves greater expenditure in time, distance, and construction. The inclusion of these topographic features also suggest that the roads were surveyed and laid-out prior to construction.

4. If the prehistoric roads served an economic function, then they would have provided linkage to Chaco Canyon for the storage and redistribution of goods.

Evaluation: The fact that the roadways lead into Chaco Canyon from distant locations surrounding the Canyon and lead to large-room suites suggest the concept of redistribution. In fact, many versions of redistribution have been presented and were supported by the original population estimates which envisioned thousands of residents at the great houses. Recent research and excavation (Windes 1987; Lekson et al. 1988) have dramatically lowered these estimates. At Pueblo Alto, for instance, Windes (1987) found that of 85 rooms, only 5 were used for habitation. Similar patterns of low population were found throughout all the other great houses. The extent of the roadway system that is currently known and the number of Phase III structures on the periphery of the Canyon now demonstrate that this vast domain would not be efficient in a redistribution system (Lekson et al. 1988:109).

Original speculation by previous investigators had predicted that the roads connected to outlier sites, suggesting an economic link between them and the Canyon. This investigation has determined that only the North and South Roads have been confirmed to connect to outlier sites. Even then the evidence is uncertain for the North Road continues beyond the outlier site of Pierre's Ruin and ends at Kutz Canyon while the termination of the South Road remains unknown.

Two hypotheses were also developed to explore whether or not the Chacoan roads served a religious function rather than an economic one. The test results of these hypotheses are discussed below.

1. If the prehistoric roads served a religious function then they would have connected to a major center of ritual activity (Chaco Canyon) where they would have been associated with religious features such as shrines, kivas, great houses, and ceremonial ceramic breakage.

Evaluation: Evidence of ritual activity has been documented by location of shrines and effigy figures found near the roads such as that found at Pueblo Alto (Holsinger 1901:68). The original function of Pueblo

Alto, located high on the north mesa, may have been to interface with a shrine communication system (Hayes and Windes 1975; Toll and McKenna 1983). Five structures that resemble historic Pueblo shrines are found on the North Road near Pierre's Complex. Many small, remote, elevated structures such as the horseshoe-shaped herraduras are consistently located on major topographic breaks along the course of the roadways. The location of shrine-like topographic features have aroused an interest in communication and signalling systems (Hayes and Windes 1975:143-156; Drager 1976; Robertson 1981). These features have cultural analogues in Southwestern culture (Cushing 1967; Parsons 1939; White 1932). The Chacoan roadway system is reminiscent of the Inca Ceque system in Peru which was composed of 41 straight lines with 328 shrines located along their course and was used for recording superimposed cycles of ritual events (Zuidema 1977).

The Anasazi roads are also directly associated with the great houses which are in turn associated with kivas, great kivas, and earthworks. The kivas were underground chambers that were used for ritual activity. The great kiva is an elaboration of the kiva and there are 18 great kivas in Chaco that are associated with the great houses and earthworks. The earthworks demonstrate that they were formed from ceremonial ceramic breakage (Lekson et al. 1988) and that a large volume of earthwork material was deliberately placed rather than haphazardly discarded (BLM 1987:15). The ceramic materials in the earthworks appear to have been deposited intermittently suggesting seasonal occupation. The earthworks are also devoid of normal midden materials that would reflect daily occupation. Ceremonial ceramic breakage also occurs along the roadways, particularly at the crests of ridges and hills. These features are generally 20 meters wide and up to 400 meters long (John Roney, personal communication, 1989). Ceremonial ceramic breakage is often associated with rituals relating to the dead in Southwestern cultures (Parsons 1939:72-77) and in Costa Rica (Sheets et al. n.d.). Linear grooves embedded into the bedrock at the borders of the prehistoric roads are reflective of the grooves used in healing ceremonies in Pueblo ritual (Parsons 1939:339).

Chaco Canyon may also have been perceived as being a "central place" to the Anasazi and the roads may have connected sacred features upon the landscape. The concept of central place figures prominently in Pueblo cosmology (Parsons 1939; Williamson 1984:65) and the physical landscape is an important aspect of emergence myths (Ladd 1983; Stephen 1936; Stirling 1942). In summary, there is ample evidence from the remote sensing data, archeological features, and ethnographic analogies to suggest that the roads are associated with religious features and ceremonial activity.

> 2. If the prehistoric roads served a religious function then they would incorporate elevated areas of topographic relief into their course such as pinnacles, mesa tops, or other observational areas, and they will be associated with ritualistic concepts such as directional symbolism, orientation, and astronomy; i.e., they continue on their predetermined course in spite of topographic obstacles.

Evaluation: At first glance, the prehistoric roads appear to be more linear than they are in actuality. The remotely sensed data, however, reveal that the roads are making minor deviations to include topographic features into their trajectory. This construction is economically inefficient. The inclusion of topographic features suggests a religious purpose when they are compared to ethnographic analogues in Southwestern culture. These analogies demonstrate the importance of topographic features in Pueblo ceremony (Cushing 1967; Ortiz 1969; McCluskey 1977; Williamson 1984:67; Horgan 1971:37). Astronomy is another important aspect of Pueblo ritual (Ellis 1975; Parsons 1939; Cushing 1967) and there are a number of Anasazi astronomical features associated with the roadways (Sofaer et al. 1979; Reyman 1971; Williamson 1984). Astronomy is also related to directional symbolism and this is apparent in both Pueblo ritual (Dozier 1970:207; Parsons 1939:362; Roberts 1930:156; Reyman 1971; Cushing 1967) and in Chacoan architecture (Williamson 1984:135-136; Reyman 1971). Not only is directional symbolism apparent in Chacoan structures such as kivas (Williamson 1984; Reyman 1971;), it is also a primary consideration in the entire North Road alignment which may be a cosmographic Anasazi expression (Sofaer et al. 1986).

SUMMARY OF CHACOAN RESEARCH

Remote sensing analysis has made significant contributions to the mapping of prehistoric roads in Chaco Canyon. This information has been incorporated into hypotheses testing to determine whether the prehistoric roadway system served primarily an economic or religious function. Various hypotheses have been developed to determine the function of the roadway system. After testing these hypotheses the conclusion has been reached that these constructional features served a religious function and that they were economically inefficient. The roads are associated with features of ceremonial activity. They connected Chaco Canyon, a central place, to sacred features upon the landscape and they were used to integrate settlements throughout the San Juan Basin and beyond into Anasazi society.

COSTA RICA

This study has investigated prehistoric social integration and human adaptation in the tropical rainforest of northwestern Costa Rica. A sequence of ten volcanic eruptions in the area have buried and preserved the artifacts of several phases of human occupation in an environment that is notorious for decomposition and decay. Two objectives have been achieved in this investigation. The first objective has determined that linear anomalies seen in remotely sensed imagery are indicative of prehistoric footpaths that were created by human traffic and preserved through erosional and depositional processes. The second objective has determined that prehistoric site characteristics essentially remained intact throughout the course of several millennia, indicating a stability in human adaptation strategies throughout a cycle of cataclysmic events.

The Arenal study area is located in northwestern Costa Rica and is dominated by a volcanic ridge which runs in a northwest to southeast direction along the Continental Divide. Volcan Arenal is located near this ridge and has erupted nine times in the past 4,000 years depositing successive layers of ashfall upon the landscape. Arenal's first eruption occurred about 2,000 B.C. The year-round wind direction from the northeast has blown the ashfall material toward the western side of Volcan Arenal throughout all eruptions.

Typical of most rainforest environments, the Arenal study area maintains a rather constant temperature throughout the year. Seasonality is determined by rainfall amounts which divide the year into "dry" and "wet" seasons. The area is rich in biological and botanical diversity, providing prehistoric inhabitants with a wealth of edible resources. Most of the soils in the area (93%) were formed by the weathering of volcanic ash. This weathering process resulted in soils that were more fertile than those normally present in rainforest environments.

Archeological survey and excavation have revealed that Lake Arenal was a prominent feature in settlement patterns throughout all phases of prehistoric cultural occupation. The current lake has been altered by dam construction in 1980, but the prehistoric lake was a shallow feature that provided a number of resources to the inhabitants. The lake is surrounded by rolling hills that ascend to a mountainous landscape. The rapid rise in elevation provides a number of environmental niches or life zones, each of which contains unique botanical and biological resources. Most prehistoric settlements were located on the south side of Lake Arenal along a transition zone between lake and the high forest resources.

Although archeological research has been conducted in northwest Costa Rica since the turn of the century (Hartman 1907; Lothrop 1926; Willey 1971; Snarskis 1981; Lange 1984), research in the Arenal area has only recently been conducted (Metcalf n.d.; Aguilar 1984). The most intensive of these projects was the "Proyecto Prehistorico Arenal" beginning in 1983. This was an interdisciplinary project funded by the National Science Foundation and the National Geographic Society. NASA provided remote sensing support to the project since 1985 and has acquired a number of satellite and airborne data sets for analysis. This research investigation has analyzed various types of remote sensing and ancillary data information in order to determine which data types hold the greatest potential for archeological analysis in a tropical forest environment.

REMOTE SENSING

The rainforest environment in the Arenal study area offers many challenges to remote sensing research. Prehistoric population levels were low in all phases and thus the impact upon the landscape was slight. Although they have aided in preservation and dating, the sequence of 10 volcanic eruptions have repeatedly buried the surface evidence of the cultural landscapes. Prevalent cloud conditions and high amounts of rainfall hinder data acquisition both from planes and satellites. Finally, the dense forest canopy and rich tropical vegetation make it difficult to determine the location of remote sensing anomalies from ground level.

As a result of a cooperative agreement between NASA, the National Science Foundation, and the University of Colorado, assistance was provided by NASA to determine the utility of remote sensing in archeological research. Several types of remotely sensed data have been acquired and analyzed. These data include aerial photography, Lidar, Radar, and TIMS imagery. The most dramatic outcome of this research has been the detection of prehistoric footpaths in the imagery that were used during the end of the Arenal Phase and for most of the Silencio Phase. These footpaths were subsequently buried by volcanic eruptions and erosional processes. The footpaths allow us to walk in the steps of the prehistoric occupants and thus provide us with an insight into their daily activities.

Since a large number of linear anomalies were seen in several types of remotely sensed data, a hypothesis was developed to test whether linear features seen in the remotely sensed imagery were prehistoric footpaths or the effects of erosional processes. This hypothesis stated that:

> if the linear patterns in the remotely sensed data are prehistoric footpaths, then they will connect localities that are of a cultural nature. Specifically, the paths will demonstrate a linkage system between resources, villages, and other cultural areas.

Evaluation: Examination of the various types of remotely sensed data indicated that CIR photography was the best medium for detecting ancient footpaths in open, grassland areas and the TIMS imagery was the best for locating footpaths in heavily forested areas. In the CIR the footpaths show up as positive crop marks. From ground level they can be seen as linear depressions that become incised in proportion to the degree of slope. On flat areas the paths are often not visible from ground level. The paths can be seen connecting cultural features such as villages sites, cemeteries, springs, storage areas, and manufacturing areas. They can often be separated from geological or erosional processes which are formed in relationship to the physical dynamics of gravity and slope. As opposed to erosional gulleys which flow off perpendicular to ridge tops, prehistoric path depressions can be seen parallel to and along the middle of ridgetops. In addition, erosional features do not tend to repeatedly link cultural features with each other. The atypical pattern of linear anomalies and their relationship with cultural features proved to be key indicators in determining path locations. Although they have not been verified from excavation, linear anomalies in the TIMS imagery have been identified as being potential prehistoric pathways. This is based on circumstantial evidence which shows linear anomalies in the forest regions linking directly with known pathways in the CIR.

The prehistoric footpaths tends to remain relatively straight and are generally located along ridgetops rather than meandering around and avoiding topographic obstacles. Occasional parallel segments and looping segments also occur in relationship to the footpaths. The pathway linearity along ridgetops demonstrates that the prehistoric inhabitants were avoiding low-lying, swampy terrain. The parallel segments reveals that paths were abandoned in some locations after they had worn down to the slippery clay surface. Looping segments occur on steep slopes and suggest that they were used to carry heavy loads or that they helped the aged and infirmed to negotiate the steep hillside.

The importance of excavation, however, for final verification of pathway locations is demonstrated by the fact that some of the linear anomalies turned out to be recent and historical roads rather than prehistoric paths. These features look similar in the remotely sensed data and from ground level. Only excavation was able to identify their time of use by the location of each particular feature in the stratigraphic profile.

FOOTPATH FORMATION AND FUNCTION

The footpaths were formed initially by human traffic which destroyed the surface vegetation and produced a natural conduit for water run-off from the frequent rains. Erosion formed a U-shaped indentation for the path itself which is generally only about 30 centimeters wide. The banks of the path, however, continued their rapid erosion and formed a V-shaped indentation that is often 10 meters wide at the present surface. This deep, V-shaped trench would have remained intact and erosion would have continued had it not been for the deposition of several ashfall layers which served to fill the depression.

The footpaths were used to link the inhabitants with cultural and natural features upon the landscape. Footpaths have been found connecting villages with cemeteries, cemeteries with storage areas, and cemeteries with springs. Attempts were made to quantify the use of prehistoric footpaths, but analysis results reveal that there are too many variables in the data that are not being sufficiently controlled by a sample of 38 trenches. The greatest amount of footpath use was discovered near the Silencio Phase cemetery, which correlates with artifactual evidence that the cemetery was an area of intense activity and that visitors stayed in the area for extensive lengths of time. The footpath network demonstrates that in addition to communication and transportation functions, the footpaths served to integrate Arenal society through religion and ritual. Ethnographic analogies among the Cuna (Dillon 1984) demonstrate the relationship and importance of cemeteries and footpaths to the religious activities of a tropical forest society.

PREHISTORIC SITE CHARACTERISTICS

The ceramic and lithic evidence throughout all phases of occupation indicates a continuing stability in human adaptation in the Arenal area. It was felt that there was a relationship between technological adaptation and site characteristics. For instance, if a culture shifted from a hunting and gathering subsistence to agriculture, this would be reflected in their lithic technology. One would find hoes, manos, and metates in the agricultural period that were non-existent during the hunting and gathering period. Similarly, site characteristics would also shift as village locations were altered to adjust to an agricultural environment.

A Geographic Information System (GIS) was developed over the Arenal area that included landcover, elevation, slope, distance to drainage, site locations, aspect, and life zones. The GIS was used to assist in testing the hypothesis that:

> If the adaptive strategy to the rainforest environment was similar throughout all phases of cultural occupation, then the archeological materials will be similar through time. Specifically, the ceramic and lithic traditions will be similar if the variables of site locations are similar.

Evaluation: Using a combination of GIS technology, field information, and statistical testing (ANOVA) it was demonstrated that village site characteristics did not significantly change throughout all phases of cultural occupation. Although population levels significantly fluctuated and settlement patterns changed, sites' characteristics remained relatively intact. Prehistoric occupants preferred living near permanent streams, at a transitional life zone on the southern side of Lake Arenal, on aspects that faced the Lake, and did not show a dramatic shift from one soil type to another. Oxidation measurements for the soils within the paths show that the area was heavily forested throughout prehistoric occupation. This collaborates with the evidence that there was never a reliance on a staple crop and major land clearing techniques were not used. Like the ceramic and lithic traditions that remained essentially constant through time, site characteristics remained unchanged. The Arenal occupants had developed a successful adaptive strategy to the rainforest environment that was passed from one generation to the next, despite numerous volcanic eruptions from Volcan Arenal.

SUMMARY OF COSTA RICAN RESEARCH

Remote sensing and GIS analysis have made significant contributions to understanding social integration and human adaptation in a tropical rainforest environment. Despite the limiting physical and cultural obstacles presented by a wet, tropical forest environment to remote sensing technology, this study has demonstrated remote sensing can be a valuable tool in providing information not readily apparent through traditional archeological techniques. Analysis results indicate that the prehistoric inhabitants in Arenal successfully adapted to the diverse, but delicate, resources of a rainforest economy. Through the mapping of the prehistoric footpath network, we have gained an insight as to how the prehistoric inhabitants negotiated the terrain and what features of the landscape figured prominently into their daily lives. From their unchanging traditions in lithics and ceramics, as well as their continuing preference in village site characteristics, we have seen a remarkable stability in environmental adaptation and a resiliency in recovering from cataclysmic events.

EVALUATION OF REMOTELY SENSED DATA TYPES

This investigation has analyzed several different types of remotely sensed data. The following discussion evaluates the utility of each remotely sensed data type that were employed either in Chaco Canyon, New Mexico or Arenal, Costa Rica. This discussion presents an evaluation of the advantages and disadvantages of the data types used in this investigation. The reader is reminded that instruments and analytical techniques that are currently being developed through remote sensing research will provide archeologists with even more effective tools in the future.

Black and White Aerial Photography

Black and white aerial photography still represents one of the most effective mediums for remote sensing analysis. Black and white aerial photography provides high resolution and detail. It is inexpensive when compared to digital imagery and can be flown more or less at the discretion of the investigator. An investigator has greater latitude in scheduling time of day or time of year for data acquisition than he has for digital data. This is because there are more aircraft available for photographic missions than aircraft modified to hold the electronics and instrumentation of scanner systems. Finally, black and white aerial photography has been acquired for many decades and provides historic information that is particularly useful upon landscapes that have undergone severe natural and man-made alterations.

The data is limited in its visual range in that it records only what the human eye can see. While a person who is untrained in photointerpretation can see many features within the data there are many subtle features that can be easily overlooked. A short course in photographic interpretation or the reading of introductory books on the topic can be a profitable investment for the archeologist. It will not only improve the ability to discriminate features within the photography but assist in determining when to schedule data acquisition missions so that particular features of interest are recorded. For instance, research in Chaco Canyon has demonstrated that early morning, low sun-angle photography recorded prehistoric road segments better than photography acquired at noon.

CIR Photography

CIR photography is similar in its advantages and disadvantages to black and white photography with the exception that it is able to record information in the near infrared portion of the spectrum. CIR photography is especially useful in recording features upon landscapes covered in vegetation. Often these features are not visible to the naked-eye. CIR photography is more expensive to process than black and white photography but in areas covered in vegetation the additional expense is worthwhile.

Although CIR photography did record some prehistoric Anasazi road segments it generally had limited use in the desert conditions of Chaco Canyon. In the tropical forest of Costa Rica, however, CIR photography represented the most effective medium for the detection of prehistoric footpaths in grassland and pastureland areas. The chlorophyllic layers of live vegetation reflected strongly in the infrared region and thus the footpaths appeared as red lineaments in the imagery. CIR photography is useful in archeological research because vegetation variations are sensitive to subsurface features such as soils, moisture, buried structures, and other man-made disturbances.

MSS and TM Satellite Data

MSS and TM satellite are digital data sources which are effective in the mapping of land areas. As opposed to aerial photography, digital data require computer hardware and software to process the data into meaningful information. These operations can take place either on mainframe or personal computers. The data is ordered from the EOSAT corporation and costs $3,200 a frame (100 miles X 100 miles). Hardware and software computer capability for digital processing at an effective minimal level can be purchased for about $20,000. Most universities, however, have remote sensing facilities or computers that can be modified for remote sensing analysis.

The advantage of MSS and TM satellite data is that it provides repetitious data (every 16 days) over the same area. After the initial hardware/software purchasing costs it provides cost-effective analysis capability. The disadvantage of the data is its resolution (80 meters for MSS and 30 meters for TM). Often this resolution is insufficient for the detection of many archeological features. TM data was unable to locate any evidence of prehistoric roads in Chaco Canyon nor prehistoric footpaths in Costa Rica. MSS and TM data, however, were effective in Costa Rica in mapping general environmental gradients, detecting rainforest variability, and tracing the volcanic impact of the 1968 Arenal eruption on the research area. Current competition by foreign markets and private industry in satellite technology will soon provide effective resolutions for archeological analysis (5-10 meters).

TMS DATA

Digital aircraft data is processed similar to satellite data. Many of the statistical and analytical techniques employed in digital satellite analysis are used in digital aircraft analysis. The TMS is a seven channel instrument that records information in the visible, near infrared, and thermal infrared portions of the electromagnetic spectrum. The TMS was flown over Chaco Canyon at 30 and 10 meter resolution and provided the first clue as to the detection of ancient roadways in the thermal infrared portion of the electromagnetic spectrum. The broad thermal band (band 7) was able to map roadway segments better than any of the six other visible and near infrared bands. The thermal band also mapped prehistoric road segments that were not visible on simultaneously acquired CIR photography.

The major advantages of digital aircraft data are that 1) they can be acquired at high resolutions since spatial resolution is a function of aircraft altitude, 2) they can be flown at different times of the day or year, 3) specific flight lines can be selected for data acquisition, 4) particular sensors or bandwidths can be selected to detect specific archeological targets, and 5) particular instructions in data recovery can be imparted to the pilot. These advantages are especially evident when compared to the orbiting satellites that acquire data at fixed-resolutions and fixed-paths, always at the same time of day, whether or not cloud conditions are favorable.

The foremost disadvantage for digital aircraft data in archeological research at this time is the cost. For example, the Lear jet at the Stennis Space Center costs $1950.00 per airtime hour. After reaching the study area an additional cost of $26.00 per flight line mile is added to handle the operation of the scanner and camera systems. After data acquisition, expensive costs can be incurred in data analysis. For example, georeferencing aircraft flight lines represents one of the most expensive items in data processing and can represent over 70% of the total data analysis cost.

TIMS Data

The TIMS records information in six narrow bandwidths in the thermal infrared portion of the electromagnetic spectrum. The TIMS was the most efficient instrument for detecting prehistoric roads in Chaco Canyon. The TIMS recorded road segments that were not visible in the simultaneously acquired CIR photography as well as segments that were not seen in previous black and white photography. Other archeological features such as buried walls, small sites, and an agricultural field were detected in the imagery.

In Costa Rica the TIMS appears to have detected prehistoric footpaths in the tropical forest along Lake Arenal. Although the lineaments in the TIMS imagery have not been verified through excavation, there are numerous connections of TIMS lineaments with confirmed footpaths in the CIR photography.

This investigation has determined that the thermal infrared region such as that recorded by the TIMS holds great potential for archeological research. The TIMS was superior than any other instrument in the detection of prehistoric roads in a desert environment and holds great potential for the detection of subtle features such as prehistoric footpaths in tropical forest environments. Remote sensing archeological research stands to gain substantially as new thermal instruments and thermal analysis techniques are developed in the future.

CAMS Data

CAMS data were acquired over the Chaco Canyon study site. The CAMS is a nine channel calibrated instrument that records information in the visible, near infrared, and thermal infrared portions of the spectrum. Unfortunately, the thermal channel on the CAMS was not working at the time of data acquisition so no conclusion was reached regarding its thermal infrared potential. Since the CAMS is a calibrated instrument, atmospheric corrections can be made during data processing to improve the quality of the data. Like CIR photography, the CAMS recorded prehistoric road segments in areas that had vegetation cover, but was less effective in bare soil or sand areas. Since the CAMS was not flown in Costa Rica no conclusion can be reached regarding its utility in tropical forest regions.

Radar Data

This study evaluated L-band, 24cm radar data that were acquired at 10 meter resolution over the Costa Rica study area. Radar data has great potential for archeological research because of its ability to record geometric, linear, and curvilinear patterns on the surface. Unlike all other remote sensing instruments, the microwave frequencies of radar systems can penetrate clouds and can be equally operated at any time of day or night. The prominent disadvantages of radar data are that they are in a developmental state of research and require sophisticated digital analysis by specialists. At this time radar data is the most expensive form of remotely sensed information.

The application of radar data over the Arenal study area revealed that it was an inefficient approach for the detection of prehistoric footpaths. The radar recorded numerous lineaments even though filtering techniques were applied to reduce this effect. Comparative data analysis with other remotely sensed data revealed that the radar is recording prehistoric paths in both the forest and pastureland areas, but it is also recording a large number of additional linear features that may be attributable to natural features or noise in the data. Unless one already knew where to look for the pathways there would be no evidence to separate the pathways from the other linear features.

Lidar Data

Lidar data were collected by a NASA aircraft 400 meters above terrain over the Costa Rica study area. Lidar is an expensive form of data that has the ability to penetrate forest canopy and is capable of providing microtopographic data. Lidar is extremely useful in forest environments for mapping the height of trees above the surface. The limitation of lidar data is that it only records a transect of successive points. It does not record scan lines of information like the other scanner systems used in this investigation.

The application of lidar data to this investigation demonstrated that it was an inefficient technique for detecting prehistoric footpaths. From the data alone it is difficult to determine if the large number of dips and depressions in the terrain are due to natural or cultural causes. However, lidar data would be a useful tool in such forested areas as the Peten, Guatemala for detecting large features such as Maya ruins, sacbes, pyramids, and other cultural features hidden beneath the forest canopy.

CONCLUSIONS

This investigation has demonstrated the use of remote sensing technology in detecting the impacts of prehistoric activities upon an arid and humid landscape. Just as prehistoric populations have left a permanent record in the stratigraphy that can be recovered through excavation, they have also left a record upon the earth's surface that can only be appreciated from a distance. Remote sensing is a tool which allows us to detect these faint traces which are often invisible to the human eye. This study has demonstrated that remote sensing will never replace excavation, but it does allow the archeologist the opportunity to detect features that are not apparent through traditional techniques.

The roots of remote sensing trace back to the time when archeology was becoming a science. Archeologists were among the very first to incorporate remote sensing into their research. Originally this information was in the form of aerial photography, but the pioneering tradition continues today as archeologists include digital remote sensing and computer-implemented analysis into their research designs.

Beginning at the turn of the century, archeologists used black and white aerial photography at a number of sites throughout the world. Initially the interest in aerial photography began with European archeologists. American interests began later in the 1920's and was championed by Charles A. Lindbergh and archeologist A.V. Kidder. The introduction of Color Infrared Photography (CIR) during World War II expanded the utility of aerial photography with its ability to detect positive crop-marks as indicated by lush vegetation.

Digital remote sensing applications began in 1971 and have made dramatic advances in the last two decades. Digital sensors allow archeologists to record phenomena in portions of the electromagnetic spectrum that are invisible to the human eye. Through the use of computers, this information is brought back to visible light in the form of photographic-like images.

In this study, both optical and digital remotely sensed data have been successfully applied to diverse environmental and cultural conditions. Prehistoric roads constructed by the Anasazi during the 10th and 11th centuries in the dry, arid desert of Chaco Canyon, have been detected and mapped. This information has been important in understanding the function of the prehistoric roadways. These roads were used primarily for ritual rather than for economic purposes. Remotely sensed data has also been used in the moist, tropical forests of Costa Rica. A system of footpaths has been located which has provided an insight into the environmental and cultural conditions near Lake Arenal approximately 2,000 years ago. The footpaths link cultural and physical features in the landscape. They demonstrate that prehistoric Arenal society was integrated through ritual and document the communication and transportation routes used by the inhabitants. Analysis of the soils within the paths also indicate that the prehistoric environment was composed of a forest canopy. Despite several eruptions from the nearby Volcan Arenal, the prehistoric inhabitants developed an adaptive strategy to a rainforest environment that was employed for several millennia.

During this investigation several types of remote sensing approaches using different instrumentation were attempted that proved to be unsuccessful for the specific archeological objectives of Chaco Canyon and Costa Rica. These negative results are important yet they are not to be considered conclusive. These techniques may be successful if they are applied to a different archeological target or environmental setting. Many of the instruments, such as radar, are in a state of rapid development and may have successful application for archeological studies in the near future.

This investigation has been a small step in advancing the application of remote sensing technology for archeological research. It is a link in the chain of discoveries that will ultimately provide archeologists with the ability to decipher the secrets of the past. It takes very little imagination to see the capabilities that rest on the technological horizon. We live in a generation that is preparing to journey to Mars and already nations are joining together to launch new instruments into space that will orbit the planet. It is an exciting time; it is a time of immense responsibility. The same instruments that will pave our future are capable of helping us look back into our past, and archeologists can play an important role in the development of the new technology. Man is a tropical creature who has successfully adapted to every type of environment. Now he is moving into the most difficult environment of all--space. The archeological record may prove to be one of the most crucial resources for understanding how human beings successfully adapt to their environment.

REFERENCES CITED

Adams, R.E.W., W.E. Brown, Jr., and T.P. Culbert.
1981 Radar, Mapping, Archeology, and Ancient Maya Land Use. Science, Vol. 213, No. 4515.

Adams, Robert McC. and Hans J. Nissen
1972 The Uruk Countryside. University of Chicago Press.

Aguilar P., C.
1984 Introduction a la Arqueologia de la Region del Volcan Arenal. Anales, Academia de Geografia e Historia de Costa Rica, San Jose.

Akins, N. J. and J. D. Schelberg
1984 Evidence for Organizational Complexity as Seen From the Mortuary Practices at Chaco Canyon. In Recent Research on Chaco Prehistory, edited by W. J. Judge and J. D. Schelbrg, pp. 89-102. U.S. Dept. of the Interior, National Park Service, Albuquerque, NM.

Allan, William D., and John B. Broster
1978 An Archeological Application of the Christaller Model. Paper presented at the 54th Annual Meeting of the Southwestern and Rocky Mountain Division of the American Asociation for the Advancement of Science, Albuquerque, NM.

Ambrosia, Vincent, and Gary T. Whiteford
1983 Aerial Photograph Interpretation in Remote Sensing. In Remote Sensing of the Environment, edited by B.F. Richason, pp. 57-84. Kendall/Hunt Publishing Co., Dubuque, Iowa.

Avery, T. Eugene
1968 Interpretation of Aerial Photographs. Burgess Publishing Co., Minneapolis, MN.

Beazeley, Lieut.-Col. G.A.
1919 Air Photography in Archaeology. The Geographical Journal. May, p. 30.
1920 Survey in Mesopotamia During the War. The Geographical Journal. Feb., pp. 118-19.

Bennett, Jack, Lawson Smith, and Mark Laustrup
1986 The Red River Valley Archeological Project. In The TIMS Data User's Workshop. JPL, California Inst. of Technology, p. 6.

Berry, Michael S.
n.d. Sampling and Predictive Modeling on Federal Lands. Dept. of Anthropology, University of Utah, Salt Lake City, Utah.

Binford, Lewis R.
1962 Archaeology as Anthropology. American Antiquity 28:217-225.
1964 A Consideration of Archaeological Research Designs. American Antiquity 29:425-441.
1972 Review of K.C. Chang's "Rethinking Archaeology". In An Archaeological Perspective. Seminar Press Inc., New York. Pp. 74-77.

Barisano E., and B. Helly
1985 Remote Sensing and Archaeological Research in Thessaly (Greece): New Prospects in "Archaeological" Landscape. Proceedings of the EARScL/ESA Symposium. Strasbourg, 31 March-3 April, pp. 203-209.

Barnouw, Victor
1971 An Introduction to Anthropology: Volume Two, Ethnology. Dorsey Press, Homewood, Illinois.

Bartlett, Alexandra S. and Elso S. Barghoorn
1973 Phytogeographic history of the Istmus of Panama during the past 12,000 years. Ed. Alan H. Graham, In Vegetation and Vegetational History of Northern Latin America. Elsevier Scientific Publishing Co., New York.

Berlin, G. L., M. A. Tarabzouni, K. M. Sheikho, and A. Al-Naser
1985 SIR-A and Landsat MSS observations of Eolian Sand Deposits on the Al Labbah Plateau, Saudi Arabia. Proceedings of the 19th International Symposium on Remote Sensing of the Environment: 311-321. Environmental Research Institute of Michigan, Ann Arbor.

Borgia, A., C. Poore, M. Carr, W. Melson, and G. Alvarado
n.d. Structural, Stratigraphic, and Petrologic Aspects of the Arenal-Chaco Volcanic System, Costa Rica: Evolution of a young Stratovolcanic Complex. Ms on file.

Brand, Donald D., Florence M. Hawley, Frank C. Hibben
1937 Tseh So, A Small House Ruin, Chaco Canyon, New Mexico. The University of New Mexico Bulletin 308, Anthropological Series, Vol. 2, No. 2.

Brandt, John C., and Ray A. Williamson
1979 The 1054 Supernova and Native American Rock Art. Archeoastronomy, supp. to Journal for the History of Astronomy, No. 1.

Breternits, Cory Dale
1982 An Evolutionary Model of Anasazi Cultural Development in the Central San Juan Basin. in Bis sa;ani: A Late Bonito Phase Community on Escavada Wash, Northwest New Mexico, Vol. 3, edited by Cory Dale Breternitz, David E. Doyel, and Michael P. Marshall, pp. 1241-1249. Navajo Nation Papers in Anthropology 14, Window Rock, AZ.

Broadbent, Sylvia M.
1968 A Prehistoric Field System in the Chibcha Territory, Colombia. Nawa Pacha 6:135-147.

Brown, Walter
1989 Personal communicaton.

Bryan, Kirk
1954 The Geology of Chaco Canyon, New Mexico, in Relation to the Life and Remains of the Prehistoric Peoples of Pueblo Bonito. Smithsonian Miscellaneous Collections, 122, (7). Washington, D.C..

Bureau of Land Management
1983 Chaco Roads Project Phase I: A Reappraisal of Prehistoric Roads in the San Juan Basin, edited by Chris Kinkaid. Albuquerque, NM.
1987 Chacoan Roads in the Southern Periphery: Results of Phase II of the BLM Chaco Roads Project. By Fred Nials, John Stein, and John Roney. Albuquerque, NM.

Bushnell, David I., Jr.
1922 Archaeological Reconnaissance of the Cahokia and Related Mound Groups. Explorations and Fieldwork of the Smithsonian Institution in 1921. Smithsonian Miscellaneous Collections, Vol. 72, no. 15.

Butzer, Karl W.
1980 Context in Archaeology: an Alternative Perspective. Journal of Field Archaeology 7:417-422.

1982 Archaeology as Human Ecology. Cambridge University Press, Cambridge.

Bowen, H.C.
1962 Air Photographs and the Study of Ancient Fields in England. Internat. Arch. of Photogrammetry, Vol. 14, pp. 411-418.

Caldwell, Joseph R.
1964 Interaction Spheres in Prehistory. In Hopewellian Studies edited by Joseph Campbell and Robert L. Hall, Illinois State Museum Scientific Papers, Vol. 12, pp. 133-143.

Cameron, H.L.
1958 History from the Air. Photogrammetric Engineering 24: 366-375.

Capper, Col. J. E.
1907 Photographs of Stonehenge as Seen from a War Balloon. Archaeologia, p. 571.

Carlson, T.N.
1986 Regional-Scale Estimates of Surface Moisture Availability and Thermal Inertia Using Remote Thermal Measurements. Remote Sensing, 1:197-247.

Carstens, K.C., T.C. Kind, and N.V. Weber
1982 Using Remote Sensing in a Predictive Model: The Jackson Purchase Region, Kentucky. Proceedings of Pecora VII Symposium. U.S. Dept. of the Interior, Washington D.C., pp. 494-507.

1983 Application of Remote Sensing in Cultural Resource Management: Archaeology. In Remote Sensing of the Environment, edited by B. Richason, pp. 299-316. Kendall/Hunt Publishing Co., Dubuque, Iowa.

Carson, M.A., and M.J. Kirkby
1972 Hillslope Form and Process. Cambridge University Press, Cambridge.

Chagnon, Napoleon A.
1974 Studying the Yanamamo. Holt, Rinehart, and Winston Inc., New York.
1968 Yanamamo: The Fierce People. Holt, Rinehart, and Winston Inc., New York.

Chang, K.C.
1967 Rethinking Archaeology. Random House, New York.

Chevallier, R.
1962 L'Archeologie Aerienne en France. Internat. Arch. of Photogramm., Vol. 14, pp. 401-407.

Clarke, David L.
1977 Spatial Archaeology. Academic Press, New York.

Conant, F.P., and T.K. Cary
1977 A First Interpretation of East Africa Swiddening Via Computer-assisted Analysis of 3 Landsat Tapes. Proceedings, 1977, Machine Processing of Remotely Sensed Data Symposium. Purdue University, West Lafayette, Indiana, pp. 36-43.

Conant, F.P.
1976 Satellite Analysis of Human Ecosystems in the Sahel of East Africa. Proposal submitted to the National Science Foundation.

Cooke, R.
1984 Archaeological Research in Central and Eastern Panama: A Review of Some Problems. In The Archaeology of Lower Central America. Ed. by F. Lange and D. Stone, pp. 263-302. University of New Mexico Press, Albuquerque.

Crawford, O.G.S., and Alexander Keiller
1928 Wessex from the Air. The Clarendon Press, Oxford.

Crumley, Carole L.
1983 Archaeological Reconnaissance at Mont Dardon, France. Archaeology, May/June, pp. 12-17.

Cushing, Frank H.
1967 My Adventures in Zuni (Reprint of 1882-1883). Filter Press, Palmer Lake, CO.
1896 Outlines of Zuni Creation Myths. Bureau of American Ethnology, Annual Report, No. 13, pp. 321-447.

Dahlin, Bruce H., and Kevin O. Pope
n.d. A Critical Review of Ancient Maya Wetland Agriculture: New Insights from Ecological and Remote Sensing Research. Paper submitted to the Journal of Field Archaeology.

Deuel, Leo
1969 Flights into Yesterday: The Story of Aerial Archaeology. St. Martin's Press, New York.

Dozier, H. E. P.
1970 The Pueblo Indians of North America. Prentice-Hall, Englewood Cliffs.

Dillon, Brian D.
1984 Island Building and Villages of the Dead: Living Archaeology in the Comarca de San Blas, Panama. Journal of New World Archaeology, Vol. VI, No. 2. February.

Drager, Dwight L.
1976 An Analysis of a Possible Communication System in the San Juan Basin of New Mexico. Ms. on file, Division of Cultural Research (Chaco Center), Southwest Cultural Resources Center, National Park Service, Albuquerque.

Ebert, James I.
1973 Field Report--Remote Sensing Project. Ms on file, Branch of Remote Sensing, Division of Cultural Research, Southwest Cultural Resoruces Center, NPS, Albuquerque.

Ebert, James I., and Robert K. Hitchcock
1975 Chaco Canyon's Mysterious Highways. Horizon 17 (4):48-53.
1980 Locational Modeling in the Analysis of the Prehistoric Roadway System At and Around Chaco Canyon, New Mexico. In Cultural Resources Remote Sensing, edited by Thomas R. Lyons and Frances Joan Mathien, pp. 169-207. National Park Service, Washington, D.C.

Ebert, James I., and Thomas R. Lyons
1983 Archaeology, Anthropology, and Cultural Resources Management. In Manual of Remote Sensing, edited by Robert N. Colwell. Volume II, Intepretation and Applications. American Society of Photogrammetry, pp. 1233-1304.

Ediene, Bernard
1956 Une Methode Practique pour la Detection Aerienne des Sites Archaeologiques, en Particulier par la Photographie sur Films en Couleurs et sur Films Infra-rogues. Bulletin de la Societe Prehistorique Francaise 53:540-546.

Elachi, Charles, L. E. Roth, and G. G. Schaber
1984 Spaceborne Radar Subsurface Imaging in Hyperarid Regions. IEEE Transactions on Geoscience and Remote Sensing, July 1984, Vol. GE-22:383-387.

Elachi, Charles, C.V. Haynes, B. Issawi, and J.F. McCauley.
1982 Use of the Space Shuttle for Remote Sensing Research: Recent Results and Future Prospects. Science Vol. 218, No. 4576, pp. 993-1020.

Ellis, Florence H.
1975 A Thousand Years of the Pueblo Sun-Moon-Star Calendar. In Archaeoastronomy in Pre-Columbian America, edited by Anthony Aveni. University of Texas Press, Austin, TX.
1967 Where Did the Pueblo People Come From? El Palacio 74:35-43.

Ellis, F. H. and L. Hammack
1968 The Inner Sanctum of Feather Cave. American Antiquity, 33, No. 1, pp. 25-44.

Encyclopedia of Photography
1984 International Center of Photography, Encyclopedia of Photography. Edited by William L. Broecker, Crown Publishers, Inc., New York.

Estes, J. and D.S. Simonett
1975 Fundamentals of Image Interpretation. In Manual of Remote Sensing, edited by R. G. Reeves, pp.869-1076. American Society of Photogrammetry, Falls Church, VA.

Eveleigh, T.J., and J.F. Custer
1985 A Landsat-generated Predictive Model for Prehistoric Archaeological Sites-- An Example from Deleware's Coastal Plain. American Society for Photogrammetry, Vol. 2 (A86-46051), pp. 450-459.

Fagan, Brian M.
1985 In the Beginning: An Introduction to Archaeology. Little, Brown and Co., Boston.

Fanale, R.
1974 Utilization of ERTS-1 Imagery in the Analysis of Settlement and Land Use of the Dogon of Mali. M.S. Thesis, Department of Anthropology, Catholic University.

Farley, James A., W. Fredrick Limp, and Jami Lockhart
1988 The Archeologists Workbench: Integrating GIS, Remote Sensing, EDA, and Database Management. Paper presented in the Symposium of Geographic Information Systems Applications in Archeology, 53rd Annual Society for American Archeology Meetings, Phoenix, Arizona.

Ferrero, Luis
1981 Ethnohistory and Ethnography in the Central Highlands-Atlantic Watershed and Diquis. In Precolumbian Art of Costa Rica. Harry Abrams, Inc., New York. pp. 93-103.

Fewkes, J. Walter
1917 Archaeological Investigations in New Mexico, Colorado, and Utah. Smithsonian Miscellaneous Collections 68(1).
1892 A Few Summer Ceremonials at the Tusayan Pueblos. American Ethnology and Archaeology 2.

Flannery, Kent V.
1968 Archaeological Systems Theory and Early Mesoamerica. Anthropological Archaeology in the Americas, edited by Betty J. Meggers, Washington: Anthropological Society of Washington, pp. 67-87.
1973 The Origins of Agriculture. Biennial Review of Anthropology 12:271-310.
1976 The Early Mesoamerican Village. Academic Press, New York.

Flynn, Leo L.
1981 Report on the Mapping of Linearities from 1930's Aerial Photography for the Bisti-Star Lake coal lease area, San Juan, NM. Ms. on file, Albuquerque District Office, BLM, Albuquerque, NM.

Forde, C. Daryll
1931 Hopi Agriculture and Land Ownership. Journal of the Royal Anthropological Institute of Great Britain and Ireland 61, pp. 357-405.

Fowler, Melvin L.
1977 Aerial Archeology at the Cahokia Site. In Aerial Remote Sensing Techniques in Archeology, edited by Thomas R. Lyons and Robert Hitchcock, pp. 65-80. Chaco Center, Albuquerque, New Mexico.

Fransted, Dennis
1979 An Introduction to the Navajo Oral History of Anasazi Sites in the San Juan Area. Ms. on file, Division of Cultural Research (Chaco Center), Southwest Cultural Resources Center, National Park Service, Albuquerque.

Gardner, Joseph L. (editor)
1986 Mysteries of the Ancient Americas. Reader's Digest Association, Pleasantville, New York.

Garnett, D. (editor)
1938 The Letters of T.E. Lawrence. Spring Books, London.

Goddard, George
1969 Overview. Doubleday and Company, New York.

Gumerman, George J., and James A. Neely
1972 An Archaeological Survey of the Tehuacan Valley, Mexico: A Test of Color Infrared Photography. American Antiquity 37:520-527.

Hackman, R.J.
1967 Time, Shadows, Terrain, and Photointerpretation. In USGS Professional Paper 575, pp. B155-B160. United States Geological Survey, Reston, VA.

Hall, Robert L.
1968 The Goddard-Ramey Cahokia Flight: A Pioneering Aerial Photographic Survey. The Wisconsin Archaeologist, Vol. 49, No. 2.

Hansen, Donald B.
1983 Generic GIS (Geographic Evaluation Network for Earth Resource Inventory and Classification). Western Energy Land Use Team, Division of Biological Services, U.S. Fish and Wildlife Services, Ft. Collins, CO.

Harp, Elmer, Jr.
1958 Optimum Scales and Emulsions in Air Photo Archaeology. Paper presented at the VIII International Congress of Anthropological and Ethnological Sciences, Tokyo, Japan.
1968 Anthropological Interpretation from Color. In Manual of Color Aerial Photography, edited by J.T. Smith, Falls Church, Virginia: American Society of Photogrammetry.
1977 Aerial Photography for the Artic Archaeologist. In Remote Sensing Techniques in Archeology, edited by Thomas R. Lyons and Robert Hitchcock, pp. 51-64. Chaco Center, Albuquerque, New Mexico.

Harris, D.
1973 The Prehistory of Tropical Agriculture: An Ethnoecological Model. In The Explanation of Culture Change. Ed. by C. Renfrew, pp. 391-417. Duckworth, London.

Hart, E. R.
1985 The Zuni Indian Tribe and Title to Kolhy/wala:wa (Kachina Village). Institute of the American West, (Unpublished).

Hartman, C.
1907 Archaeological Researches on the Pacific Coast of Costa Rica. Memoirs, Carnegie Museum, No. 3. Pittsburgh, PA.

Hayes, Alden C.
1975 Archaeological Survey of Chaco Canyon National Monument. Ms. on file with the National Park Service, Chaco Center, University of New Mexico.
1981 A Survey of Chaco Canyon Archeology. In Archeological Surveys of Chaco Canyon New Mexico, by Alden C. Hayes, David M. Brugge, and W. James Judge. National Park Service Publications in Archeology 18A.

Hayes, Alden C., and Thomas C. Windes
1975 An Anasazi Shrine in Chaco Canyon. In Collected Papers In Honor of Florence Hawley Ellis, edited by Theodore R. Frisbie, pp. 143-156. Papers of the Archaeological Society of New Mexico, No. 2, Santa Fe, NM.

Heaslip, G.G.
1975 Environmental Data Handling. John Wiley and Sons, Inc. New York.

Henderson, Floyd M., and James W. Merchant
1983 Microwave Remote Sensing. In Remote Sensing of the Environment, edited by B. Richason, pp. 191-217. Kendall/Hunt Publishing Co., Dubuque, Iowa.

Hitchcock, Robert K.
1973 Archaeological Research Strategies: The Chaco Canyon Road Survey, summer 1973. Ms. on file, Branch of Remote Sensing, Division of Cultural Research, Southwest Cultural Resources Center, NPS, Albuquerque, NM.

Hoffman, Michael Allen
1982 The Practical Archaeological Uses and Potential of Remote Sensing in the Arid Lands. Paper presented at the 15th International Symposium on Remote Sensing of Environment, First Thematic Conference: "Remote Sensing of Arid and Semi-Arid Lands," Cairo, Egypt.

Holdridge, Leslie R.
1966 Life Zone Ecology. Tropical Science Center, San Jose, Costa Rica, CA.

Holsinger, S.J.
1901 Report on Pre-Historic Ruins of Chaco Canyon, NM. General Land Office Letter "P", National Archives, Washington, D.C.

Hoopes, J.
1984 A Preliminary Ceramic Sequence for the Cuenca de Arenal, Cordillera de Tilaran region, Costa Rica. Vinculos 10:1-2:129-148.
1985 El Complejo Tronadora: Ceramica del Periodo Formativo en el Cuenca de Arenal, Guanacaste, Costa Rica. Vinculos 11:1-2:111-118.
1987 Early Ceramics and the Origins of Village Life in Lower Central America. Ph.D. Dissertation, Department of Anthropology, Harvard University, Cambridge. University Microfilms, Ann Arbor.

Hoopes, John and Mark Chenault
n.d. Proyecto Prehistorico Arenal Excavations in the Rio Santa Rosa Valley. In Archaeology and Volcanism in the Arenal Area, Costa Rica. Ed. by Payson Sheets and Brian McKee. MS, University of Colorado, Boulder.

Horgan, Paul
1971 The Heroic Triad: Essays in the Social Energies of Three Southwestern Cultures. World Publishing, New York, NY.

Hudson, Travis
1963 Anasazi Measurement Systems at Chaco Canyon, New Mexico. In The Kiva Vol 38 No. 72, p. 27.

Inglis, M., T.K. Budge, and J.I. Ebert
1984 Preliminary Evaluation of Simulated SPOT data for Cultural Resource Assessment-- An Experiment at Bandelier National Monument, New Mexico. Proceedings of the SPOT Symposium, Scottsdale, Arizona. American Society of Photogrammetry, pp. 73-82.

Jensen, J.R.
1986 Introductory Digital Image Processing. Prentice-Hall. Englewood Cliffs.

Johnson, G.R., and R.R. Platt
1930 Peru from the Air. American Geographical Society, Special Publication No. 12, Washington.

Judd, Neil M.
1954 The Material Culture of Pueblo Bonito. Smithsonian Miscellaneous Collections 124.
1964 The Architecture of Pueblo Bonito. Smithsonian Miscellaneous Collections 147(1).

Judge, W. James
1984 New Light on Chaco Canyon. In New Light on Chaco Canyon, edited by D. G. Noble, pp. 1-12. School of American Research Press, Santa Fe, NM.
1983 Chaco Canyon-San Juan. Paper presented to the School of American Research Advanced Seminar, "Dynamics of Southwestern Prehistory." Santa Fe, NM.

Judge, W. James, H. Wolcott Toll, William B. Gillespie, and Stephen H. Lekson
1981 Tenth Century Developments in Chaco Canyon. In Collected Papers in Honor of Erik Kellerman Reed, edited by Albert H. Schroeder. Papers of the Archaeological Society of New Mexico 6:65-98.

Junkin, B.G. and R.W. Pearson, B.R. Seyfarth, M.T. Kalcic, and M.H. Graham
1981 Earth Resources Laboratory Applications Software (ELAS). Report No. 183. NASA, National Space Technology Laboratories, Earth Resources Laboratory, NSTL, MS.

Kahle, A. and A. Goetz
1983 Mineralogic Information from a New Airborne Thermal Infrared Multispectral Scanner. Science 222:24-27.

Kelley, K. B.
1984 Historic Cultural Resources in the San Augustine Coal Area. Ms. on file at the Bureau of Land Management, Socorro District, New Mexico.

Kincaid, Chris (editor)
1983 Chaco Roads Project, Phase I: A Reappraisal of Prehistoric Roads in the San Juan Basin, 1983. BLM, U.S. Dept. of Interior, Albuquerque, NM.

Knightley, P., and C. Simpson
1971 The Secret Lives of Lawrence of Arabia. Bantam Books, New York.

Kohler, Timothy A., and Sandra C. Parker
1986 Predictive Models for Archaeological Resource Location. In Advances in Archaeological Method and Theory, Vol 9, Academic Press, New York.

Krabil, W.B.
1980 Airborne Laser Topographic Mapping Results from Initial Joint NASA/U.S. Army Corps of Engineers Experiment. NASA TM 73287. Wallops Flight Center. Wallops Island, VA.

Ladd, E.
1983 Pueblo Use of High-Altitude Areas: Emphasis on the A:Shiwi. In High Altitude Adaptations in the Southwest, edited by J. C. Winters, pp. 168-176. U. S. Forest Service, Southwest Region Report No. 2.

Lange, F.W.
1978 Coastal Settlements in Northwestern Costa Rica. In Prehistoric Coastal Adaptations, edited by B. Stark and B. Voorhies. Academic Press, New York.
1984 The Greater Nicoya Archaeological Subarea. In The Archaeology of Lower Central America, Ed. by F. Lange and D. Stone. University of New Mexico Press, Albuquerque, NM.

Lange, F. and S. Abel-Vidor
1980 The Formative Zoned Bichrome Period in Northeastern Costa Rica (800 BC to AD 500). Vinculos 6:33-42.

Lavigne, D.M, N.A. Oristsland, and A. Falconer
1977 Remote Sensing and Ecosystem Management. Skrifter Nr. 166 (Oslo, Norway: Norsk Polar Institute).

Lekson, Stephen H., Thomas C. Windes, and W. James Judge
1988 The Chaco Canyon Community. Scientific American, July, 1988.

Levi-Strauss, C.
1963 Do Dual Organizations Exist? In Structural Anthropology, pp. 132-163. Basic Books, Inc., New York, NY.
1955 The Structural Study of Myth. In Myth: A Symposium, edited by T. A. Sebeok. University of Indiana Press, Bloomington, IN.

Lillesand, Thomas M., and Ralph W. Kiefer
1979 Remote Sensing and Image Interpretation. John Wiley and Sons, New York, p.38.

Lind, A.
1981 Applications of aircraft and satellite data for the study of archaeology and environment-- Mekong Delta, Vietnam. In International Symposium on Remote Sensing of Environment, Proceedings, Vol. 3. pp. 1529-1537.

Lister, Robert H., and Florence C. Lister
1981 Chaco Canyon. University of New Mexico Press, Albuquerque.

Lothrop, Samuel K.
1926 Pottery of Costa Rica and Nicaragua. Contributions from the Museum of the American Indian, Heye Foundation, No. 8, 2 volumes. New York.

Lulla, Kamlesh, and Paul Mausel
1983 Ecological Applications of Remotely Sensed Multispectral Data. In Remote Sensing of the Environment, edited by B. Richason, pp. 354-377. Kendall/Hunt Publishing Co., Dubuque, Iowa.

Luvall, Jeff
1988 Personal communication.

Luvall, Jeff and H.R. Holbo
1989 Modeling Surface Temperature Distributions in Forest Landscapes. Remote Sensing of the Environment, 27:11-24.

Lyons, Thomas R.
1981 Remote Sensing Multispectral Analyses of Cultural Resources: Chaco Canyon and Bandelier National Monument. Supplement No. 5, Cultural Resources Management, National Park Service, Washington, D.C.
1973 Archaeological Research Strategies: The Chaco Canyon Road Survey, Summer, 1973. Ms on file, Division of Cultural Research (Chaco Canyon), Southwest Cultural Resources Center, National Park Services, Albuquerque.

Lyons, T.R., and T.E. Avery
1977 Remote Sensing: A Handbook for Archeologists and Cultural Resource Managers. National Park Service, Washington, D.C. (U.S. Government Printing Office, Stock No. 024-005-00688-5).

Lyons, T.R., and J.I. Ebert
1978 Remote Sensing and Non-destructive Archeology. Cultural Resource Managers Division, National Park Service, Washington, D.C.

Lyons, T.R., and R.K. Hitchcock
1977 Aerial Remote Sensing Techniques in Archeology. Reports of The Chaco Center, No. 2. National Park Service and University of New Mexico, Albuquerque.

Lyons, T.R., M. Inglis, and R.K. Hitchcock
1972 The Application of Space Imagery to Anthropology. Proceedings: Third annual Conference of Remote Sensing In Arid Lands, pp.244-265. The University of Arizona, Tuscon.

Lyons, T.R., and F.J. Mathien
1980 Cultural Resources Remote Sensing. Cultural Resources Management Division, National Park Service, Washington, D.C.

Lyons, T.R. (editor)
1976 Remote Sensing Experiments in Cultural Resource Studies: Non-destructive Methods of Archeological Exploration, Survey, and Analysis. Reports of the Chaco Center, No. 1, National Park Service and University of New Mexico, Albuquerque.

MacArthur, R.H.
1972 Geographical Ecology: Patterns in the Distribution of Species. Harper and Row, New York.

MacNeish, R.S.
1958 Preliminary Archaeological Investigations in the Sierra de Tamaulipas, Mexico. Transactions of the American Philosophical Society 48:6.

1975 Excavations and Reconnaissance, Vol. 5, The Prehistory of the Tehuacan Valley. University of Texas Press, Austin.

Madry, Scott L.H.
1983 Remote Sensing in Archaeology. Archaeology, May/June, pp. 18-20.

Marble, Duane F., H.W Calkins, and D.J. Peuquet
1984 Basic Readings in Geographic Information Systems. SPAD Systems Ltd. Williamsville, New York.

Marshall, Michael P., John R. Stein, Richard W. Loose, and Judith E. Novotny
1979 Anasazi Communities of the San Juan Basin. Public Service Company of New Mexico, Albuquerque, and New Mexico State Historic Preservation Bureau, Santa Fe, NM.

McCluskey, Stephen C.
1977 The Astronomy of the Hopi Indians. In Journal for the History of Astronomy 8, part 2.

McKern, W.C.
1939 The Midwestern Taxonomic Method as an Aid to Archaeological Culture Study. American Antiquity 4, 301-313.

Melson, W.
n.d. 1968 Eruption and Tephra Stratigraphy of Arenal Volcano, Costa Rica. In Archaeology and Volcanism in the Arenal Area, Costa Rica. Ed. by Payson Sheets and Brian Mckee. MS U. of Colorado, Boulder.
1978 Eruption of Arenal Volcano, Costa Rica, 1968-1973. National Geographic Society Research Reports, pp. 433-446.

1982 Alternation Between Basaltic Andesite and Dacite in Historic and Prehistoric Eruptions for Arenal Volcano, Costa Rica.. Unpublished MS, Smithsonian Inst., Washington, DC.

Metcalf, G.
n.d. Archeological Investigations in the Vicinity of Volcan Arenal, Costa Rica. MS, Smithsonian Institution, Washington, D.C.

Meuller, James W.
1975 Sampling in Archaeology. University of Arizona Press, Tuscon.

Mueller, Marilynn
n.d. A Study of Settlement Patterns in the Highlands of Northwestern Costa Rica. Proposal submitted to the National Science Foundation, 1987.

Mid-America Remote Sensing Center
1983 Determination of the Utility of Remote Sensing Data for Land Use/Cover Analyses in the Lower Appalacia Region-- Assessing the Utility of Remote Sensing Data For Archeological Site Recognition. Final Report, NASA Contract NAS13-200.

Miller, W. Frank
1981 Remote Sensing Techniques in Historical Site Discrimination. Remote Sensing of Environment 11:463-471.

Morenon, E. Pierre
1975 Chaco Roads and Adaptation: How a Prehistoric Population Can Define and Control its Social and Natural Environment. Paper presented at the 40th Annual Meeting of the Society for American Archaeology, Dallas, TX.
1977a A View of the Chacoan Phenomenon From the "Backwoods": A Speculative Essay. Ms. on file, Archeological Program of the Institute of Applied Sciences, North Texas State University, Denton, TX.
1977b Summary of Energy Study Results Conducted in Chaco Canyon National Monument. Ms. on file, Division of Cultural Research (Chaco Center), Southwest Cultural Resources Center, National Park Service, Albuquerque, NM.

Morris, Earl H.
1915 The Excavation of a Ruin near Aztec, San Juan County, New Mexico. American Anthropologist 17(4):666-684.

Morrison, Charles Randall
1973 Field Report on Prehistoric Road Survey by the Chaco Center Remote Sensing Program, 1973. Ms. on file, Branch of Remote Sensing, Division of Cultural Research, Southwest Cultural Resources Center, NPS, Albuquerque.

Morrison, Tony
1978 Pathways to the Gods: The Mystery of the Andes Lines. Harper and Row, New York, NY.

Moore, G.K.
1980 Objective Procedure for Lineament Enhancement and Extraction. Photogrammetric Engineering and Remote Sensing. Vol. 49, No. 5, pp. 641-647.

Moorehead, Warren King
1922 The Cahokia Mounds: A Preliminary Report. University of Illinois Bulletin, Vol. 19, No. 35.
1928 The Cahokia Mounds. University of Illinois Bulletin, Vol. 26, No. 4.

Myers, J. Wilson, F.P. Hemans, and James Wiseman
1987 Remote Sensing from a Tethered Blimp in Greece. Technical Paper No. 2, Center for Remote Sensing, Boston.

NASA
1985 FY86 Aircraft Operations Plan. Earth Resources Laboratoy. NSTL, MS.

National Park Service
1980 Cultural Resources Assessment for the San Juan Basin Regional Uranium Study. Branch of Indian Cultural Resources, National Park Service, Santa Fe, NM.

Nations, James
1988 Tropical Rainforests: Endangered Environment. Franklin Watts, New York.

New Mexico Highway Journal
1928 Prehistoric Chaco Canyon "roads" Puzzle Scientists. New Mexico Highway Journal, March:9.

Newhall, B.
1969 Airborne Camera. Hastings House, New York.

Nials, Fred L.
1983 Physical Characteristics of the Chacoan Roads. In Chaco Roads Project: Phase I; A Reappraisal of Prehistoric Roads in the San Juan Basin 1983, edited by Chris Kincaid, Chapter 6. BLM, U.S. Dept. of the Interior, Albuquerque, NM.

Obenauf, M.
1983 Evaluation of Aerial Photography. In Chaco Roads Project, Phase I A Reappraisal of Prehistoric Roads in the San Juan Basin, 1983, edited by Chris Kincaid, Chapter 4. BLM, U.S. Dept. of Interior, Albuquerque, NM.
1980a The Chacoan Roadway System. Unpublished M.A. thesis, Department of Anthropology, University of New Mexico.
1980b A History of Research on the Chacoan Roadway System. In Cultural Resources Remote Sensing, edited by T.R. Lyons and F.J. Mathien, pp. 123-167. National Park Service, Washington.

Ortiz, A.
1969 The Tewa World: Space, Time, Being, and Becoming In Pueblo Society. University of Chicago Press, Chicago.
1965 Dual Organization as an Operational Concept in the Pueblo Southwest. Ethnology, 4 (No. 4):389-396, Pittsburg, PA.

Pallucone F. and G. Meeks
1985 Therman Infrared Multispectral Scanner (TIMS): An Investigative Guide to TIMS Data. JPL Publication 85-32. Pasadena, CA.

Parsons, E. C.
1939 Pueblo Indian Religion. University of Chicago Press, Chicago, IL.
1925 The Pueblo of Jemez. Papers of the Phillips Academy Southwestern Expedition, 3. Yale University Press, New Haven.

Parsons J.J., and William Denevan
1967 Pre-Columbian Ridged Fields. Scientific American No. 217, pp. 92-101.

Pelletier R.E. and M.C. Ochao
1986 Applications of TIMS Data in Agricultural Areas and Related Atmoshperic considerations. In TIMS Data Users Workshop, edited by A. Kahle and E. Abbott, pp. 57-58. JPL Publication 86-38. Pasadena, CA.

Pfeiffer, John E.
1982 The Creative Explosion. Cornell University Press. Ithaca, New York.

Piperno, Dolores
n.d. Phytolith Records from the Proyecto Prehistorico Arenal. In Archaeology and Volcanism in the Arenal Area, Costa Rica. Ed. by Payson Sheets and Brian McKee. University of Colorado, Boulder.

Plog, Stephen, Fred Plog, and Walter Wait
1978 Decesion Making in Modern Surveys. In Advances in Archaeological Method and Theory, Vol. 1, edited by Michael B. Schiffer, pp. 383-421. Academic Press, New York.

Podwysocki, M.H., J.G. Moik, and W.D. Shoup
1975 Quantification of Geologic Lineaments by Manual and Machine Processing Techniques. Proceedings: NASA Earth Resources Survey Symposium, Houston, TX. pp. 885-903.

Posey, D.
1983 Indigenous Ecological Knowledge and Development in the Amazon. In The Dilemma of Amazonian Development, edited by E. Moran, Westview Press, Boulder CO. Pp.225-257.

Potter, L.D., and N.E. Kelley
1980 Aerial Photointerpretation of Vegetation of Chaco Canyon National Monument. In Cultural Resources Remote Sensing, pp. 87-104, edited by Thomas Lyons and Frances Joan Mathien. Southwest Cultural Resources Center, NPS, Albuquerque, NM.

Powers, Robert, Stephen Lekson, and William Gillespie
1977 Preliminary Investigations into the Chacoan Outlier System: A Functional and Regional Perspective. Ms. on file, Division of Cultural Research (Chaco Center), Southwest Cultural Resources Center, National Park Service, Albuquerque, NM.

Powers, Robert P., William B. Gillespie, and Stephen H. Lekson
1983 The Outlier Survey: A Regional View of the Settlement In the San Juan Basin. Reports of the Chaco Center 3.

Ramenofsky, Ann F.
1986 The Persistene of the Late Archaic Subsistence-Settlement in Louisiana. In Foraging, Collecting, and Harvesting: Archaic Period Subsistence and Settlement in the Eastern Woodlands, edited by Sarah W. Neusius, pp. 289-312. Occasional Paper No. 6. Center for Archaeological Investigations, Southern Illinois University, Carbondale, IL.

Redman, Charles L.
1982 Archaeological Survey and the Study of Mesopotamian Urban Systems. Journal of Field Archaeology 9:375-382.

Reeves, Dache M.
1936 Aerial Photography in Archaeology. American Antiquity 2:102-107.

Reichel-Dollmatoff, Gerardo
1971 Amazonian Cosmos: The Sexual and Religious Symbolism of the Tukano Indians. University of Chicago Press, Chicago, IL.

Reining, P.
1973 Utilization of ERTS-1 Imagery in Cultivation and Settlement Site Identification and Carrying Capacity Estimates in Upper Volta and Niger. National Technical Information Center, Springfield, VA.

1974a Human Settlement Patterns in Relation to Resources of Less Developed Countries. Proceedings: COSPAR Meetings, San Paulo, Brazil. (On file at International Office, American Association for the Advancement of Science, Washington, D.C.

1974b Use of ERTS-1 Data in Carrying Capacity Estimates for Sites in Upper Volta and Niger. Paper presented at the 1974 Annual Meeting of the American Anthropological Association, Mexico City. (On file at International Office, American Association for the Advancement of Science, Washington, D.C.

1978 Handbook on Desertification Indicators. Based on the Science Association's Nairobi Seminar on Desertification. American Association for the Advancement of Science, Washington, D.C.

Reyman, Jonathan

1971 Mexican Influence on Southwestern Ceremonialism. Ph.D. diss., Southern Illinois University.

Richason, Benjamin F. (editor)

1983 Remote Sensing: An Overview. In Remote Sensing of the Environment, edited by B. Richason, pp. 3-15. Kendall/Hunt Publishing Co., Dubuque, Iowa.

Ricketson, Oliver, Jr., and A.V. Kidder

1930 An Archeological Reconnaissance by Air in Central America. The Geographical Review, Vol. XX, No. 2.

Rickman, D.

1986 Personal communiction.

1983 The Mt. Emmons, Colorado Geology Study Site: Acquisition and Computer Processing of Airborne Thematic Mapper Simulator Data for a Mountainous, Partially Vegetated Area. Report No. 220. NASA National Space Technology Laboratories, Earth Resources Laboratory, NSTL, MS.

Rickman, D. and M. Kalcic.

1982 Noise Removal by Principal Component Analysis. Report No. 203. NASA National Space Technology Laboratories, Earth Resources Laboratory, NSTL, MS.

Rickman, D. and S.K. Grant

1985 Nighttime TIMS, TMS, and Chemical Data from the Pyramid Mountains South of Lordsburg, New Mexico. International Symposium on Remote Sensing of Environment, 4th Thematic Conference, ERIM, Ann Arbor, Michigan.

Roberts, Frank H.H., Jr.
1931 The Ruins at Kiatuthlanna, eastern Arizona. Bureau of American Ethnology, Bulletin 100.

Robertson, Ben P.
1981 Draft Research Proposal: Chaco Roads Project. Ms. on file, Albuquerque District Office, Bureau of Land Management, Albuquerque, NM.

Roney, John
1989 Personal Communication.

Ross, Joseph Ray
1978 A Three-Dimensional Facies Analysis of the Canyon Alluvial Fill Sequence, Chaco Canyon, New Mexico. Unpublished Master's thesis, Dept. of Geology, University of New Mexico, Albuquerque, NM.

Rostworowski de Diez Canseco, Maria
1977 Coastal Fishermen, Merchants, and Artisans in Pre-Hispanic Peru. In The Sea in the Pre-Columbian World, edited by Elizabeth P. Benson, pp.167-186. Dumbarton Oaks Research Library and Collections, Washington, D.C.

Rowe, John Howland
1953 Technical Aids in Anthropology: A Historical Survey. In Anthropology Today, edited by Alfred L. Kroeber. Chicago University Press, Chicago, Illinois.

Sader, S.A.
1986 Investigations of Forest Canopy Temperatures Recorded by the TIMS at H.J. Andrews Experimental Forest. In TIMS Data Users Workshop, edited by A. Kahle and E. Abbott, pp. 55-56. JPL Publication 86-38. Pasadena.

Saenz, R., and W.G. Melson
1976 La Erupcion del Volcan Arenal, Costa Rica en Julio, 1968. Revista Geograficade, America Central, no. 5:55-148.

St. Joseph, J.K.S. (editor)
1966 The Uses of Air Photography: Nature and Man in a New Perspective. John Baker, London.

Schaber, Gerald G., and George Gumerman
1969 Infrared Scanning Images: An Archaeological Application. Science 164:712-713.

Schellart, A.I.J.M.
1962 Experiences with Aerial Photographs in the Study of Castles. International Archaeology of Photogrammetry, Vol. 15, pp. 425-431.

Schorr, T.S.
1974 Aerial Ethnography in Regional Studies: A Reconnaissance of Adaptive Change in the Cauca Valley of Columbia. In Aerial Photography, edited by E.Z. Vogt, Harvard University Press.

Sever, Thomas L.
1983 Feasibility to Determine the Utility of Remote Sensing in Archeological Investigations. Earth Resources Lab., Report No. 227. NASA, National Space Technology Lab., NSTL, MS.
1987 An Environmental and Archeological Assessment of the Piedras Negras Region of Guatemala and Mexico. NASA Research Announcement. Funded proposal #NASA-NRA-077. Washington, D.C.
1988 Remote Sensing. In Benchmarks in Time and Culture: An Introduction to Palestinian Archaeology. Scholars Press, Atlanta, GA.

Sever, Thomas L., and James Wiseman
1985 Remote Sensing and Archaeology: Potential for the Future. Report on a Conference, March 1-2, 1984. National Aeronautics and Space Administration, National Space Technology Laboratories, Earth Resources Laboratory, Mississippi.

Sever, Thomas L., Brian McKee, and Payson Sheets
n.d. Prehistoric Footpaths in Costa Rica: Remote Sensing and Field Verification. In Archaeology and Volcanism in the Arenal Area, Costa Rica. Ed. by Payson Sheets and Brian McKee. MS, University of Colorado, Boulder.

Shankman, Paul, Tom Sever, and Daniel Gross
1987 Cultural and Ecological Applications of Remote Sensing. Final Report of a Conference, April 23-25, University of Colorado, Boulder.

Shazly, E.M.
1983 Space Borne Imagery Interpretation of Mega Features Related to Egyptian Archeology. International Geoscience and Remote Sensing Symposium, Vol. 1, New York.

Sheets, Payson; William Melson; Thomas Sever, John Hoopes, Marilynn Mueller; Brian McKee; John Bradley; and Mark Chenault
n.d. Prehistory, Volcanism, and Remote Sensing in the Arenal Area, Northwestern Costa Rica. American Antiquity, in press.

Sheets, Payson D., and Thomas L. Sever
n.d. Prehistoric Footpaths in Costa Rica: Transportation and Communication in a Tropical Rainforest. In C. Trombold (Ed.) Ancient Road Networks and Settlement Hierarchies in the New World. NY: Cambridge University Press.

Sheets, Payson D.
n.d. The Proyecto Prehistorico Arenal: An Introduction. In Archaeology and Volcanism in the Arenal Area, Costa Rica. Ed. by Payson Sheets and Brian McKee. MS, University of Colorado, Boulder.
1981 Volcanoes and the Maya. Natural History, 90(8):32-41. August.
1983 Archaeology and Volcanism in Central America: The Zapotitan Valley of El Salvador. University of Texas Press, Austin.
1984a Research Proposal to the National Science Foundation.
1984b The Proyecto Prehistorico Arenal: An Introduction. Vinculos 10:31-33.

Shippee, R.
1933 Air Adventure in Peru. National Geographic Magazine, January.

Simons, Li, and Asociates, Inc.
1982 Final Report: Erosion Study at Chaco Culture National Historic Park New Mexico. Submitted to the National Park Service, Southwest Region, Santa Fe, Contract No. CX 7029-10018. Fort Collins, CO.

Snarskis, Michael J.
1979 Turrialba: A Paleo-Indian Quarry and Workshop Site in Eastern Costa Rica. American Antiquity 44:125-38.
1981 The Archaelogy of Costa Rica. In Between Continents, Between Seas: PreColumbian Art of Costa Rica, edited by Elizabeth Benson. Harry N. Abrams, New York.
1984 Central America: The Lower Caribbean. In The Archaeology of Lower Central America. Ed. by F. Lange and D. Stone. University of New Mexico Press, Albuquerque, NM.

Sofaer, Anna, Michael Marshall, and Rolf M. Sinclair
1986 The Great North Road: A Cosmographic Expression of the Chaco Culture of New Mexico. Proceedings of the Oxford II Conference on Archaeoastronomy, Merida, Yucatan.

Sofaer, Anna, Volker Zinser, and Rolf Sinclair
1979 A Unique Solar Marking Construct. Science 206, pp. 283-291.

Stein, John R.
1983 Road Corridor Descriptions. In Chaco Roads Project Phase I: A Reapraisal of Prehistoric Roads in the San Juan Basin, 1983, edited by Chris Kincaid, Chapter 8. Bureau of Land Management, U.S. Dept. of the Interior, Albuquerque, NM.

Stein, John R. and Daisy F. Levine
1983 Documentaiton of Selected Sites Recorded During the Chaco Roads Project. In Chaco Roads Project, Phase I: A Reappraisal of Prehistoric Roads in the San Juan Basin 1983, edited by Chris Kincaid. U.S. Dept. of the Interior, BLM, Albuquerque, NM.

Stephen, Alexander M.
1936 Hopi Journal of Alexander M. Stephen. Edited by E.C. Parsons. Columbia University Contributions to Anthropology Vol. 23 (2 vols.), New York, NY.

Steward, Julian H.
1955 Irrigation Civilizations: A Comparative Study. Social Science Monographs 1.

Stirling, M.W.
1942 The Origin Myth of Acoma and Other Records. Smithsonian Institution Bureau of American Ethnology Bulletin 135.

Stone, D.
1977 Pre-Columbian Man in Costa Rica. Peabody Museum Press, Cambridge.

Strandberg, C.H.
1974 Fort Frederick Photoarchaeological Study. Maryland Department of Natural Resources, p. 55.

Stuart, George
1988 Personal communication, May.

Tartaglia, Louis J.
1977 Infrared Archeological Reconnaissance. In Remote Sensing Techniques in Archeology, edited by Thomas R. Lyons and Robert Hitchcock, pp. 35-50. Chaco Center, Albuquerque, New Mexico.

Thomas, David H.
1969 Regional Sampling in Archaeology: A Pilot Great Basin Research Design. University of California Archaeological Survey, Annual Report 11, pp. 87-100.

Thompson, G.
1879 Notes on the Pueblos and their inhabitants. In Report Upon United States Geographical Surveys West of the One Hundredth Meridian, Vol. VII: Archaeology, Part II: The Pueblo Ruins and the Interior Tribes. By Frederick W. Putnam, pp. 319-324. U.S. Engineer Dept. Wash. D.C.

Toll, H. Wolcott
1984 Trends in Ceramic Import and Distribution in Chaco Canyon. In Recent Research on Chaco Prehistory, edited by W. James Judge and John D. Schelberg, pp. 115-135. Reports of the Chaco Center No. 8, Division of Cultural Research, National Park Service, Albuquerque, NM.
1981 Ceramic Comparisons Concerning Redistribution in Chaco Canyon, New Mexico. In Production and Distribution: A Ceramic Viewpoint, edited by Hilary Howard and Elaine L. Morris. British Archaeological Reports International Series 120: 83-121.

Toll, H. Wolcott, and Peter J. McKenna
1983 The Ceramography of Pueblo Alto. Ms. on file, Branch of Cultural Research, National Park Service, Albuquerque, NM.

Toll, H. Wolcott, Thomas C. Windes, and Peter J. McKenna
1980 Late Ceramic Patterns in Chaco Canyon: The Pragmatics of Modeling Ceramic Echange. In Models and Methods in Regional Exchange, edited by Robert E. Fry. SAA Papers 1:95-117.

Tomlinson, R.F.
1984 Geographic Information Systems-A New Frontier. Proceedings, International Symposium on Spatial Data Handling:1-14. Zurich, Switzerland.

Tosi, J.
1980 Estudio Ecologico Integral de las Zonas de Afectacione del Proyecto Arenal Centro Cienitifico Tropical, San Jose.

Trombold, Charles
n.d. Ancient Road Networks and Settlement Hierarchies in the New World. Edited by Charles Trombold. Cambridge Press.
1989 Personal communication.

Turnbull, Colin
1962 The Forest People: A Study of the Pygmies of the Congo. Simon and Shuster, New York.

Vivian, Gordon
1948 Memorandum to Superintendent McNeil, Chaco Canyon, National Monument. Subject: Interview with Mrs. Marietta Wetherill. Date: Oct 29, 1948. Ms on file at the Chaco Culture National Historic Park.

Vivian, R. Gwinn
1970 An Inquiry into Prehistoric Social Organization in Chaco Canyon, New Mexico. In Reconstructing Prehistoric Pueblo Societies, edited by William A. Longacre, pp. 59-83. School of American Research, Santa Fe, NM.
1972 Prehistoric Water Conservation in Chaco Canyon. Final Technical Letter Report for N.S.F. Grant No. G.S. 3100.
1983 Identifying and Interpreting Chacoan Roads: An Historical Perspective. In Chaco Roads Project, Phase I: A Reappraisal of Prehistoric Roads in the San Juan Basin, 1983, edited by Chris Kincaid, Chapter 3. BLM, Albuquerque, NM.

Vivian, R. Gwinn, and Robert C. Buettner
1971 Field Notes and Data Collected for 1970-1971 NSF Grant 3100: Prehistoric Water Conservation in Chaco Canyon. Ms. on file, Arizona State Museum, Tucson, and Albuquerque District Office, BLM, Albuquerque, NM.

Vivian, Gordon, and Tom Mathews
1965 Kin Kletso, a Pueblo III Community in Chaco Canyon, New Mexico. Southwestern Monuments Association, Technical Series 6(1), Globe, AZ.

Von Hagen, Victor W.
1952 America's Oldest Roads. Chapter 4, July.

Wadleigh, F.A.
1916 Ancient Road Near Aztec, NM. El Palacio 3(4):52.

Walthall, John A., and Ned J. Jenkins
1976 The Gulf Formational Stage in Southeastern Prehistory. Southeastern Archaeological Conference, Bulletin 19:43-49.

Ware, John A., and George Gummerman
1977 Remote Sensing Methodology and the Chaco Canyon Prehistoric Road System. In Aerial Remote Sensing Techniques in Archeology, edited by Thomas R. Lyons and Robert K. Hitchcock. Reports of the Chaco Center 2: 135-167.

Waters, Frank
1963 The Book of the Hopi. Viking Press, NY.

Watzinger, Carl
1944 Theodor Wiegand, ein Deutscher Archaeologe, 1864-1936. C.H. Beck, Munich, Germany.

Wells, I., J. Custer, and V. Klemas
1981 Locating Prehistoric Sites Using Landsat Data. International Symposium of Remote Sensing of Environment, 15th, Ann Arbor, MI, May 11-15, 1981, Proceedings. Vol. 2.

Weslowski, L. V.
1981 Native American Land Use Along Redondo Creek. In High Altitude Adaptation Along Redondo Creek, edited by C. Baker and J. C. Winter. Office of Contract Archaeology, U. of New Mexico, Albuquerque, NM.

White, Leslie A.
1932 The Acoma Indians. BAE-AR No. 47.

1942 The Pueblo of Santa Ana, New Mexico. Memoirs of the American Anthropological Association, 60. Menasha, WI.
1960 The World of the Keresan Pueblo Indians. In Culture in History: Essays in Honor of Paul Radin, edited by Stanley Diamond, pp. 53-64. Columbia University Press, New York, NY.

1962 The Pueblo of Sia. Bureau of American Ethnology Bulletin 184, Smithsonian Institution, Washington, D.C.
1973 The Acoma Indians. Rio Grande Press, Glorieta, New Mexico.

Wiegand, Theodor
1920 Sinai. Wissenschaftliche Veroffentlichungen des Deutsch-Turkischen Denkmalschutzkommandos, Heft 1. W. de Gruyter, Berlin, Germany.

Willey, Gordon R., and Philip Phillips
1958 Method and Theory in American Archaeology. University of Chicago Press, Chicago.

Willey, Gordon R., and Jeremy Sabloff
1980 A History of American Archaeology. 2nd edition, W.H. Freeman, San Francisco, CA.

Willey, Gordon R.
1953 Prehistoric Settlement Patterns in the Viru Valley, Peru. BAE Bull. 155. Smithsonian Institution, Washington, D.C.
1959 Aerial Photographic Maps as Survey Aids in the Viru Valley. In The Archaeologist at Work, edited by R.F. Heizer. Harper, New York.
1971 An Introduction to American Archaeology, Vol. 2: South America. Prentice Hall, Englewood Cliffs.
1972 The Viru Valley Settlement Pattern Study. In Archaeological Researches in Retrospect, edited by Gordon R. Willey. Winthrop Publishers, Inc. Cambridge, MA.

Williamson, R.A.
1984 Living the Sky. Houghton Mifflin, Boston, MA.

Windes, Thomas C.
1982 The Prehistoric Road Network at Pueblo Alto, Chaco Canyon, New Mexico. Paper presented at the 81st Annual Meeting of the American Anthropological Association, Washington, D.C.
1987 Investigations at the Pueblo Alto Complex Chaco Canyon New Mexico, 1975-1979. Volume I, Summary of Tests and Excavations at the Pueblo Alto Community. National Park Service, U.S. Dept. of Interior, Santa Fe, NM.
1988 Chaco Province. In Historical Dictionary of North American Archaeology, Edited by Edward B. Jelks. Greenwood Press, New York, NY.

Wiseman, James
1978 The Land of the Ancient Corinthians. Studies in Mediterranean Archaeology. Goteborg, Sweden.

1983 Letter to Dr. Hans Mark, Deputy Administrator, National Aeronautics and Space Administration, in behalf of the Coordinating Council of Archeological Societies, 22 September, 1983.

Wray, James R.
1971 Locating Archaeological Sites by Image Interpretation. USGS/NASA Geographic Applications Program, Washington, D.C.

Wu, Steve, and Steve Sader
1987 Multipolarization SAR Data for Surface Feature Delineation and Forest Vegetation Characterization. IEEE Transaction on Geosceince and Remote Sensing, Vol. GE-25, No. 1.

Wynne-Edwards, V.C.
1962 Animal Dispersion in Relation to Social Behavior. Oliver and Boyd, Edinburgh.

Zuidema, R.T.
1977 The Inca Calendar. In Native American Astronomy, edited by Anthony F. Aveni, pp. 219-259. University of Texas Press, Austin and London.

APPENDIX A

GLOSSARY OF TERMS[1]

Absorptance: A measure of the ability of a surface to absorb incident energy, often at specific wavelengths. (A)

Absorption: The process by which radiant energy is absorbed and converted into other forms of energy. (A)

Absorption band: A range of wavelengths (or frequencies) in the electromagnetic spectrum within which radiant energy is absorbed by a substance. (A)

Absorption spectrum: The array of absorption lines and absorption bands that results from the passage of radiant energy from a continuous source through a selectively absorbing medium cooler than the source. (A)

Absorptivity: The capacity of a material to absorb incident radiant energy. A special case of absorptance, it is a fundamental property of material that has a specular (optically smooth) surface and is sufficiently thick to be opaque. It may be further qualified as spectral absorptivity. The suffix (-ity) implies a property intrinsic with a given material, a limiting value. (A)

Accuracy: The success in estimating the true value. The closeness of an estimate of a characteristic to the true value of the characteristic of the population. (D)

Active system: A remote sensing system that transmits its own electromagnetic emanations at an object(s) and then records the energy reflected or refracted back to the sensor. (A)

Active microwave: Ordinarily referred to as a radar. (A)

Additive color process: A method for creating essentially all colors through the addition of light of the three additive color primaries (blue, green, and red) in various proportions through the use of three separate projectors. In this type of process, each primary filter absorbs the other two primary colors and transmits only about one-third of the luminous energy of the source. It also precludes the possibility of mixing colors with a single light source because the addition of a second primary color results in total absorption of the light transmitted by the first color. (A)

Aerial photograph, vertical: An aerial photograph made with the optical axis of the camera approximately perpendicular to the Earth's surface and with the film as nearly horizontal as is practicable. (A)

Aerial reconnaissance: The securing of information by aerial photography or by visual observation from the air. (A)

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[1] Sources:
- (A) Reeves (ed.) *Manual of Remote Sensing.*
- (B) Swain and Davis, *Remote Sensing: The Quantitative Approach*
- (C) Sabins, *Remote Sensing: Principles and Interpretation.*
- (D) *Glossary of Statistical, Remote Sensing, and Image Processing Terms*, Ed. Ind. (unpublished).

Albedo: (1) The ratio of the amount of EMR reflected by a body to the amount incident upon it, often expressed as a percentage, e.g., the albedo of the Earth is 34 percent. (2) The reflectivity of a body as compared to that of a perfectly diffusing surface at the same distance from the Sun, and normal to the incident radiation. (A)

Algorithm: (1) A fixed step-by-step procedure to accomplish a given result; usually a simplified procedure for solving a complex problem; also a full statement of a finite number of steps. (2) A computer-oriented procedure for resolving a problem. (D)

Alphanumeric: A character set composed of letters, integers, punctuation marks, and special symbols. Usually the number of characters in a set varies between forty-eight and sixty-four. (D)

Analog: A form of data display in which values are shown in graphic form, such as curves. Also a form of computing in which values are represented by directly measurable quantities, such as voltages or resistances. Analog computing methods contrast with digital methods in which values are treated numerically. (A)

Ancillary data: In remote sensing, secondary data pertaining to the area or classes of interest, such as topographical, demographic, or climatological data. Ancillary data may be digitized and used in the analysis process in conjunction with the primary remote sensing data. (B)

Angle of depression: In SLAR usage, the angle between the horizontal plane passing through the antenna and the line connecting the antenna and the target. (C)

Angle of incidence: (1) The angle between the direction of incoming EMR and the normal to the intercepting surface; (2) In SLAR systems this is the angle between the vertical and a line connecting antenna and target. (C)

Angle of reflection: The angle that EMR reflected from a surface makes with the perpendicular (normal) to the surface. (A)

Angle of view: The angle subtended by lines that pass through the center of the lens to diametrically opposite corners of the plate or film used. (A)

Angstrom (Å): Unit of measurement, 10^{-10} m. (A)

Anomaly: An area on an image that differs from the surrounding normal area. For example, a concentration of vegetation within a desert scene constitutes an anomaly. (C)

Atmospheric windows: Those wavelength ranges in which radiation can pass through the atmosphere with relatively little attenuation; in the optical portion of the spectrum, approximately 0.3-2.5, 3.0-4.0, 4.2-5.0, and 7.0-15.0 μm. (B)

Attenuation: In physics, any process in which the flux density (or power, amplitude, intensity, illuminance) of a "parallel beam" of energy decreases with increasing distance from the energy source. (A)

Attitude: The angular orientation of a remote sensing system with respect to a geographical reference system. (C)

Azimuth: The geographical orientation of a line given as an angle measured clockwise from north. (C)

Background: Any effect in a sensor or other apparatus or system, above which the phenomenon of interest must manifest itself before it can be observed. (See background noise.) (A)

Background luminance: In visual-range theory, the luminance (brightness) of the background against which a target is viewed. (A)

Background noise: (1) In recording and reproducing, the total system noise independent of whether or not a signal is present. The signal is not to be included as part of the noise. (2) In receivers, the noise in the absence of signal modulation on the carrier. Ambient noise detected, measured, or recorded with the signal becomes part of the background noise. Included in this definition is the interference resulting from primary power supplies, which separately is commonly described as hum. (A)

Backscatter: The scattering of radiant energy into the hemisphere of space bounded by a plane normal to the direction of the incident radiation and lying on the same side as the incident ray; the opposite of forward scatter. Also called backscattering. (A)

Band: (1) A selection of wavelengths. (2) Frequency band. (3) Absorption band. (4) A group of tracks on a magnetic drum. (5) A range of radar frequencies, such as X-band, Q-band, etc. (A)

Band-pass filter: A wave filter that has a single transmission band extending from a lower cutoff frequency greater than zero to a finite upper cutoff frequency. (A)

Bandwidth: (1) In an antenna, the range of frequencies within which its performance, with respect to some characteristic, conforms to a specified standard. (2) In a wave, the least frequency interval outside which the power spectrum of a time-varying quantity is everywhere less than some specified fraction of its value at a reference frequency. (3) The number of cycles per second between the limits of a frequency band. (A)

Base-height ratio: Air base (ground distance between centers of successive overlapping photos) divided by aircraft height. This ratio determines vertical exaggeration on stereo models. (C)

Batch processing: A method whereby items are coded and collected into groups and then processed sequentially. (D)

Beam: A focused pulse of energy. (C)

Blackbody, black body (symbol bb used as subscript): An ideal emitter which radiates energy at the maximum possible rate per unit area at each wavelength for any given temperature. A blackbody also absorbs all the radiant energy incident upon it. No actual substance behaves as a true blackbody, although platinum black and other soots rather closely approximate this ideal. In accordance with Kirchhoff's law, a blackbody not only absorbs all wavelengths, but also emits at all wavelengths and does so with maximum possible intensity for any given temperature. (A)

Blackbody radiation: The electromagnetic radiation emitted by an ideal blackbody; it is the theoretical maximum amount of radiant energy of all wavelengths that can be emitted by a body at a given temperature. The spectral distribution of blackbody radiation is described by Planck's law and related radiation laws. (A)

Brightness: (1) The attribute of visual perception in accordance with which an area appears to emit more or less light. (2) Luminance. (3) The luminous flux emitted or reflected per unit projected area per unit solid angle. The unit of brightness, the lambert, is defined as brightness of a surface which emits or reflects one/π lumen per square centimeter per steradian. (A)

Brightness temperature: (1) The temperature of a blackbody radiating the same amount of energy per unit area at the wavelengths under consideration as the observed body. Also called effective temperature. (2) The apparent temperature of a nonblackbody determined by measurement with an optical pyrometer or radiometer. (A)

Calibration: The act or process of comparing certain specific measurements in an instrument with a standard. (A)

Camera, multiband: A camera that exposes different areas of one film, or more than one film, through one lens and a beam splitter, or two or more lenses equipped with different filters, to provide two or more photographs in different spectral bands. (A)

Category: Each unit is assumed to be of one and only one given type. The set of types is called the set of "classes" or "categories," each type being a particular category. The categories are chosen specifically by the investigator as being the ones of interest to him. (D)

Cathode ray tube (CRT): A vacuum tube capable of producing a black-and-white or color image by beaming electrons onto a sensitized screen. As a component of a data-processing system, the CRT can be used to provide rapid, pictorial access to numerical data. (B)

Cell: An area on the ground from which EMR is emitted or reflected. (A)

Change-detection images: Images prepared by digitally comparing two original images acquired at different times. The gray tones of each pixel on a change-detection image portray the amount of difference between the original images. (C)

Chopper: A device, usually one that rotates, used to interrupt a continuous wave signal in a transmitter, receiver, or sensor. (A)

Class: A surface characteristic type that is of interest to the investigator, such as forest by type and condition, or water by sediment load. (D)

Classification: The process of assigning individual pixels of a multispectral image to categories, generally on the basis of spectral reflectance characteristics. (C)

Clustering: The analysis of a set of measurement vectors to detect their inherent tendency to form clusters in multidimensional measurement space. (B)

Color: That property of an object which is dependent on the wavelength of the light it reflects or, in the case of a luminescent body, the wavelength of light that it emits. If, in either case, this light is of a single wavelength, the color seen is a pure spectral color; but if light of two or more wavelengths is emitted, the color will be mixed. White light is a balanced mixture of all the visible spectral colors. (A)

Color balance: The proper intensities of colors in a color print, positive transparency, or negative, that give a correct reproduction of the gray scale (as faithful as can be achieved by photographic representation of the true colors of a scene.) (A)

Color composite (multiband photography): A color picture produced by assigning a color to a particular spectral band. In Landsat, blue is ordinarily assigned to MSS band 4 (0.5-0.6 μm), green to band 5 (0.6-0.7 μm), and red to band 7 (0.8-1.1 μm), to form a picture closely approximating a color-infrared photograph. (A)

Color infrared film: Photographic film sensitive to energy in the visible and near-infrared wavelengths, generally from 0.4-0.9 μm; usually used with a minus-blue (yellow) filter, which results in an effective film sensitivity of 0.5-0.9 μm. Color infrared film is especially useful for detecting changes in the condition of the vegetative canopy which are often manifested in the near-infrared region of the spectrum. Note that color infrared film is not sensitive in the thermal infrared region and therefore cannot be used as a heat-sensitive detector. (B)

Color temperature: An estimate of the temperature of an incandescent body, determined by observing the wavelength at which it is emitting with peak intensity (its color), determined by applying the Wien law. (A)

Computer-compatible tapes: Tapes containing digital Landsat data. These tapes are standard 19-cm (7½-in) wide magnetic tapes in 9-track or 7-track format. Four tapes are required for the four-band multispectral digital data corresponding to one Landsat scene. (D)

Continuous spectrum: (1) A spectrum in which wavelengths, wavenumbers, and frequencies are represented by the continuum of real numbers or a portion thereof, rather than by a discrete sequence of numbers. See absorption spectrum. (2) For EMR, a spectrum that exhibits no detailed structure and represents a gradual variation of intensity with wavelength from one end to the other, as the spectrum from an incandescent solid. (A)

Contrast stretching: Improving the contrast of images by digital processing. The original range of digital values is expanded to utilize the full contrast range of the recording film or display device. (C)

Coordinates, geographical: A system of spherical coordinates for describing the positions of points on the Earth. The declinations and polar bearings in this system are the latitudes and longitudes, respectively. (A)

Covariance: The measure of how two variables change in relation to each other (covariability). If larger values of Y tend to be associated with larger values of X, the covariance will be positive. If larger values of Y are associated with smaller values of X, the covariance will be negative. When there is no particular association between X and Y, the covariance value will approach zero. (D)

Cultural features: All map detail representing man-made elements of the landscape. (D)

Cursor: Aiming device, such as a lens with cross-hairs, on a digitizer or an interactive computer display. (D)

Data acquisition system: The collection of devices and media that measures physical variables and records them prior to input to the data processing system. (B)

Data bank: A well-defined collection of data, usually of the same general type, which can be accessed by a computer. (B)

Data dimensionality: The number of variables (e.g., channels) present in the data set. The term "intrinsic dimensionality" refers to the smallest number of variables that could be used to represent the data set accurately. (B)

Data processing: Application of procedures—mechanical electrical, computation, or other—whereby data are changed from one form into another. (A)

Data reduction: Transformation of observed values into useful, ordered, or simplified information. (A)

Decision rule (or classification rule): The criterion used to establish discriminant functions for classification (e.g., nearest-neighbor rule, minimum-distance-to-means rule, maximum-likelihood rule). (B)

Density (symbol, D): A measure of the degree of blackening of an exposed film, plate, or paper after development, or of the direct image (in the case of a printout material). It is defined strictly as the logarithm of the optical opacity, where the opacity is the ratio of the incident to the transmitted (or reflected) light or transmissivity, T, as $D = \log(1/T)$. (A)

Density slicing: The process of converting the continuous gray tone of an image into a series of density intervals, or slices, each corresponding to a specific digital range. (C)

Detection: A unit is said to be "detected" if the decision rule is able to assign it as belonging only to some given subset of categories from the set of all categories. Detection of a unit does not imply that the decision rule is able to identify the unit as specifically belonging to one particular category. (D)

Detector (radiation): A device providing an electrical output that is a useful measure of incident radiation. It is broadly divisible into two groups: thermal (sensitive to temperature changes), and photodetectors (sensitive to changes in photon flux incident on the detector), or it may also include antennas and film. Typical thermal detectors are thermocouples, thermopiles, and thermistors; the latter is termed a bolometer. (A)

Dielectric constant: Electrical property of matter that influences radar returns; also referred to as complex dielectric constant. (C)

Diffraction: The propagation of EMR around the edges of opaque objects into the shadow region. A point of light seen or projected through a circular aperture will always be imaged as a bright center surrounded by light rings of gradually diminishing intensity in the shadow region. Such a pattern is called a diffraction disk, Airy disk, or centric. (A)

Diffuse reflection: The type of reflection obtained from a relatively rough (in terms of the wavelength of the EMR) surface, in which the reflected rays are scattered in all directions. (A)

Diffuse reflector: Any surface that reflects incident rays in many directions, either because of irregularities in the surface or because the material is optically inhomogeneous, as a paint; the opposite of a specular reflector. Ordinary writing papers are good examples of diffuse reflectors, whereas mirrors or highly polished plates are examples of specular reflectors in the visible portion of the EM spectrum. Almost all terrestrial surfaces (except calm water) act as diffuse reflectors of incident solar radiation. The smoothness or roughness of a surface depends on the wavelength of the incident EMR. (A)

Diffuse sky radiation: Solar radiation reaching the Earth's surface after having been scattered from the direct solar beam by molecules or suspensoids in the atmosphere. Also called skylight, diffuse skylight, sky radiation. (A)

Digitization: The process of converting an image recorded originally on photographic material into numerical format. (C)

Discriminant function: One of a set of mathematical functions which in remote sensing are commonly derived from training samples and a decision rule, and are used to divide the measurement space into decision regions. (B)

Display: An output device that produces a visible representation of a data set for quick visual access; usually the primary hardware component is a cathode ray tube. (B)

Distribution function: The relative frequency with which different values of a variable occur. (D)

DN: Digital number. The value of reflectance recorded for each pixel on Landsat CCT's. (C)

Edge: The boundary of an object in a photograph or image, usually characterized by a rather drastic change in the gray shade value from the immediate interior of the boundary to the immediate exterior of the boundary. (D)

Edge enhancement: The use of analytical techniques to emphasize transition in imagery. (A)

Electromagnetic radiation (EMR): Energy propagated through space or through material media in the form of an advancing interaction between electric and magnetic fields. The term radiation, alone, is commonly used for this type of energy, although it actually has a broader meaning. Also called electromagnetic energy. (A)

Electromagnetic spectrum: The ordered array of known electromagnetic radiations extending from the shortest cosmic rays, through gamma rays, X-rays, ultraviolet radiation, visible radiation, infrared radiation, and including microwave and all other wavelengths of radio energy. (A)

Element: The smallest definable object of interest in the survey. It is a single item in a collection, population, or sample. (D)

Emission: With respect to EMR, the process by which a body emits EMR usually as a consequence of its temperature only. (A)

Emissivity: The ratio of the radiation given off by a surface to the radiation given off by a blackbody at the same temperature; a blackbody has an emissivity of 1, other objects between 0 and 1. (B)

Emittance: The obsolete term for the radiant flux per unit area emitted by a body, or exitance. (A)

Environment: An external condition, or the sum of such conditions, in which a piece of equipment or a system operates, as in temperature environment, vibration environment, or space environment. The environments are usually specified by a range of values, and may be either natural or artificial. (A)

Ephemeral data: Data that: (1) help to characterize the conditions under which the remote sensing data were collected: (2) may be used to calibrate the sensor data prior to analysis; (3) include such information as the positioning and spectral stability of sensors, Sun angle, platform attitude, etc. (B)

Equivalent blackbody temperature: The temperature measured radiometrically corresponding to that which a blackbody would have. Most natural objects including soil, plant leaves, and water have emissivities greater than 0.9 but less than 1.0. (A)

Exitance (symbol, M): The radiant flux per unit area emitted by a body or surface. (A)

False color: The use of one color to represent another; for example, the use of red emulsion to represent infrared light in color infrared film. (A)

Far range: Refers to the portion of an SLAR image farthest from the aircraft flight path. (C)

Feature: An n-tuple or vector with components which are functions of the initial measurement pattern variables or some subsequence of the measurement n-tuples. Feature n-tuples or vectors frequently have fewer components than the initial measurement vectors and are designed to contain a high amount of information about the discrimination between units of the types of categories in the given category set. Features often contain information about gray shade, texture, shape or context. Also, a cartographic type in digital form appearing as part of the descriptor in coded form (Feature Code). (D)

Feature extraction: The process in which an initial measurement pattern or some subsequence of measurement patterns is transformed to a new pattern feature. (D)

Field of view: The solid angle through which an instrument is sensitive to radiation. Owing to various effects, diffractions, etc., the edges are not sharp. In practice they are defined as the "half-power" points, i.e., the angle outwards from the optical axis, at which the energy sensed by the radiometer drops to half its on-axis value. (A)

Filter: (1, noun) Any material which, by absorption or reflection, selectively modifies the radiation transmitted through an optical system. (2, verb) To remove a certain component or components of EMR, usually by means of a filter, although other devices may be used. (A)

Filtering: In analysis, the removal of certain spectral or spatial frequencies to highlight features in the remaining image. (A)

Focus: The point at which the rays from a point source of light reunite and cross after passing through a camera lens. In practice, the plane in which a sharp image of any scene is formed. (A)

Format: The arrangement of descriptive data in descriptors, identifiers, or labels. The arrangement of data in bit, byte, and word form in the CPU. (D)

Frame: Complete tape of a single or multidate Landsat frame covering roughly an area about 100 nautical miles square. (D)

Frequency: Number of oscillations per unit time or number of wavelengths that pass a point per unit time. (D)

Frequency response: (1) Response of a system as a function of the frequency of excitations. (2) The portion of the frequency spectrum that can be sensed by a device within specified limits of amplitude error. (A)

Gain: (1) A general term used to denote an increase in signal power in transmission from one point to another. Gain is usually expressed in decibels. (2) An increase or amplification. (A)

Gamma: A numerical measure of the extent to which a negative has been developed, indicating the proportion borne by the contrast of the negative to that of the subject on which it was exposed. The numerical figure for gamma is the tangent of the straight-line (correct exposure portion of the curve resulting from plotting exposure against density. (A)

GCP: Ground control point. A geographical feature of known location that is recognizable on images and can be used to determine geometrical corrections. (C)

Geocoding: Geographical referencing or coding of location of data items. (D)

Geometrical transformations: Adjustments made in the image data to change its geometrical character, usually to improve its geometrical consistency or cartographic utility. (B)

Gray body: A radiating surface whose radiation has essentially the same spectral energy distribution as that of a blackbody at the same temperature, but whose emissive power is less. Its absorptivity is nonselective. Also spelled *grey* body. (A)

Gray scale: A monochrome strip of shades ranging from white to black with intermediate shades of gray. The scale is placed in a setup for color photograph and serves as a means of balancing the separation negatives and positive dye images. (A)

Grid line: One of the lines in a grid system; a line used to divide a map into squares. East-west lines in a grid sytem are x-lines, and north-south lines are y-lines. (A)

Ground data: Supporting data collected on the ground, and information derived therefrom, as an aid to the interpretation of remotely recorded surveys, such as airborne imagery, etc. Generally, this should be performed concurrently with the airborne surveys. Data as to weather, soils and vegetation types and conditions are typical. (A)

Ground range: The distance from the ground track (nadir) to a given object. (A)

Ground resolution cell: The area on the terrain that is covered by the instantaneous field of view of a detector. The size of the ground resolution cell is determined by the altitude of the remote-sensing system and the instantaneous field of view of the detector. (C)

Ground track: The vertical projection of the actual flight path of an aerial or space vehicle onto the surface of the Earth or other body. (A)

Ground truth (jargon): Term coined for data and information obtained on surface or subsurface features to aid in interpretation of remotely sensed data. Ground data and ground information are preferred terms. (A)

H-D (Hurter-Driffield) Curve: A graph showing the relationship of exposure to (photo) density, where the density is plotted against the logarithm of the exposure (also known as characteristic curve). (A)

Hardware: The physical components of a computer and its peripheral equipment. Contrasted with software. (D)

Histogram: The graphical display of a set of data which shows the frequency of occurrence (along the vertical axis) of individual measurements or values (along the horizontal axis); a frequency distribution. (B)

Hue: That attribute of a color by virtue of which it differs from gray of the same brilliance, and which allows it to be classed as red, yellow, green, blue, or intermediate shades of these colors. (A)

Illumination: The intensity of light striking a unit surface is known as the specific illumination or luminous flux. It varies directly with the intensity of the light source and inversely as the square of the distance between the illuminated surface and the source. It is measured in a unit called the lux. The total illumination is obtained by multiplying the specific illumination by the area of the surface covered by the light. The unit of total illumination is the lumen. (A)

Image: (1) The counterpart of an object produced by the reflection or refraction of light when focused by a lens or mirror. (2) The recorded representation (commonly as a photo-image) of an object produced by optical, electro-optical, optical mechanical, or electronic means. It is generally used when the EMR emitted or reflected from a scene is not directly recorded on film. (A)

Image Enhancement: Any one of a group of operations that improve the detectability of the targets or categories. These operations include, but are not limited to, contrast improvement, edge enhancement, spatial filtering, noise supression, image smoothing, and image sharpening. (D)

Image Processing: Encompasses all the various operations that can be applied to photographic or image data. These include, but are not limited to, image compression, image restoration, image enhancement, preprocessing, quantization, spatial filtering and other image pattern recognition techniques. (D)

Image Restoration: A process by which a degraded image is restored to its original condition. Image restoration is possible only to the extent that the degradation transform is mathematically invertible. (D)

Incident ray: A ray impinging on a surface. (A)

Infrared: Pertaining to energy in the 0.7-100 μm wavelength region of the electromagnetic spectrum. For remote sensing, the infrared wavelengths are often subdivided into near infrared (0.7-1.3 μm), middle infrared (1.3-3.0 μm), and far infrared (7.0-15.0 μm). Far infrared is sometimes referred to as thermal or emissive infrared. (B)

Infrared, photographic: Pertaining to or designating the portion of the EM spectrum with wavelengths just beyond the red end of the visible spectrum; generally defined as from 0.7 to about 0.1 μm, or the useful limits of film sensitivities. (A)

Insolation: Incident solar energy. (C)

Instantaneous field of view: (IFOV) A term specifically denoting the narrow field of view designed into detectors, particularly scanning radiometer systems, so that, while as much as 120° may be under scan, only EMR from a small area is being recorded at any one instant. (A)

Interactive image processing: The use of an operator or analyst at a console that provides the means of assessing, preprocessing, feature extracting, classifying, identifying, and displaying the original imagery or the processed imagery for his subjective evaluations and further interactions. (D)

Irradiance: The measure, in power units, of radiant flux incident upon a surface. It has the dimensions of energy per unit time (e.g., watts). (A)

Irradiation: The impinging of EMR on an object or surface. (A)

Kelvin: A thermometer scale starting at absolute zero (-273°C approximately) and having degrees of the same magnitude as those of the Celsius thermometer. Thus, 0°C = 273°K; 100°C = 373 °K; etc.; also called the absolute scale, thermodynamic temperature scale. (A)

Kinetic temperature: The internal temperature of an object, which is determined by the molecular motion. Kinetic temperature is measured with a contact thermometer, and differs from radiant temperature, which is a function of emissivity and internal temperature. (C)

Kirchhoff's Law: The radiation law which states that at a given temperature the ratio of the emissivity to the absorptivity for a given wavelength is the same for all bodies and is equal to the emissivity of an ideal blackbody at that temperature and wavelength. This important law asserts that good absorbers of a given wavelength are also good emitters of the wavelength. (A)

Lambertian surface: An ideal, perfectly diffusing surface, which reflects energy equally in all directions. (B)

Large scale: (1) Aerial photography with a representative fraction of 1:500 to 1:10,000. (2) Maps with a representative fraction (scale) greater than 1:100,000. (A)

Layover: Displacement of the top of an elevated feature with respect to its base on the radar image. The peaks look like dip-slopes. (A)

Light: Visible radiation (about 0.4-0.7 μm in wavelength) considered in terms of its luminous efficiency; i.e., evaluated in proportion to its ability to stimulate the sense of sight. (A)

Line, flight: A line drawn on a map or chart to represent the track over which an aircraft has been flown or is to fly. The line connecting the principal points of vertical aerial photographs. (A)

Lineament: A linear topographical or tonal feature on the terrain and on images and maps, which may represent a zone of structural weakness. (C)

Linear feature: A two-dimensional, straight to somewhat curved (usually) line, linear pattern, or alignment of discontinuous patterns evident in an image, photo, a map, which represents the expression of some degree of linearity of a single or diverse grouping of natural or cultural ground features. (Definition by N.M. Short.)

Look direction: Direction in which pulses of microwave energy are transmitted by an SLAR system. Look direction is normal to the azimuth direction. Also called range direction. (C)

Luminance: In photometry, a measure of the intrinsic luminous intensity emitted by a source in a given direction; the illuminance produced by light from the source upon a unit surface area oriented normal to the line of sight at any distance from the source, divided by the solid angle subtended by the source at the receiving surface. Also called brightness (luminance is preferred). (A)

Map: A representation in a plane surface, at an established scale, of the physical features (natural, artificial, or both) of a part of the Earth's surface, with the means of orientation indicated. (A)

Map, large-scale: A map having a scale of 1:100,000 or larger. (A)

Map, medium-scale: A map having a scale from 1:100,000, exclusive, to 1:1,000,000, inclusive. (A)

Map, small-scale: A map having a scale smaller than 1:1,000,000. (A)

Map, thematic: A map designed to demonstrate particular features or concepts. In conventional use this term excludes topographical maps. (D)

Maximum likelihood rule: A statistical decision criterion to assist in the classification of overlapping signatures; pixels are assigned to the class of highest probability.

Mie scattering: Multiple reflection of light waves by atmospheric particles that have the approximate dimensions of the wavelength of light. (C)

Micrometer (abbr. μm): A unit of length equal to one-millionth (10^{-6}) of a meter or one-thousandth (10^{-3}) of a millimeter. (A)

Micron (abbr. μ): Equivalent to and replaced by micrometer; 10^{-6} m. (A)

Microwave: Electromagnetic radiation having wavelengths between 1 m and 1 mm or 300-0.3 GHz in frequency, bounded on the short wavelength side by the far infrared (at 1 mm) and on the long wavelength side by very high-frequency radio waves. Passive systems operating at these wavelengths are sometimes called microwave systems. Active systems are called radar, although the literal definition of radar requires a distance-measuring capability not always included in active systems. The exact limits of the microwave region are not defined. (A)

Minimum distance classifier: A classification technique that assigns raw data to the class whose mean falls the shortest Euclidean distance from it.

Mosaic: An assemblage of overlapping aerial or space photographs or images whose edges have been matched to form a continuous pictorial representation of a portion of the Earth's surface. (A)

Mosaic, controlled: A mosaic that is laid to ground control and uses prints that have been rectified as shown to be necessary by the control. (A)

Mosaicking: The assembling of photographs or other images whose edges are cut and matched to form a continuous photographic representation of a portion of the Earth's surface. (A)

Multiband system: A system for simultaneously observing the same (small) target with several filtered bands, through which data can be recorded. Usually applied to cameras; may be used for scanning radiometers that use dispersant optics to split wavelength bands apart for viewing by several filtered detectors. (A)

Multichannel system: Usually used for scanning systems capable of observing and recording several channels of data simultaneously, preferably through the same aperture. (A)

Multispectral: Generally used for remote sensing in two or more spectral bands, such as visible and IR. (A)

Multispectral (line) scanner: A remote sensing device that operates on the same principle as the infrared scanner, except that it is capable of recording data in the ultraviolet and visible portions of the spectrum as well as the infrared. (A)

Multivariate analysis: A data-analysis approach that makes use of multidimensional interrelations and correlations within the data for effective discrimination. (B)

Nadir: (1) That point on the celestial sphere vertically below the observer, or 180° from the zenith. (2) That point on the ground vertically beneath the perspective center of the camera lens. (A)

Nautical mile (abbr. knot): A unit of distance used principally in navigation. For practical navigation it is usually considered the length of one minute of any great circle of the Earth, the meridian being the great circle most commonly used. Also called sea mile. (A)

Near range: Refers to the portion of an SLAR image closest to the aircraft flight path. (C)

Noise: Random or regular interfering effects in the data which degrade its information-bearing quality. (B)

Orbit: The path of a satellite around a body under the influence of gravity. (C)

Overlap: The area common to two successive photos along the same flight strip; the amount of overlap is expressed as a percentage of photo area. Also called endlap. (A)

Overlay: (1) A transparent sheet giving information to supplement that shown on maps. When the overlay is laid over the map on which it is based, its details will supplement the map. (2) A tracing of selected details on a photograph, mosaic, or map to present the interpreted features and the pertinent detail. (A)

Panchromatic: Used for films that are sensitive to broadband (e.g., entire visible part of spectrum) EMR, and for broadband photographs. (A)

Passive system: A sensing system that detects or measures radiation emitted by the target. Compare active system. (A)

Pattern: (1) In a photo image, the regularity and characteristic placement of tones or textures. Some descriptive adjectives for patterns are regular, irregular, random, concentric, radial, and rectangular. (2) The relations between any more-or-less independent parameters of a response, e.g., the pattern in the frequency domain of the response from an object. (A)

Pattern recognition: Concerned with, but not limited to, problems of:

1. pattern discrimination,
2. pattern classification,
3. feature selection,
4. pattern identification,
5. cluster identification,
6. feature extraction,
7. preprocessing,
8. filtering,
9. enhancement,
10. pattern segmentation,
11. screening. (D)

Perspective: Representation, on a plane or curved surface, of natural objects as they appear to the eye. (A)

Photogrammetry: The art or science of obtaining reliable measurements by means of photography. (A)

Photograph: A picture formed by the action of light on a base material coated with a sensitized solution that is chemically treated to fix the image points at the desired density. Usually now taken to mean the direct action of EMR on the sensitized material. Compare image. (A)

Photographic interpretation: The act of examining photographic images for the purpose of identifying objects and judging their significance. Photo interpretation, photointerpretation, and image interpretation are other widely used terms. (A)

Pitch: Rotation of an aircraft about the horizontal axis normal to its longitudinal axis, which causes a nose-up nose-down attitude. (C)

Picture: Representation of a scene by a photographic positive print or transparency, made from a negative, produced by the direct action of actinic (visible) light or EMR outside the visible part of the spectrum and converted into visible EMR by an optical-mechanical or wholly electronic scanner. (A)

Pixel: (Derived from "picture element.") A data element having both spatial and spectral aspects. The spatial variable defines the apparent size of the resolution cell (i.e., the area on the ground represented by the data values), and the spectral variable defines the intensity of the spectral response for that cell in a particular channel. (B)

Planck's Law: An expression for the variation of monochromatic emittance (emissive power) as a function of wavelength of blackbody radiation at a given temperature; it is the most fundamental of the radiation laws. (A)

Polarization: The direction of vibration of the electrical field vector of electromagnetic radiation. In SLAR systems polarization is either horizontal or vertical. (C)

Precision: A measure of the dispersion of the values observed when measuring a characteristic of elements of a population. The clustering of sample values about their own average. (D)

Pulse: (1) A variation of a quantity whose value is normally constant; this variation is characterized by a rise and a decay, and has a finite duration. (2) A short burst of EMR transmitted by the radar. (A)

Radar: Acronym for radio detection and ranging. A method, system or technique, including equipment components, for using beamed, reflected, and timed EMR to detect, locate, and (or) track objects, to measure altitude and to acquire a terrain image. In remote sensing of the Earth's or a planetary surface, it is used for measuring and, often, mapping the scattering properties of the surface. (A)

Radar beam: The vertical fan-shaped beam of EM energy produced by the radar transmitter. (A)

Radar shadow: A dark area of no return on a radar image that extends in the far-range direction from an object on the terrain that intercepts the radar beam. (C)

Radiance: The accepted term for radiant flux in power units (e.g., W) and not for flux density per solid angle (e.g., W cm^{-2} sr^{-1}) as often found in recent publications. (A)

Radiant flux: The time rate of the flow of radiant energy; radiant power. (B)

Radiant power: Rate of change of radiant energy with time. May be further qualified as spectral radiant power, at a given wavelength. (A)

Radiant temperature: Concentration of the radiant flux from a material. Radiant temperature is the product of the kinetic temperature multiplied by the emissivity to the one-fourth power. (C)

Radiation: The emission and propagation of energy through space or through a material medium in the form of waves; for example, the emission and propagation of EM waves, or of sound and elastic waves. The process of emitting radiant energy. (A)

Radiometer: An instrument for quantitively measuring the intensity of EMR in some band of wavelengths in any part of the EM spectrum. Usually used with a modifier, such as an IR radiometer or a microwave radiometer. (A)

Radiometric correction: Correcting gain and offset variations in MSS data. Procedure calibrates and corrects the radiation data provided by the Landsat sensor detectors.

Range direction: For radar images this is the direction in which energy is transmitted from the antenna and is normal to the azimuth direction. Also called look direction. (C)

Rayleigh-Jeans Law: An approximation to Planck's Law for blackbody radiation valid in the longer (microwave) wavelengths. It is almost always of sufficient accuracy for calculations in the radio and microwave regions of the spectrum. (A)

Rayleigh scattering: The wavelength-dependent scattering of electromagnetic radiation by particles in the atmosphere much smaller than the wavelengths scattered. (B)

Real-aperture radar: SLAR system in which azimuth resolution is determined by the physical length of the antenna and by the wavelength. The radar returns are recorded directly to produce images. Also called brute-force radar. (C)

Real time: Time in which reporting on events or recording of events is simultaneous with the events. For example, the real time of a satellite is the time in which it simultaneously reports its environment as it encounters it; the real time of a computer is the time during which it is accepting data and performing operations on it. (A)

Reflectance: The ratio of the radiant energy reflected by a body to that incident upon it. The suffix (-ance) implies a property of that particular specimen surface. (A)

Reflection (EMR theory): EMR neither absorbed nor transmitted is reflected. Reflection may be diffuse when the incident radiation is scattered upon being reflected from the surface, or specular, when all or most angles of reflection are equal to the angle of incidence. (A)

Reflectivity: A fundamental property of a material that has a reflecting surface and is sufficiently thick to be opaque. One may further qualify it as spectral reflectivity. The suffix (-ity) implies a property intrinsic with a given material, a limiting value. (A)

Refraction: The bending of EMR rays when they pass from one medium into another having a different index of refraction or dielectric coefficient. EMR rays also bend in media that have continuous variations in their indices of refraction or dielectric coefficients. (A)

Registration: The process of geometrically aligning two or more sets of image data such that resolution cells for a single ground area can be digitally or visually superposed. Data being registered may be of the same type, from very different kinds of sensors, or collected at different times. (B)

Remote sensing: In the broadest sense, the measurement or acquisition of information of some property of an object or phenomenon, by a recording device that is not in physical or intimate contact with the object or phenomenon under study; e.g., the utilization at a distance (as from an aircraft, spacecraft, or ship) of any device and its attendant display for gathering information pertinent to the environment, such as measurements of force fields, electromagnetic radiation, or acoustic energy. The technique employs such devices as the camera, lasers, and radio frequency receivers, radar systems, sonar, seismographs, gravimeters, magnetometers, and scintillation counters. (A)

Resolution: The ability of an entire remote sensor system, including lens, antennae, display, exposure, processing, and other factors, to render a sharply defined image. It may be expressed as line pairs per millimeter or meter, or in many other ways. In radar, resolution usually applies to the effective beam-width and range measurement width, often defined as the half-power points. For infrared line scanners the resolution may be expressed as the instantaneous field of view. Resolution may also be expressed in terms of temperature or other physical property being measured. (A)

Resolution cell: The smallest area in a scene considered as a unit of data. For Landsat-1 and -2 the resolution cell approximates a rectangular ground area of 0.44 hectares or 1.1 acres (see pixel, instantaneous field of view). (B)

Reststrahlen (residual) rays: The difference in intensities or radiance at certain frequencies (wavelengths) between the special signatures for the ideal (perfect blackbody) and actual emission curves of a substance.

Return beam vidicon (RBV): A modified vidicon television camera tube, in which the output signal is derived from the depleted electron beam reflected from the tube target. The RBV can be considered as a cross between a vidicon and an orthicon. RBVs provide highest resolution TV imagery, and are used in the ERTS (Landsat) series. (A)

Roll: Rotation of an aircraft about the longitudinal axis to cause a wing-up or wing-down attitude. (C)

Roughness: For radar images this term describes the average vertical relief of small-scale irregularities of the terrain surface. (C)

Sample: A subset of a population selected to obtain information concerning the characteristics of the population. (D)

Sampling rate: The temporal, spatial, or spectral rate at which measurements of physical quantities are taken. Temporally, sampling variables may describe how often data are collected or the rate at which an analog signal is sampled for conversion to digital format; the spatial sampling rate describes the number, ground size, and position of areas where spectral measurements are made; the spectral sampling rate refers to the location and width of the sensor's spectral channels with respect to the electromagnetic spectrum. (B)

Scale: The ratio of a distance on a photograph or map to its corresponding distance on the ground. The scale of a photograph varies from point to point because of displacements caused by tilt and relief, but is usually taken as f/H, where f is the principal distance (focal length) of the camera and H is the height of the camera above mean ground elevation. Scale may be expressed as a ratio 1:24,000; a representative fraction, 1/24,000; or an equivalence, 1 in. = 2,000 ft. (A)

Scan line: The narrow strip on the ground that is swept by the instantaneous field of view of a detector in a scanner system. (C)

Scanner: (1) Any device that scans, and thus produces an image. See scanning radiometer. (2) A radar set incorporating a rotatable antenna, or radiator element, motor drives, mounting, etc. for directing a searching radar beam through space and imparting target information to an indicator. (A)

Scanning radiometer: A radiometer, which by the use of a rotating or oscillating plane mirror, can scan a path normal to the movement of the radiometer. (A)

Scattering: (1) The process by which small particles suspended in a medium of a different index of refraction diffuse a portion of the incident radiation in all directions. (2) The process by which a rough surface reradiates EMR incident upon it. (A)

Scene: In a passive remote sensing system, everything occurring spatially or temporally before the sensor, including the Earth's surface, the energy source, and the atmosphere, that the energy passes through as it travels from its source to the Earth and from the Earth to the sensor. (B)

Sensitivity: The degree to which a detector responds to electromagnetic energy incident upon it. (C)

Sensor: Any device that gathers energy, EMR or other, converts it into a signal and presents it in a form suitable for obtaining information about the environment. (A)

Sidelap: The extent of lateral overlap between images acquired on adjacent flight lines. (C)

Signal: The effect (e.g., pulse of electromagnetic energy) conveyed over a communication path or system. Signals are received by the sensor from the scene and converted to another form for transmission to the processing system. (B)

Signal-to-noise ratio: The ratio of the level of the information-bearing signal power to the level of the noise power. Abbreviated as S/N.

Signature: Any characteristic or series of characteristics by which a material may be recognized in an image, photo, or data set. See also spectral signature. (A)

Signature analysis techniques: Techniques that use the variation in the spectral reflectance or emittance of objects as a method of identifying the objects. (A)

Signature extension: The use of training statistics obtained from one geographical area to classify data from similar areas some distance away; includes consideration of changes in atmosphere, and other geographical and temporal conditions that can cause differences in signal level for single classes of interest (see spectral signature). (B)

Smoothing: The averaging of densities in adjacent areas to produce more gradual transitions. (A)

Slant range: For radar images this term represents the distance measured along a line between the antenna and the target. (C)

Software: The computer programs that drive the hardware components of a data processing system; includes system monitoring programs, programming language processors, data handling utilities, and data analysis programs. (B)

Spatial filter: An image transformation, usually a one-to-one operator used to lessen noise or enhance certain characteristics of the image. For any particular (x, y) coordinate on the transformed image, the spatial filter assigns a gray shade on the basis of the gray shades of a particular spatial pattern near the coordinates (x, y). (D)

Spatial information: Information conveyed by the spatial variations of spectral response (or other physical variables) present in the scene. (B)

Spectral band: An interval in the electromagnetic spectrum defined by two wavelengths, frequencies, or wavenumbers. (A)

Spectral interval: The width, generally expressed in wavelength or frequency of a particular portion of the electromagnetic spectrum. A given sensor (e.g., radiometer or camera film) is designed to measure or be sensitive to energy received at the satellite from that part of the spectrum. Also termed spectral band. (A)

Spectral reflectance: The reflectance of electromagnetic energy at specified wavelength intervals. (C)

Spectral regions: Conveniently designated ranges of wavelengths subdividing the electromagnetic spectrum; for example, the visible region, X-ray region, infrared region, middle-infrared region. (B)

Spectral response: The response of a material as a function of wavelength to incident electromagnetic energy, particularly in terms of the measurable energy reflected from and emitted by the material. (B)

Spectral signature: Quantitative measurement of the properties of an object at one or several wavelength intervals. (A)

Spectrometer: A device to measure the spectral distribution of EMR. This may be achieved by a dispersive prism, grating, or circular interference filter with a detector placed behind a slit. If one detector is used, the dispersive element is moved so as to sequentially pass all dispersed wavelengths across the slit. In an interferometer-spectrometer, on the other hand, all wavelengths are examined all the time, the scanning effect being achieved by rapidly oscillating two, partly reflective, (usually parallel) plates so that interference fringes are produced. A Fourier transform is required to reconstruct the spectrum. Also called spectroradiometer. (A)

Specular reflection: The reflectance of electromagnetic energy without scattering or diffusion, as from a surface that is smooth in relation to the wavelengths of incident energy. Also called mirror reflection. (B)

Stefan-Boltzmann Law: One of the radiation laws stating that the amount of energy radiated per unit time from a unit surface area of an ideal blackbody is proportional to the fourth power of the absolute temperature of the blackbody. (A)

Steradian: The unit solid angle that cuts unit area from the surface of a sphere of unit radius centered at the vertex of the solid angle. There are 4π steradians in a sphere. (A)

Subtractive color process: A method of creating essentially all colors through the subtraction of light of the three subtractive color primaries (cyan, magenta and yellow) in various proportions through use of a single white light source. (A)

Supervised classification: A computer-implemented process through which each measurement vector is assigned to a class according to a specified decision rule, where the possible classes have been defined on the basis of representative training samples of known identity. (B)

Swath width (total field of view): The overall plane angle or linear ground distance covered by a multispectral scanner in the across-track direction. (B)

Synchronous satellite: An equatorial west-to-east satellite orbiting the Earth at an altitude of 34,900 km, at which altitude it makes one revolution in 24 h synchronous with the Earth's rotation. (A)

Synoptic view: The ability to see or otherwise measure widely dispersed areas at the same time and under the same conditions; e.g., the overall view of a large portion of the Earth's surface which can be obtained from satellite altitudes. (B)

System: Structured organization of people, theory, methods and equipment to carry out an assigned set of tasks. (D)

Target: (1) An object on the terrain of specific interest in a remote sensing investigation. (2) The portion of the Earth's surface that produces by reflection or emission the radiation measured by the remote sensing system. (B,C)

Thermal band: A general term for middle-infrared wavelengths which are transmitted through the atmosphere window at 8-14 μm. Ocasionally also used for the windows around 3-6 μm. (A)

Thermal capacity (symbol, C): The ability of a material to store heat, expressed in cal g^{-1} $°C^{-1}$ (C)

Thermal conductivity (symbol K): The measure of the rate at which heat passes through a material, expressed in cal cm^{-1} s^{-1} $°C^{-1}$. (C)

Thermal crossover: On a plot of radiant temperature versus time, this refers to the point at which the temperature curves for two different materials intersect. (C)

Thermal inertia (symbol, P): A measure of the response of a material to temperature changes, expressed in cal cm^{-2} $°C^{1}$ $s^{-½}$. (C)

Thermal infrared: The preferred term for the middle wavelength range of the IR region, extending roughly from 3 μm at the end of the near infrared, to about 15 or 20 μm, where the far infrared begins. In practice the limits represent the envelope of energy emitted by the Earth behaving as a gray body with a surface temperature around 290°K (27 °C). (A)

Threshold: The boundary in spectral space beyond which a data point, or pixel, has such a low probability of inclusion in a given class that the pixel is excluded from that class. (D)

Tone: Each distinguishable shade of gray from white to black on an image. (C)

Training: Informing the computer system which sites to analyze for spectral properties or signatures of specific land cover classes; also called signature extraction.

Training samples: The data samples of known identity used to determine decision boundaries in the measurement or feature space prior to classification of the overall set of data vectors from a scene. (B)

Training sites: Recognizable areas on an image with distinct (spectral) properties useful for identifying other similar areas.

Transmissivity: Transmittance for a unit thickness sample. One may further qualify it as spectral transmissivity. The suffix (ity) implies a property intrinsic with a given material. (A)

Transmittance: The ratio of the radiant energy transmitted through a body to that incident upon it. The suffix (-ance) implies a property of that particular specimen. (A)

Ultraviolet radiation: EMR of shorter wavelength than visible radiation but longer than X-rays; roughly, radiation in the wavelength interval between 10 and 4000 Å.

Variance: Variance of a random variable is the expected value of the square of the deviation between that variable and its expected value. It is a measure of the dispersion of the individual unit values about their mean. (D)

Vidicon: (1) A storage-type electronically scanned photoconductive television camera tube, which often has a response to radiations beyond the limits of the visible region. Particularly useful in space applications, as no film is required. (2) An image-plane scanning device. See return beam vidicon. (A)

Vignetting: A gradual reduction in density of parts of a photographic image caused by the stopping of some of the rays entering the lens. (A)

Visible wavelengths: The radiation range in which the human eye is sensitive, approximately 0.4-0.7 μm. (B)

Wavelength (symbol λ): Wavelength = velocity/frequency. In general, the mean distance between maxima (or minima) of a roughly periodic pattern. Specifically, the least distance between particles moving in the same phase of oscillation in a wave disturbance. Optical and IR wavelengths are measured in nanometers (10^{-9} m), micrometers (10^{-6} m) and Angstroms (10^{-10} m). (A)

Wiens Displacement Law: Describes the shift of the radiant power peak to shorter wavelengths with increasing temperature. (C)

Window: A band of the electromagnetic spectrum which offers maximum transmission and minimal attenuation through a particular medium with the use of a specific sensor. (D)

Yaw: Rotation of an aircraft about its vertical axis, causing the longitudinal axis to deviate from the flight line. (C)

Zenith: The point in the celestial sphere that is exactly overhead: opposed to nadir. (A)

ACRONYMS AND ABBREVIATIONS

ADP: Automatic Data Processing
AEM: Applications Explorer Mission
AMS: Army Map Service
ASAP: Advanced Scientific Array Processor
ASCS: Agricultural Stabilization and Conservation Service
ATI: Apparent Thermal Inertia
ATS: Applications Technology Satellite

BPI: Bits per inch

CA: Canonical Analysis
C&D: Chesapeake and Delaware Canal
CCT: Computer Compatible Tape
CRT: Cathode Ray Tube
CZCS: Coastal Zone Color Scanner

DCA: Department of Community Affairs (New Jersey)
DCP: Data Collection Platform
DCS: Data Collection System
DIDS: Domestic Information Display System
DN: Digital Number
DWQ: Division of Water Quality (New Jersey)

EBR: Electron Beam Recorder
ED: Enumeration District
EDC: Eros Data Center (Sioux Falls, S. Dak.)
EDIPS: EDC Digital Image Processing System
EM: Electromagnetic
EMR: Electromagnetic Radiation
EPA: Environmental Protection Agency
ERE: Effective Resolution Element

ACRONYMS (CONT'D.)

ERIS: Earth Resources Inventory System
ERL: Earth Resources Laboratory (Bay St. Louis, Miss.)
EROS: Earth Resources Observing System
ERRSAC: Eastern Regional Remote Sensing Applications Center (Greenbelt, Md.)
ESMR: Electrically Scanned Microwave Radiometer
ESRI: Environmental Systems Research Institute

FOV: Field of View

GCP: Ground Control Point
GE: General Electric (Company)
GES: Geographic Entry System
GIS: Geographic Information System
GOES: Global Operational Environmental Satellite
GPS: Global Positioning System
GSFC: Goddard Space Flight Center

HDT: High Density Tape
Hg-Cd-Te: Mercury-Cadmium-Telluride (Detector)
HOM: Hotine Oblique Mercator
HRIR: High Resolution Infrared Radiometer

IBM: International Business Machines (Inc.)
IDIC: Image Dissector Camera System
IDIMS: Interactive Digital Image Manipulation System
IFOV: Instantaneous Field of View
IPF: Image Processing Facility
IR: Infrared
IRIS: Infrared Interferometer Spectrometer

JPL: Jet Propulsion Laboratory (Pasadena, Calif.)

LAPR: Linear Array Pushbroom Radiometer
LARS: Laboratory for Applications of Remote Sensing (W. Lafayette, Ind.)
LUDA: Land Use and Data Analysis (System)

MLA: Multilinear Array
MMS: Multi-Modular Satellite
MSS: Multispectral Scanner

NASA: National Aeronautics and Space Administration
NCIC: National Cartographic Information Center
NESS: National Earth Satellite Service

NIR: Near Infrared
NOAA: National Oceanic and Atmospheric Administration

OCS: Ocean Color Scanner
OMB: Office of Management and Budget
ORSER: Office of Remote Sensing of Earth Resources (Pennsylvania State University)

PCA: Principal Components Analysis
PFRS: Portable Field Reflectance Spectrometer
PP&L: Pennsylvania Power and Light (Company) (Allentown, Pa.)

RA: Rural Area
Radar: Radio Detection and Ranging
R&D: Research and Development
RBV: Return Beam Vidicon
RJE: Remote Job Entry

SAR: Synthetic Aperture Radar
SCMR: Surface Composition Mapping Radiometer
SEOS: Synchronous Earth Observations Satellite
SLAR: Side-Looking Airborne Radar
SMS: Synchronous Meteorological Satellite
SMSA: Standard Metropolitan Statistical Area
S/N: Signal to Noise
SOM: Space Oblique Mercator
SWIR: Short Wave Infrared

TDRS: Tracking and Data Relay Satellite
TIR: Thermal Infrared
TIROS: Television Infrared Observation Satellite
TM: Thematic Mapper

UA: Urban Area
USGS: United States Geological Survey
UTM: Universal Transverse Mercator
UV: Ultraviolet

VI: Vegetation Index
VICAR: Video Image Communication and Retrieval (System)

WRAP: Western Regional Applications Center (Moffett Field, Calif.)

ZTS: Zoom Transfer Scope

APPENDIX B

INVENTORY OF REMOTELY SENSED
DATA ACQUIRED OVER CHACO CANYON

SENSOR	MISSION	DATE	FILE NAME	RESOLUTION	CCT #	ANALOG #	CIR FRAMES
TMS	284	1APR82	REF284F1.11	10m	2497,203	1057	1 - 23
"	"	"	" .21	"	203	"	24 - 38
"	"	"	" .31	"	583	"	39 - 53
"	"	"	" .41	"	203,1886	"	54 - 69
"	"	"	" .51	"	1886	"	70 - 85
"	"	"	" .61	"	1886,875	"	86 -100
"	"	"	" .71	"	2497	"	101 -116
"	"	"	" .81	30m	1124	"	117 -131
"	"	"	" .91	10m	2487	"	132 -142
"	"	"	" .10	30m	1124	1058	143 -151
"	"	"	" .011	"	583	"	152 -157
"	"	"	" .12	"	1124	"	158 -163
"	"	"	" .13	"	1124,583	"	164 -170
TMS	321	28OCT82	REF321F1.11	30m	0947	1094	46 - 51
TIMS	518	28AUG82	REF518F1.11	5m	1731	1079	150 -164

INVENTORY OF REMOTELY SENSED
DATA ACQUIRED OVER CHACO CANYON

SENSOR	MISSION	DATE	FILE NAME	RESOLUTION	CCT #	ANALOG #	CIR FRAMES
TIMS	518	28AUG82	REF518F1.21	5m	1731	1079	165 -177
"	"	"	" .12	"	1731	"	178 -191
"	"	"	" .22	"	0603	"	192 -205
"	"	29AUG82	REF518F2.11	"	"	"	N/A
"	645	1SEP87	REF645F2.31	"	733,1256	1203	93 - 99
"	"	"	" .181	"	"	"	100 -121
"	"	"	REF645F2.151	"	282	"	122 -141
"	"	"	" .171	"	"	"	142 -160
"	"	"	" .141	"	"	"	161 -178
"	"	"	" .161	"	"	"	179 -197
"	"	"	REF645F2.101	"	733	"	198 -214
TIMS	645	2SEP87	REF645F3.91	5m	282	"	1 - 18
"	"	"	" .131	"	282,533	"	19 - 36
"	"	"	REF645F3.81	"	1256	"	37 - 55
"	"	"	" .121	"	1204,808	"	56 - 74

INVENTORY OF REMOTELY SENSED
DATA ACQUIRED OVER CHACO CANYON

SENSOR	MISSION	DATE	FILE NAME	RESOLUTION	CCT #	ANALOG #	CIR FRAMES
TIMS	645	2SEP87	REF645F3.71	5m	1204,808	1203	75 - 93
"	"	"	" .111	"	1204	"	94 -112
"	"	"	" .61	"	808	"	113 -131
"	"	"	" .41	"	1204	"	132 -149
"	"	"	" .51	"	"	"	150 -169
TIMS	645	4SEP87	REF645F3.191	"	"	1204	
TIMS	FCF	29JAN88	FCFJANF1.51	5m	1962	1216	1 - 8
"	"	"	" .41	"	4212	"	9 - 26
"	"	"	" .31	"	2970	"	27 - 39
"	"	"	" .21	"	3312	"	40 - 53
"	"	"	" .11	"	14040	"	54 -111
CAMS	416	16OCT88	FLP416F1.11	5m	6162	598	29 - 54
"	"	"	" .21	"	6161	"	55 - 74
"	"	"	" .31	"	6448	"	75 - 95
"	"	"	" .41	2.3m	3874	547	96 -118
"	"	"	" .51	"	3309	547	119 -137