ARTICLE 3: PREHISTORIC ERUPTIONS OF ARENAL VOLCANO, COSTA RICA

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ABSTRACT

The tephra sequence deposited west of Volcán Arenal reveals a minimum of 9 major prehistoric explosive eruptions. These range from dacite to basalt in composition and were separated by long periods of repose, on the order of two to five hundred years. The last major explosive eruption, in 1968, has served as a key to the deciphering of the nine prehistoric eruptions.

Volumetrically, it is the smallest of the ten eruptions. The last prehistoric eruption, in about 1520 A.D., produced a particularly easy-to-identify dacitic pumice unit. Paleosols are developed on all the prehistoric tephra units. Arenal had its first major explosive eruption around 1000 B.C. and the volcanic cone itself may have grown to its current size since that time.

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INTRODUCTION

Arenal Volcano (10° 27.8'N, 84° 42.3'W) is a small stratovolcano in the Cordillera Central of Alajuela Province. To the west is a large graben which was formerly filled by a natural marshy lake and which has now been flooded to create the reservoir of the Arenal Hydroelectric Project. Just to the southeast, and overlapping onto Arenal, is the presumably extinct, truncated volcano Cerro Chato (Malawassi, 1979), which has a small crater lake at about 1,000 meters.

Arenal is midway between the two active groups of Costa Rican volcanoes, with Poás to the east and Tenorio to the west. Arenal's nearly perfectly symmetrical cone contrasts sharply with the irregular, large shapes of other Costa Rican volcanoes. Arenal's cone is largely composed of flows and tephra of basaltic andesite, and we now know that its eruptions are typically separated by long periods of repose. Also, each eruption typically begins with violent explosions, which are recorded in the thick, westward downwind tephra section draped over the Lake Arenal region and extending to about 30 kilometers west of Arenal. At the time of this writing (April 1984) Arenal's lava field, which started to flow in September of 1968, continues to grow. The major explosive eruptions typically tap a zoned magma chamber, more acidic at the top (Melson, in press). Lava flows, adding to the bulk of the cone appear late in a given cycle, if the 1968 and continuing eruption is used as a model for the prehistoric eruptions.

Costa Rican volcanoes increase in both elevation and frequency of eruptions (Table 1 and Fig. 1) moving from northwest (Orosi) to southeast (Turrialba). Irazú and Poás have been the historically most active volcanoes, but the 1968 eruption of Arenal (Melson and Saenz 1974; Saenz and Melson 1976) Volcano appears to have been one of the most violent in terms of loss of human life. Note that Arenal's elevation marks a dip in the trend of generally increasing elevation moving southeast along the chain (Fig. 2). Based

Table 1. Physical Features and eruption summary of Costa Rican volcanoes. "Vol" is volume above base in cubic kilometers.

Volcano	Lat	Long	El (m)	Vol	Eruption Summary
Rincón de la Vieja	10.98N	85.33W	1806	130	Four eruptions, 1860-1970. 3 in 1966. Small
Orosi	10.98N	85.47W	1440	55	Uncertain.
Miravalles	10.75N	85.15W	2028	120	Uncertain.
Tenorio	10.67N	85.02W	1916	95	Uncertain.
Arenal	10.47N	84.73W	1552	15	10 major explosive eruptions 1000 B. C. to 1968 A. D.
Cerro Poco Sol	10.32N	84.66W	1300	?	Uncertain. Fumerolic.
Cerro Platanar	10.29N	84.37W	2183	50	Uncertain.
Poás	10.20N	84.22W	2704	95	23 historic eruptions, mainly small explosive.
Barba	10.13N	84.08W	2894	255	One, small, 1867.
Irazú	9.98N	83.85W	3432	300	Nineteen eruptions, 1723–1964 major quiet mainly strombolian.
Turrialba	10.03N	83.77W	3335	290	Three minor. 1750–1866.

Data are from Simkin et al., 1981; Carr, 1984, and, for Arenal, this paper.

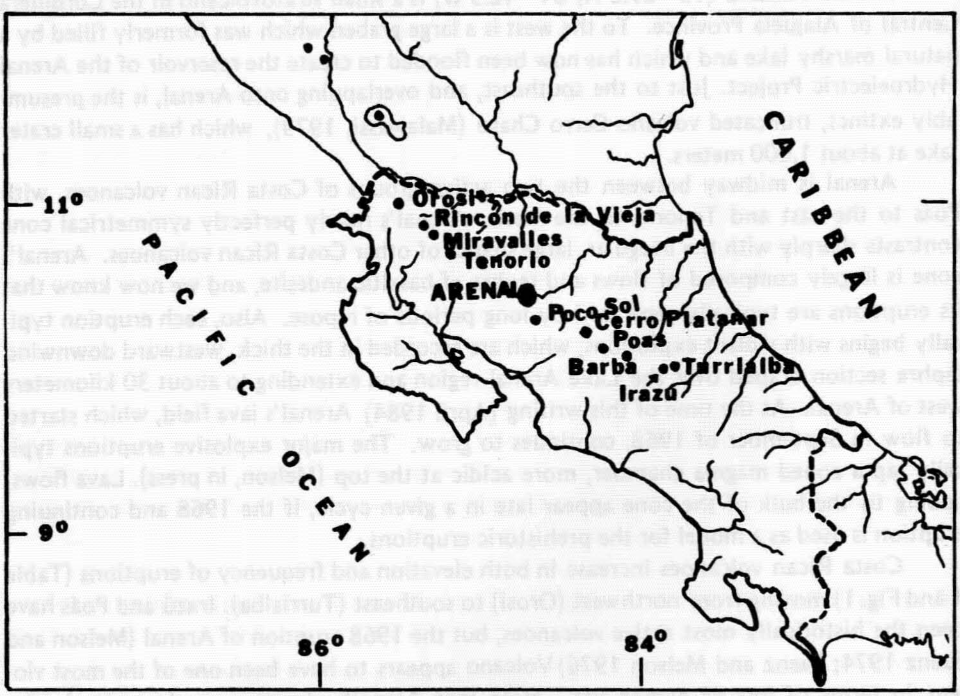

Figure 1. Location of Costa Rican volcanoes.

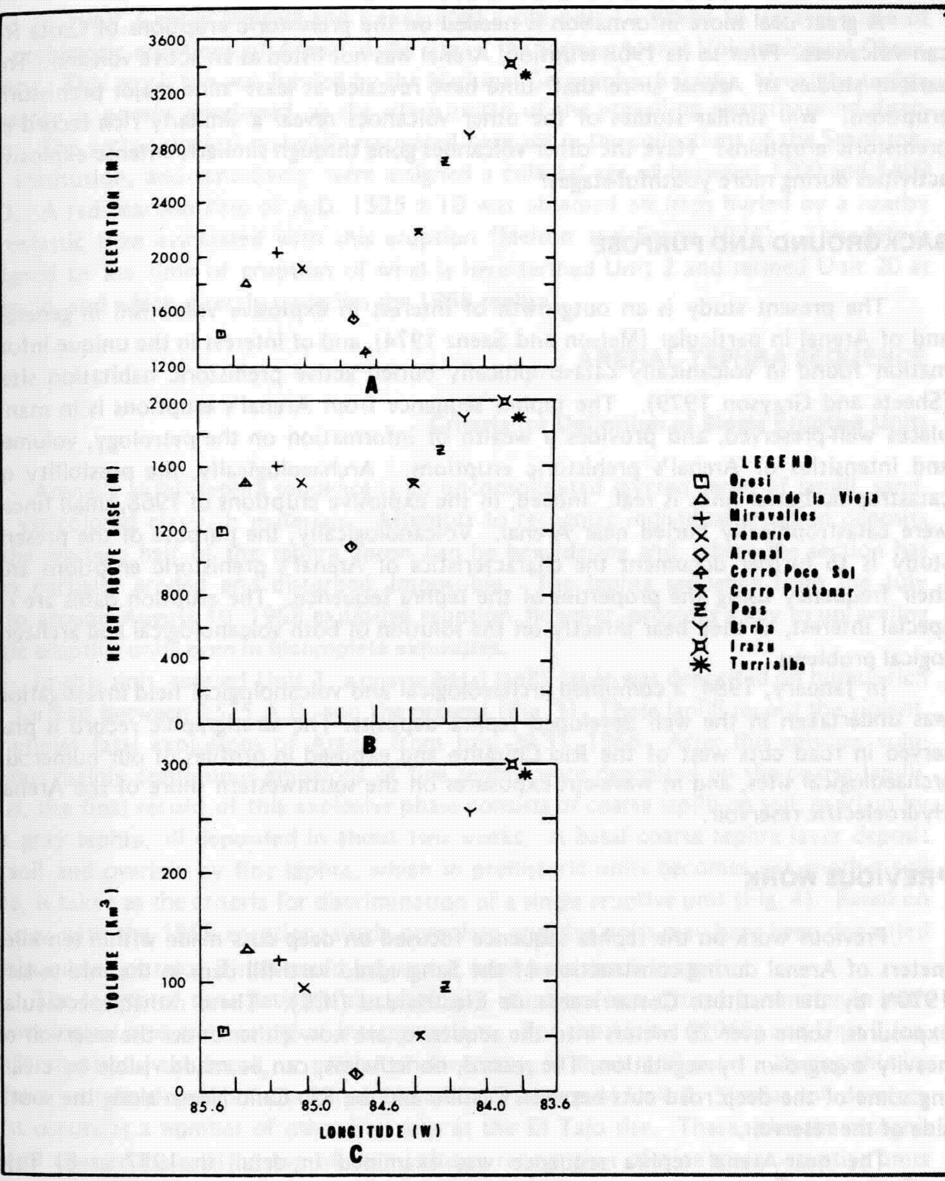

Figure 2. Elevation, height above base and cone volume for Costa Rican volcanoes. Data from Simkin, et al. (1981) and Carr (1984). Height above base and volume are not available for Cerro Poco Sol.

on the dates of its prehistoric eruptions, it may well be one of the youngest —if not the youngest—of the major Costa Rican volcanoes. Prior to the growth of Arenal and its neighbor Cerro Chato, there was a probable "volcanic gap" in the Costa Rican chain between Tenorio and Cerro Platanar. Does the rapid growth of Arenal represent a stage in the maturing, the filling out, of the chain?

A great deal more information is needed on the prehistoric eruptions of Costa Rican volcanoes. Prior to its 1968 eruption, Arenal was not listed as an active volcano. The various studies of Arenal since that time have revealed at least nine major prehistoric eruptions. Will similar studies of the other volcanoes reveal a similarly rich record of prehistoric eruptions? Have the other volcanoes gone through similarly intense explosive activities during more youthful stages?

BACKGROUND AND PURPOSE

The present study is an outgrowth of interest in explosive volcanism in general, and of Arenal in particular (Melson and Saenz 1974), and of interest in the unique information found in volcanically catastrophically buried active prehistoric habitation sites (Sheets and Grayson 1979). The tephra sequence from Arenal's eruptions is in many places well-preserved, and provides a wealth of information on the petrology, volumes and intensities of Arenal's prehistoric eruptions. Archaeologically, the possibility of catastrophic burial finds is real. Indeed, in the explosive eruptions of 1968, small fincas were catastrophically buried near Arenal. Volcanologically, the purpose of the present study is to further document the characteristics of Arenal's prehistoric eruptions and their frequency using the properties of the tephra sequence. The eruption dates are of special interest, as they bear directly on the solution of both volcanological and archaeological problems.

In January, 1984, a combined archaeological and volcanological field investigation was undertaken in the well developed tephra deposits. The stratigraphic record is preserved in road cuts west of the Rio Chiquito and exposed in profiles of our numerous archaeological sites, and in wave-cut exposures on the southwestern shore of the Arenal Hydroelectric reservoir.

PREVIOUS WORK

Previous work on the tephra sequence focused on deep cuts made within ten kilometers of Arenal during construction of the Sangregado earthfill dam in the mid-to-late 1970's by the Instituto Costarricense de Electricidad (ICE). These rather spectacular exposures, some over 20 meters into the sequence, are now either under the reservoir or heavily overgrown by vegetation. The record, nonetheless, can be made visible by clearing some of the deep road cuts between Castillo and the Rio Caño Negro along the south side of the reservoir.

The near-Arenal tephra sequence was examined in detail in 1977 at El Tajo (10^{o} 45'N, 84^{o} 76'W), a hilltop site about 7 kilometers due west and downwind of Arenal's summit. Here, ICE excavated the south side of the hill to a depth of about 20 meters and revealed a remarkably clear tephra sequence. Over nine major prehistoric explosive eruptions of Arenal were revealed, involving tephra ranging from dacite to basalt in bulk composition (Melson, in press). Simultaneously with my work on the total tephra sequence, Prof. Carlos Aguilar of the Universidad de Costa Rica excavated prehistoric Indian remains uncovered deep within the sequence. This work was funded by a National Geographic Society grant and benefited greatly from the cooperation of ICE through Ing. Jorge Umaña and Ing. Miguel Dengo. The archaeological materials are now at the Universidad de Costa Rica in San José.

In 1969, George Metcalf and I excavated a site near La Palma to unravel some of the prehistoric eruptions of Arenal at the site of the former Arenal Volcanological Observatory. This work too was funded by the National Geographic Society. Here, the tephra sequence is poorly developed, as the site is north of the prevailing westerly wind direction. The archaeological materials recovered here are in the collections of the Smithsonian Institution, and tentatively were assigned a cultural age of between 1200 and 1400 A.D. A radiocarbon date of A.D. 1525 ± 10 was obtained on trees buried by a nearby pyroclastic flow associated with this eruption (Melson and Saenz 1974). This date is assigned to the time of eruption of what is here termed Unit 2 and termed Unit 20 at Silencio, and which directly underlies the 1968 tephra.

ARENAL TEPHRA SEQUENCE

Criteria for Definition of Single Eruptive Units

Arenal's airfall tephra sequence is an unconsolidated layered series of lapilli, sand, and varicolored clay-rich materials. Attempts to recognize individual eruption deposits in the western half of the tephra apron can be bewildering and, where the section has been partially eroded and disturbed, impossible. The tephra sequence from the July 29 to around August 10, 1968 explosive eruption, however, provides a key to unraveling single eruptive units even in incomplete exposures.

In this unit, termed Unit 1, a coarse basal lapilli layer was deposited on humus-rich soil formed between 1525 A.D. and the present (Fig. 3). These lapilli record the violent, sometimes fatal explosions of Arenal from July 29-31, 1968. After this episode, voluminous mainly continuous emissions of fine tephra were deposited on the coarse lapilli. Thus, the final record of this explosive phase consists of coarse lapilli on soil, overlain by fine gray tephra, all deposited in about two weeks. A basal coarse tephra layer deposit on soil and overlain by fine tephra, which in prehistoric units becomes yet another soil zone, is taken as the criteria for discrimination of a single eruptive unit (Fig. 4). Based on analogy with the 1968 eruption, single complete eruptive units may have been deposited within a week or two. Times could, of course, have been much longer.

The length of time between the explosive eruptions is a critical parameter in both volcanological and archaeological interpretations. For the Unit 1 (1968) and Unit 2 (ca. 1525) eruptions, the break, or period of dormancy, is about 450 years. During this interval a well-developed humus-rich soil formed on the top of Unit 2. Similar soil development occurs at a number of other horizons at the El Tajo site. These, plus the recognition of coarser material on top of them, allows recognition of nine major eruptive units (Figs. 4 and 5). If we count Unit 10, which has only its upper portion exposed at El Tajo, as yet another major event, there were ten major explosive eruptions.

This is a minimum number of eruptions because: (1) some units may have been removed by erosion, (2) the time between eruptions may have been too short for recognizable soil development, and (3) a significant, recognizable unit may not have been deposited here because of other-than-westerly wind directions during the eruption. The strong prevalence of westerly trade winds in recorded times and the absence of significant tephra sequences north, east, or south of the volcano makes this third factor unlikely. Factors one and two are more difficult to preclude. Erosional features are common along the tops of units. In places, at El Tajo and in nearby road cuts, the soil zones can be traced

Figure 3. Excavation through the 1968 tephra near Pueblo Nuevo. Note the fine upper tephra zone, the basal lapilli zone, and dark–colored soil developed on Unit 2 near the base of the test pit.

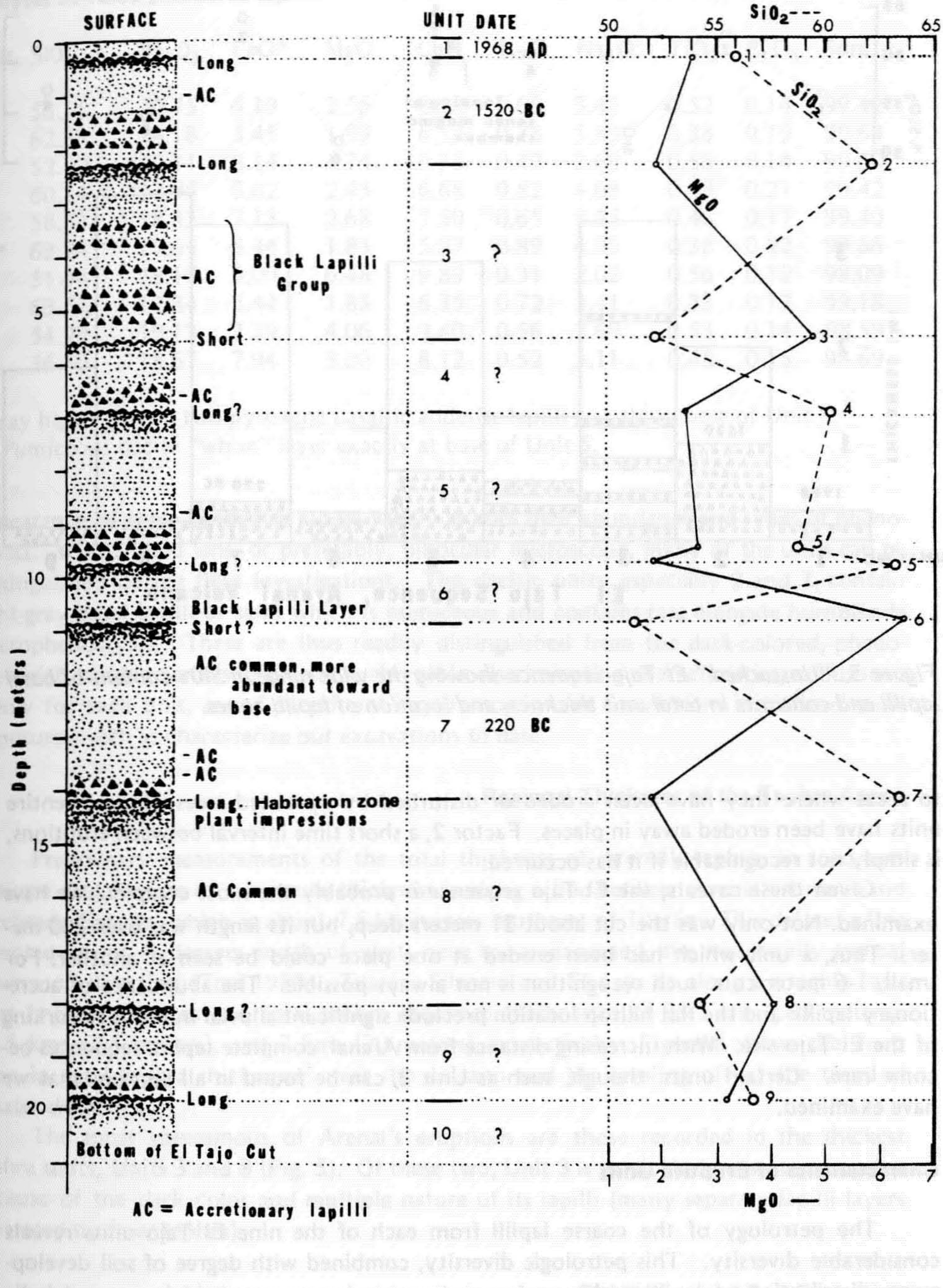

Figure 4. El Tajo eruptive sequence, showing the nine clearly discernible eruptive units, and the top of Unit 10. The archaeological excavations of Prof. Carlos Aguilar were done at the top of Unit 8.

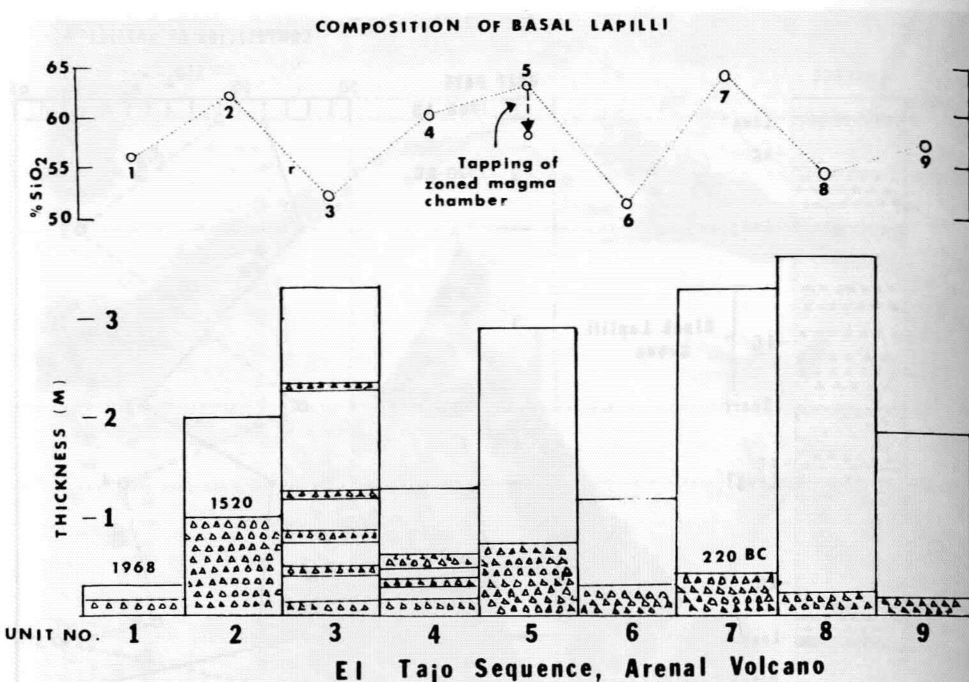

Figure 5. "Unstacked" El Tajo sequence showing the wide range in SiO_2 content of basal lapilli and contrasts in total unit thickness and location of lapilli zones.

to areas where they have been eroded or disturbed by uprooted trees. Indeed, entire units have been eroded away in places. Factor 2, a short time interval between eruptions, is simply not recognizable if it has occurred.

Given these caveats, the El Tajo sequence is probably the most complete we have examined. Not only was the cut about 21 meters deep, but its length was over 200 meters. Thus, a unit which had been eroded at one place could be seen at another. For small, 1-6 meter cuts such recognition is not always possible. The abundance of accretionary lapilli and the flat hilltop location preclude significant alluvial input or reworking of the El Tajo site. With increasing distance from Arenal, complete tephra sequences become rare. Certain units, though, such as Unit 2, can be found in all sections that we have examined.

Characteristics of Eruptive Units

The petrology of the coarse lapilli from each of the nine El Tajo units reveals considerable diversity. This petrologic diversity, combined with degree of soil development, distribution of lapilli within a given unit, ceramic ages, total thickness, and individual thicknesses of the lapilli and fine zones, can allow correlations of given units throughout the Arenal tephra apron in undisturbed sections.

The bulk compositions of the lapilli range from dacite to basalt (Table 2). The

Table 2. Composition of basal lapilli from the El Tajo site. Analyses by electron probe analyses of fused powdered lapilli.

Unit	SiO_2	Al_2O_3	FeO*	MgO	CaO	K_2O	Na_2O	TiO_2	P_2O_5	Sum
1	56.15	20.75	6.19	2.56	8.98	0.68	3.45	0.52	0.14	99.42
2	62.32	18.18	5.45	1.99	6.52	0.78	3.83	0.38	0.19	99.64
3	52.40	20.11	8.14	4.74	10.38	0.42	2.69	0.58	0.14	99.60
4	60.14	17.95	6.62	2.43	6.68	0.82	4.08	0.49	0.21	99.42
5*	58.83	18.43	7.13	2.68	7.50	0.65	3.55	0.46	0.17	99.40
5**	63.24	17.64	5.44	1.83	5.97	0.89	4.05	0.38	0.22	99.66
6	51.44	18.18	9.09	6.48	9.89	0.31	2.02	0.56	0.12	98.09
7	63.57	17.34	5.44	1.85	6.35	0.72	3.41	0.33	0.17	99.18
8	54.29	19.13	7.79	4.06	9.40	0.56	2.69	0.53	0.14	98.59
9	56.50	18.67	7.94	3.20	8.12	0.52	3.11	0.48	0.15	98.69

*Gray highly phyric two pyroxene basaltic andesite lapilli just above base of Unit 5.
** Pumiceous dacite "white" layer exactly at base of Unit 5.

appearance of these lapilli also ranges widely as does their abundance and types of phenocrysts. With a hand lens, or preferably, binocular microscope, many of the units can be distinguished during field investigations. The dacitic units, especially 2 and 7, contain light-gray basal lapilli or sand which is pumiceous and contains rare elongate hornblende microphenocrysts. These are thus readily distinguished from the dark-colored, phenocryst-rich basalt-to-andesite units. Such visible discriminating characteristics, as outlined below for each unit, are of paramount importance in unit correlations in isolated small exposures, such as characterize our excavations to date.

Regional Thickness of the Tephra Apron

Preliminary measurements of the total thickness of Arenal's tephras in road cuts indicate that its axis of maximum thickness is along a line between Arenal's summit and Quebrada Grande, which is about 7.5 kilometers southeast of Tilarán. This defines a line oriented about 8 degrees south of west, near to, as expected, the historically typical downwind direction (Tosi 1980). Tilarán, Silencio and El Tajo lie along a roughly east-west line at distances and total tephra sequence thicknesses of 28.5 kms (.85 meters), 23.5 kms (2.5 meters), and 7 kms (20 meters), respectively. Figure 6 shows the sharp drop in total tephra thicknesses near the volcano and the leveling off of the trend at greater distances.

The most voluminous of Arenal's eruptions are those recorded in the thickest tephra units, Units 3 and 8 (Fig. 5). Of these two, Unit 3 is particularly easy to recognize because of the dark color and multiple nature of its lapilli (many separate lapilli layers separated by finer tephra).

Weathering and Soil Formation

The long periods between many of the eruptions permitted considerable weathering and enrichment in humus. Some soil zones are particularly well-developed on a regional scale. Some of the most striking occur on the top of Units 2, 3, 6, 8, and 9. Weathering effects are most clearly visible and most rapidly developed in fine-grained tephras because of increased surface area. Humus enrichment, however, appears to be more directly related to length of exposure, although any climatic and/or unit vegetation changes will also affect this. Once a unit soil is buried, it appears that weathering is slowed, presumably due to less water infiltration and circulation, and less disintegration due to lower concentrations of organic, plant-derived acids. Remarkably, lapilli at the base of even the oldest units (7, 8, and 9) are quite fresh. This is a necessary condition for our ability to infer the magma types of Arenal's explosive eruptions. The slower weathering of basal lapilli results partly from their larger grain size, giving but a very thin alteration rind. A weathered rind of but .2 millimeters on the lapilli would have barely noticeable effects, whereas a similar weathering penetration on the fine, overlying tephra would lead to nearly total alteration. Presumably, this is why the finer parts of most units are more altered, more orangish-brown tinted, than basal lapilli units. One exception to this tendency is the fine, gray, fresh-looking tephra of Unit 41 in the Silencio sequence. Its resistance to erosion is believed to be due to partial cementation by minerals (gypsum?) released in volcanic emanations by the tephra immediately after deposition, a common phenomenon in places in the fine upper tephra from the 1968 eruption.

The K_2O and P_2O_5 content of all Arenal's tephras is considerably higher than in the lateritic, highly leached soils on the top of the Aguacate Formation. Such Aguacate soils usually are poorly developed in regard to humus content in the Tilarán region. The rich, black humus soils developed, for example on Unit 8, probably reflect a more luxurious growth and more rapid humus accumulation on the higher K_2O, P_2O_5 soils.

Erosion and Other Disturbance of Tephra Sequences

All well-exposed tephra sections reveal evidence of postdepositional changes. Such disturbances result from: (1) erosion during periods of dormancy, including landslides, (2) disturbance by plant roots and soil fauna, (3) uprooting of trees, and (4) activities of man. Generally, these effects are most dramatic near the distal parts of the apron. For example, with a uniform erosion rate, 5 cm of erosion would have little effect on a 200 cm unit at El Tajo, but would result in complete removal of a 5 cm unit in the distal part of the apron. Similarly, root penetration and other soil disturbances could completely homogenize thin near-surface units, but would have little effect on thicker units. This partially explains the clearly visible stratigraphy of the thick units at El Tajo compared to the more difficult to interpret stratigraphy at, for example, Silencio.

Bioturbation has homogenized a number of separate thin units in the Silencio and Tilarán regions. Such homogenization may involve the topmost units only or may involve units subsequently buried by still recognizable units. Such homogenization can produce mixed ceramic assemblages as well as mixed lapilli types. Radiocarbon dates on wood or charcoal fragments can, theoretically, give a date related to any one of the mixed units, and are of limited value compared to those clearly entombed in a single eruptive unit.

It appears that the Arenal apron provides a close look at the properties of a tephra sequence which in all likelihood was deposited on the floor of a rain forest. Indeed, we interpret the rare preservation in places of even thin units, as at, for example, Silencio, to the erosive protection of the floor of such rain forests. Further, we can see the historic increased erosion rates resulting from deforestation, in, for example, the rapid erosion of much of the 1968 tephra.

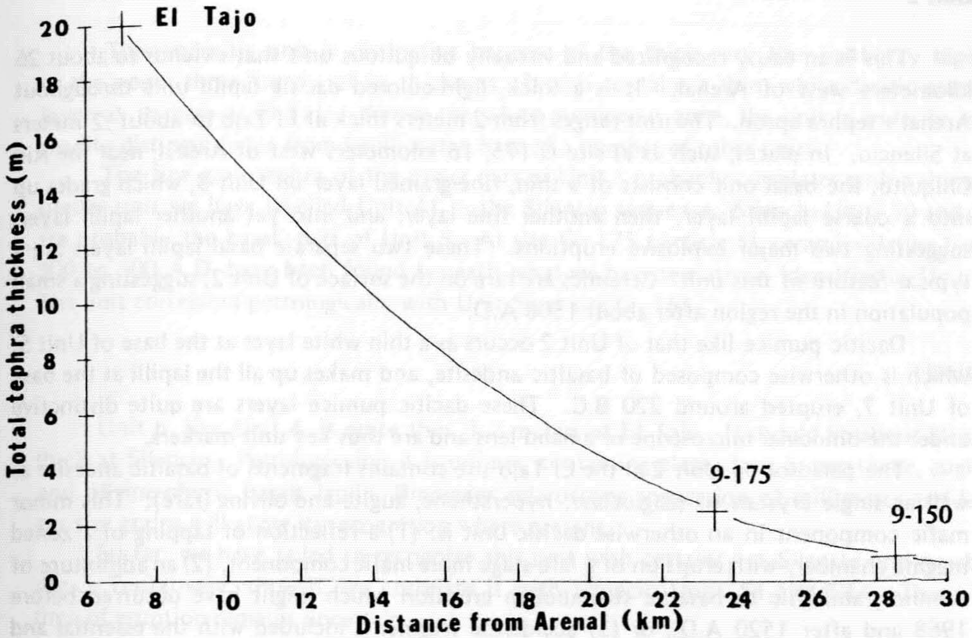

Figure 6. Variations in the total thickness of the Arenal tephra sequence between El Tajo, Site G–175, and Site G–150 (Silencio).

Discriminating Characteristics of Each Tephra Unit

Unit 1

The tephra of the 1968 eruption is readily distinguishable: it occurs, if present, at the top of each section. It is rapidly being eroded and is commonly difficult to recognize west of Rio Chiquito, about 14 kilometers west of the volcano, where it may occur now (1984) as a sprinkling of sand-sized particles mixed with the soil on top of Unit 2. Repeated measurements by Rodrigo Saenz and I of this tephra have revealed its very rapid erosion–so rapid in fact that it may soon be difficult to recognize except within 10 kilometers of the volcano. We attribute its rapid erosion to the open slopes on which it occurs. We believe the formerly extensive rain forests aided in preservation of the prehistoric sequences by impeding erosion. At the Silencio site, about 23 kilometers west of Arenal, Unit 1 occurs as scattered, sand-sized particles mixed with the topsoil. There is indeed some question as to whether or not Unit 1 would be preserved at this distance, even in a rain forest environment because of its small thickness compared to all other eruptive units (Figs. 6). Its thinness and ongoing rapid erosion suggests that eruptions of such comparatively small volumes are not typically preserved in the Arenal tehpra sequence even allowing for lower erosion rates in rain forests.

Unit 1 corresponds to Unit 10 of the Silencio stratigraphic sequence.

Unit 2

This is an easily recognized and virtually ubiquitous unit that extends to about 26 kilometers west of Arenal. It is a thick, light-colored dacitic lapilli unit throughout Arenal's tephra apron. The unit ranges from 2 meters thick at El Tajo to about .2 meters at Silencio. In places, such as at site G-175, 16 kilometers west of Arenal, near the Rio Chiquito, the basal unit consists of a thin, fine-grained layer on Unit 3, which grades up into a coarse lapilli layer, then another fine layer, and into yet another lapilli layer, suggesting two major explosive eruptions. These two separate basal lapilli layers are a typical feature of this unit. Ceramics are rare on the surface of Unit 2, suggesting a small population in the region after about 1500 A.D.

Dacitic pumice like that of Unit 2 occurs as a thin white layer at the base of Unit 5, which is otherwise composed of basaltic andesite, and makes up all the lapilli at the base of Unit 7, erupted around 220 B.C. These dacitic pumice layers are quite distinctive under the binocular microscope or a hand lens and are thus key unit markers.

The paleosol on Unit 2 at the El Tajo site contains fragments of basaltic andesite as well as single crystals of plagioclase, hypersthene, augite and olivine (rare). This minor mafic component in an otherwise dacitic unit is: (1) a reflection of tapping of a zoned magma chamber, with eruption of a late-stage more mafic component, (2) an admixture of a minor, andesitic to basaltic strombolian eruption which might have occurred before 1968 and after 1520 A.D., or (3) accidental fragments included with the essential and dominant dacitic pumice.

Unit 2 corresponds to Unit 20 of the Silencio stratigraphic sequence.

Unit 3

This unit is also distinctive because: (1) it contains numerous thin lapilli of basaltic andesite throughout the lower two-thirds of its thickness, (2) has an upper, typically orangish-brown soil zone grading in places to a humus-rich black soil, and (3) is fairly thick (about 40 cm) even at Silencio. Silencio Units 30 and 40 correspond to the top fine portion and bottom lapilli-bearing portion, respectively, of Unit 3. Middle Polychrome ceramic assemblages buried in part before the deposition of Unit 3, suggest a time of eruption after 900 A.D. Its eruption before 1520 A.D. and its well-developed, quite weathered soil zone suggest eruption before about 1200 A.D., although this is a very crude estimate of its upper age limit. Middle Polychrome ceramics found near the top of Unit 3 suggest ages of between 1000 and 1200 A.D. (Article 9). The numerous, distinct coarse lapilli layers separated by fine lapilli in much of Unit 3 probably reflect repeated violent explosive activity.

Unit 4

Unit 4 is a thin andesitic unit, measuring about 1.3 meters at El Tajo. Assuming that it thins at the same rate as Unit 2, its thickness at Silencio would be about 34 centimeters. So far, we have not been able to clearly recognize Unit 4 at sites G-175, G-151, or G-150 (Silencio). As our work progresses, we will focus partly on recognition of this unit. At El Tajo, this unit has a very poorly developed soil zone, suggesting a probable eruption date of less than around 800 A.D. The lack of well-developed soil contributes to the difficulty of recognizing this unit in the distal half of the tephra apron.

Unit 5

This andesitic unit is distinctive because of the thick very fine light-gray tephra in the upper three-fourths of its thickness. It also contains a thin, white dacitic pumice layer at its base at El Tajo. Above the white pumiceous zone, the unit is andesite, not readily distinguishable from lapilli at the base of a number of other units.

The fine gray tephra of the upper part of Unit 5 probably correlates with a thinner similar unit we have labelled Unit 41 in the Silencio sequence. Silencio Units 50 and 52 are probably the basal part of Unit 5. At site G–175 (Article 5), ceramics dating from 300 to 500 A.D. have been found beneath what we have tentatively identified as Unit 5. The unit correlated petrologically with Unit 52 at site G–151.

Unit 6

Unit 6, like Unit 4, is quite thin, 1.2 meters at El Tajo. It should be about 30 cm thick at Silencio. Petrologically, it is unique, containing plagioclase, hypersthene, augite and olivine-phyric basalt lapilli. Binocular microscope inspection of millimeter and larger size grains will allow its recognition where present.

So far, we have failed to recognize this unit with certainty at Silencio and nearby sites. Tentatively, though, we correlate it with Silencio Units 53 and 53A. Thus, its time of eruption remains uncertain.

Unit 7

Unit 7 is thick and distinctive at El Tajo and we have identified it at some sites near Silencio. Its distinctiveness centers on the hornblende-phyric dacitic pumice lapilli at its base. These are readily identifiable in sand-sized separates even in the far western, Silencio region sites. Chronologically, this is a critical unit in that it was probably erupted about 220 B.C. At El Tajo and in the Silencio area, it is typically underlain by a thick, humus-rich black soil zone, one of the most distinctive in the entire sequence. It is also a noteworthy unit because it marks Arenal's first eruption of dacitic magmas. Beneath, we find only basaltic andesite. Unit 7 appears to mark the beginning of frequent intense explosive eruptions. This is inferred from the coarser grained character of this unit and of most of the units that overlie Units 8 and 9.

Tentatively, we correlate Unit 7 with Silencio Unit 54.

Unit 8

This is a thick basaltic andesite unit, composed mainly of fine tephra with but a thin basal layer of basaltic andesite lapilli. The habitation site excavated by Carlos Aguilar at El Tajo is in the well-developed black soil zone on the top of this unit. The date of this unit remains uncertain except that it is older than 220 B.C. The extraordinarily well-developed soil indicates it may be as old as 670 B.C. assuming that, like Unit 2, such well-developed soil formation took about 450 years.

Correlations of this unit with those of the Silencio sequence remain uncertain. Units below Unit 50, and, in places, even Units 60 and 65, may correlate with Unit 8. The bichrome and other older ceramic assemblages from these units support such correlations (Article 9). Continuing work on recognition of the base of Unit 7 will clarify these Silencio-El Tajo correlations. This unit appears to correlate with Units 55 and 55A, and possibly extends upward into Unit 54.

Unit 9

This unit is similar to Unit 8, except that Unit 9 is thinner and has but a thin basal basaltic andesite lapilli zone at its base. At El Tajo, the soil zone on Unit 9 is less well-developed than that on Unit 8, pointing to a probable short time span between its eruption and the eruption of Unit 8. A rough estimate based on this observation points to an approximate eruption date of about 900 B.C. The ceramics that probably correlate with this unit in the Silencio region indicate a cultural age between 400 and 800 B.C. (Article 9).

Unit 10

A thick, black, well-developed paleosol occurs at the base of the El Tajo section, about 20 meters beneath the surface. This has been termed Unit 10. However, excavation did not reach the base of this unit. Examination of the coarse (> 24 mesh) portion of this paleosol reveals basaltic andesite fragments, including phenocrysts of plagioclase, hypersthene, augite and rarely olivine. This observation shows that this unit is not the top of the Aguacate Formation, which contains rare and deeply corroded lithic and mineral fragments.

THE TILARAN TEPHRA SEQUENCE

A series of tephra beds is well exposed in road cuts near Tronadora and Tilarán, as well as on the road between Tilarán and Quebrada Grande. This series is in places a striking alternation of light and dark-colored fine tephra, presumably paleosols (Fig. 7). The distribution of these tephras indicates that they are in fact from Arenal and that they correlate with the basal units of the El Tajo-Silencio sequences, for example, with the site G–175 basal tephra units. The distinctive appearance of this series compared to the rest of the Arenal sequence has led to their being termed the Tilarán sequence. Part of this distinctive appearance is a result of extraordinarily high carbon content in some of the black paleosols, and their high clay content. Tentatively, we correlate the typically light-colored basal layer and its upper dark soil zone with Unit 9 at El Tajo.

Unit 7 (ca. 220 B. C.) at El Tajo is also recognizable in some exposures of the Tilarán series by the occurrence of pumiceous dacite overlying a well-developed paleosol. Some of the clearest exposures of Unit 7 in the Tilarán series are in road cuts just outside of Quebrada Grande on the road to San Miguel. For ease of measurement, we have termed the basal, typically light-colored tephra "White 1" and its overlying dark-colored soil zone "Black 1". Tentative correlations with the El Tajo sequence are "White 1-Black 1" are Unit 9, "White 2-Black 2" are Unit 8, and "White 3-Black 3" are Unit 7. We have found that in many exposures of the Tilarán series, one or more of these basal units have been either obscured by bioturbation or were eroded before deposition of the next unit. Also, in the very distal exposures, the pumiceous dacite in the base of Unit 7 may be too fine-grained to be readily visible, and thus the correlations become more difficult if not impossible in the field.

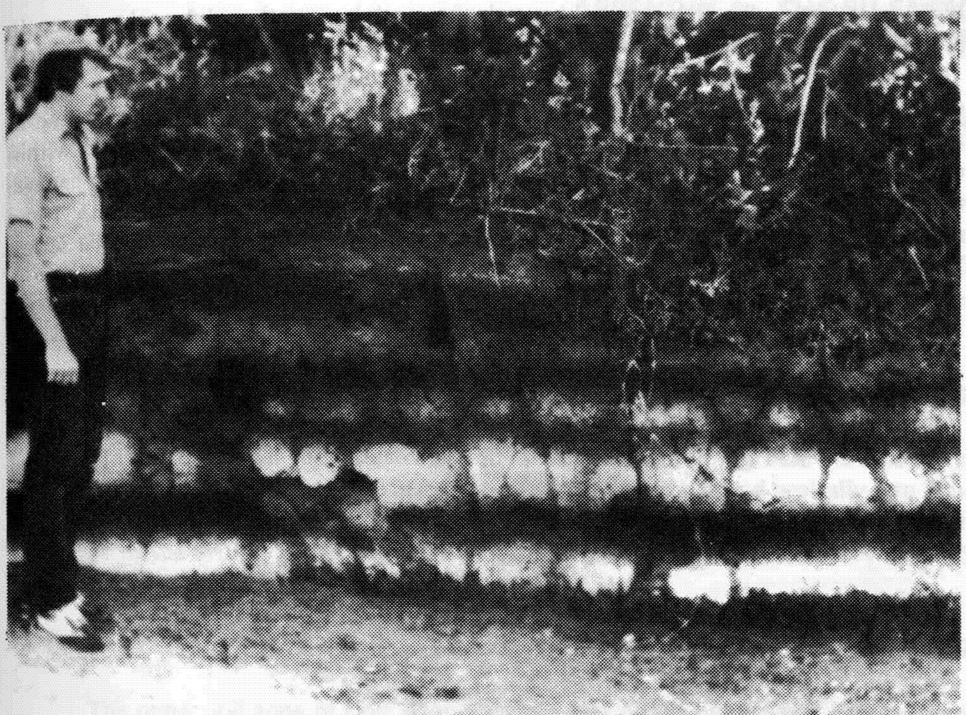

Figure 7. The Tilarán series near Tronadora. Each light–dark (soil) pair corresponds to an El Tajo unit, with the basal unit, lying on the Aguacate correlative with El Tajo Unit 10 in undisturbed sections.

The Tilarán series thins to only 20 centimeters 1.5 kilometers northwest of Guadalajara at the west end of the reservoir, a distance of 33 kilometers westnorthwest of Arenal's summit. Beyond this distance, the Tilarán series is represented by fine, dark tephra mixed with and not distinguishable from topsoil and its integrity as a separate, measurable tephra series is lost.

The age of the basal Tilarán unit ("White 1 and Black 1") is critical in dating what is presumed to be the first major eruption of Arenal, although tephra from Cerro Chato cannot be ruled out at the present time, particularly in these oldest tephras. Pottery in this unit and on the top of the Aguacate here has been assigned to the Tronadora Complex, dating to about 1000 to 500 B. C. (Article 9). This would indicate that the oldest major pyroclastic eruptions occurred no earlier than approximately 1000 B. C., and possibly, the main cone of Arenal may have begun its growth around that time. This would suggest that Arenal has grown to its present form in about 3,000 years.

TEPHRA WITHIN THE AGUACATE FORMATION

The Aguacate Formation as used here is a catch-all term for all the usually reddish, highly weathered, clay-rich material beneath the much less weathered Arenal tephras. In places, the material beneath the tephras was derived from weathering of lava flows. Such derivation can be seen in road cuts a few kilometers southwest of Tilarán on the Tilarán-Cañas road and in a road cut just west of Piedras. Elsewhere, deeply weathered tephras and even paleosols can be seen. For example, a well-developed paleosol occurs within reddish clay about three meters beneath the base of the Tilarán tephra series in excavations for the San Miguel soccer field, about 8 kilometers southeast of Tilarán. These older tephras were deeply eroded before deposition of the much younger Arenal series. Their volcanic source or sources remain uncertain but might well include Cerro Chato.

APPENDIX A: THE SILENCIO STRATIGRAPHIC SEQUENCE

MARILYNN MUELLER

This sequence has been established on the basis of visual (primarily color), textural and mineralogical characteristics of strata observed in road cuts throughout the region blanketed by tephra from Volcan Arenal's eruptions and in excavations. The most detailed and complete profiles are from G–151C and G–175 (Figs. 1 and 2). For correlations with other stratigraphic sequences see Article 3.

UNIT 10

This unit includes the modern ground surface and topsoil. Its base is a sandy, well-sorted light gray pumice with particles of relatively uniform size and typically 1 to 2 mm in diameter. Although it may reach thicknesses as great as 10 cm, it is often discontinuous or mixed with the modern top soil. This tephra unit was deposited by the 1968 eruption of Volcán Arenal.

UNIT 20

The upper soil zone of Unit 20 appears as a dark brown humic layer approximately 15 to 25 centimeters thick at G–150, El Silencio. The soil is of a friable, uniform texture, grading into a sandier orange-brown soil. Closer to Volcán Arenal, near the Rio Chiquito, this soil zone frequently contains lapilli up to 2.5 cm in diameter and is a light beige color. At G–175 it averages 42 centimeters in thickness.

The base of Unit 20 is a coarse, light gray dacitic pumice, which increases in thickness to over 40 centimeters and in size of individual lapilli up to 3.5 centimeters in diameter as one approaches the volcano. With increasing proximity to Volcán Arenal, the lapilli zone also becomes more differentiated internally. Near the Rio Chiquito, there is an upper zone of very coarse lapilli overlying a zone of very fine tephra which is quite hard when weathered. Below this is another zone of very coarse lapilli. The lowest zone consists of fine to medium grained, fairly well-sorted tephra. Farther from the volcano, it may appear as a relatively unsorted, but distinct tephra unit. The lower contact of this unit is usually quite clear.

UNIT 30

This unit is typically an orange-brown, medium-textured soil zone which tends to become sandier in the lower third as it grades into Unit 40. It contains cultural material at many locations in the Cuenca de Arenal.

UNIT 40

The appearance of this unit ranges from a coarse, sandy black lapilli up to 35 centimeters thick in some road cuts, to a coarse, sandy, dark gray zone at the base of Unit 30.

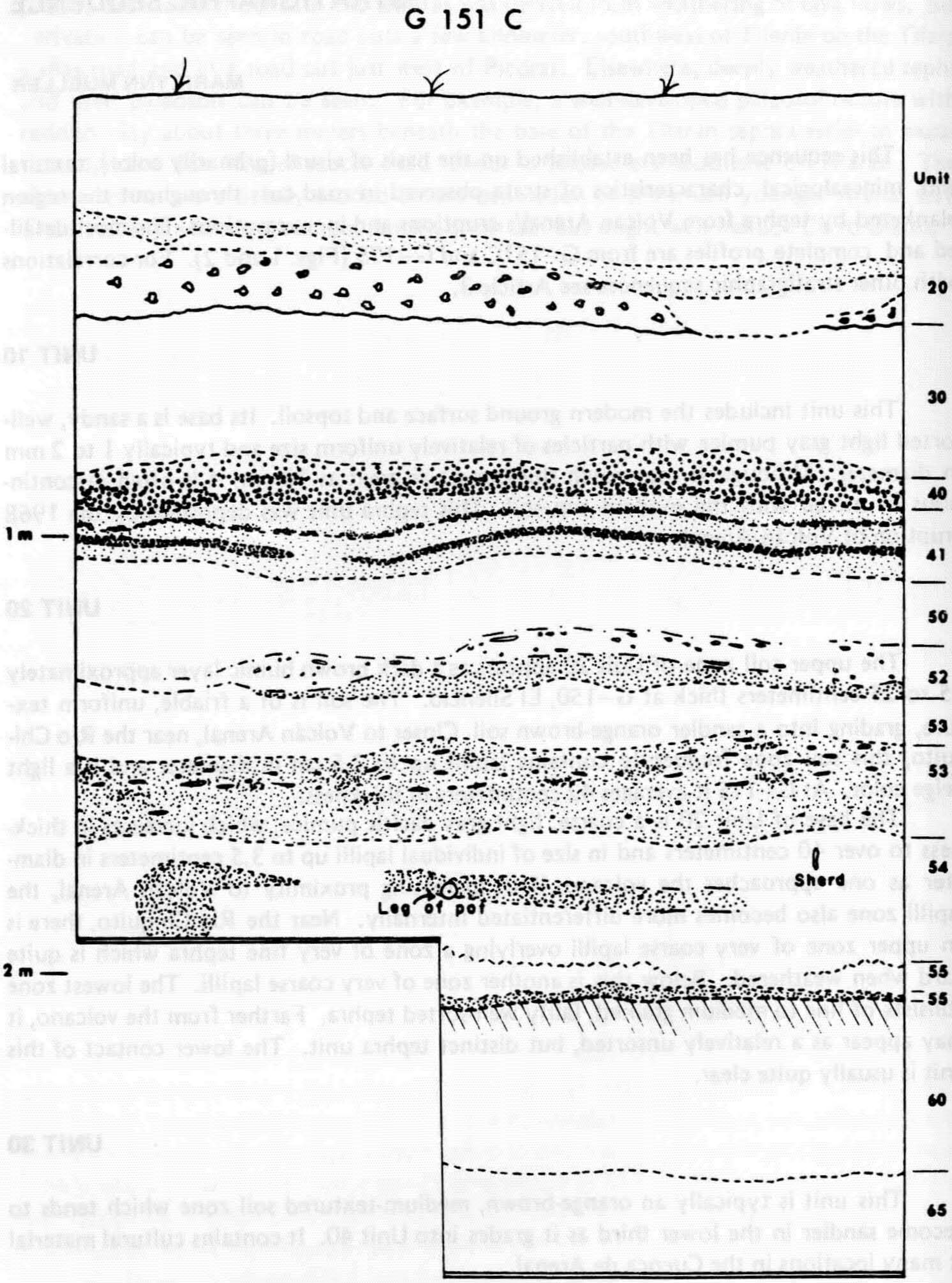

Figure 1. Profile of Operation G–151C. The "Unit 50 Complex" is shown most clearly in this profile. Internal differentiation within tephra Units 40, 41, 52 and 53 is also greater than in any other profiles examined during the 1984 field season.

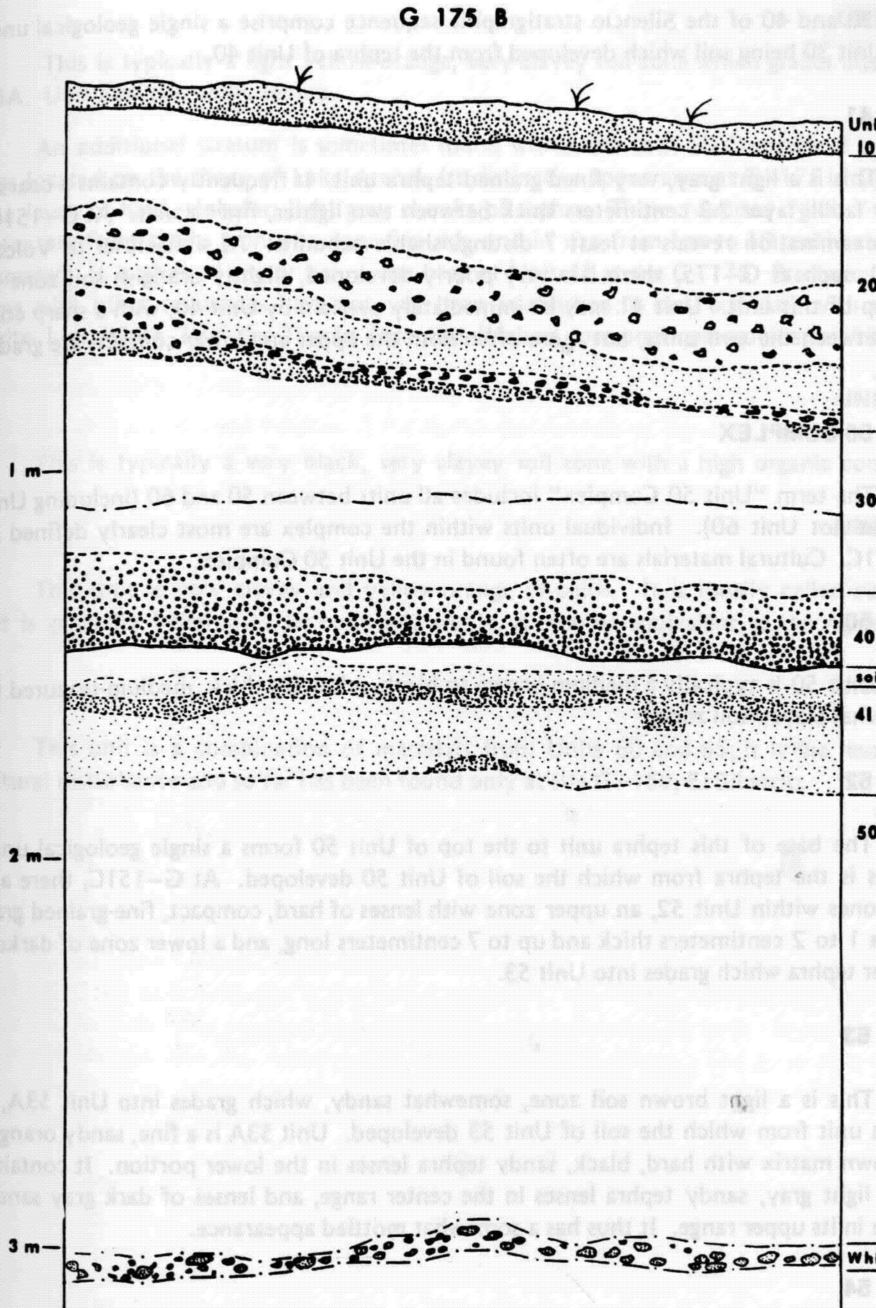

Figure 2. Profile of Operation G–175B This profile illustrates the increasing thickness and internal differentiation of tephra units (especially Unit 20) closer to Volcán Arenal. Note the soil developed from Unit 41 and the distinctive "globby" tephra at approximately 3 m depth. This profile is continued downward in Article 5, Figure 11.

Units 30 and 40 of the Silencio stratigraphic sequence comprise a single geological unit, with Unit 30 being soil which developed from the tephra of Unit 40.

UNIT 41

This is a light gray, very fined-grained tephra unit. It frequently contains a coarse, darker lapilli layer 2-3 centimeters thick between two lighter, finer zones. At G–151C, close examination reveals at least 7 distinguishable subunits. At sites closer to Volcán Arenal, such as G–175, there is a very poorly developed, slightly orangish soil zone at the top of this unit. Unit 41 may be immediately overlain by Unit 40, with a sharp contact between the two units, but more often both the upper and lower contacts are gradational.

UNIT 50 COMPLEX

The term "Unit 50 Complex" includes all units between 50 and 60 (including Unit 50, but not Unit 60). Individual units within the complex are most clearly defined at G–151C. Cultural materials are often found in the Unit 50 Complex.

UNIT 50

Unit 50 is typically a medium brown to black, relatively thick, medium-textured to somewhat clayey soil zone.

UNIT 52

The base of this tephra unit to the top of Unit 50 forms a single geological unit, as this is the tephra from which the soil of Unit 50 developed. At G–151C, there are two zones within Unit 52, an upper zone with lenses of hard, compact, fine-grained gray tephra 1 to 2 centimeters thick and up to 7 centimeters long, and a lower zone of darker, sandier tephra which grades into Unit 53.

UNIT 53

This is a light brown soil zone, somewhat sandy, which grades into Unit 53A, a tephra unit from which the soil of Unit 53 developed. Unit 53A is a fine, sandy orange-to-brown matrix with hard, black, sandy tephra lenses in the lower portion. It contains finer, light gray, sandy tephra lenses in the center range, and lenses of dark gray sandy tephra in its upper range. It thus has a somewhat mottled appearance.

UNIT 54

This unit has so far been identified only at G–151C. It contains an upper soil zone which is dark brown, somewhat sandy, and friable, overlying a discontinuous sandy tephra layer. Early ceramics have been found in these two subdivisions. The lower portion of Unit 54 is a black soil zone with a very high clay content, similar to Unit 60.

UNIT 55

This is typically a light yellow-orange, very clayey soil zone which grades into Unit 55A. Unit 55A is a sandy tephra.

An additional stratum is sometimes found within the Unit 50 Complex at several sites located on the shore of Lake Arenal. Its distinctive appearance at G–175 is typically a layer of hard, globular, light gray chunks of tephra. These rounded "globs" range in texture from sandy tephra to very fine ash, and in size from one to 10 centimeters in diameter. It is about 1 meter below the base of Unit 41 at site G–175. Precise correlations with other sequences have not yet been established; it may correlate with either White 1 or White 2 of the Tilarán sequence (Melson, personal communication 1984).

UNIT 60

This is typically a very black, very clayey soil zone with a high organic content.

UNIT 65

This unit is very clayey and yellow-orange in color. It is locally called *cascajo* and is generally believed to be culturally sterile. It may be equivalent to the Aguacate.

UNIT 62

This unit is a combination of materials from Units 60 and 65; it is the result of cultural disturbance and so far has been found only at site G–150, El Silencio.

APPENDIX B: ARENAL AREA SOILS ANALYSIS

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One of the research goals of the Proyecto Prehistórico Arenal was to test the hypothesis that recent tephra deposits in the humid tropics can weather to highly fertile soils. The fertility of tephra-derived volcanic soils has often been invoked as the major reason why volcanically active areas like the Cuenca de Arenal are repeatedly resettled, despite the volcanic and tectonic hazards. If the tephra-derived soils of the Arenal area are notably more fertile than soils from the surrounding area that were not affected by tephra deposits, and if they are also more fertile than the pre-eruption Aguacate Formation, then soil fertility may have been a contributing factor for people repeatedly or continuously occupying such a hazardous area.

Given sufficient weathering, soils developed from volcanic ash can be fertile, porous and suitable for intensive agricultural exploitation. In tropical moist climates, soils often are dense, acidic, and clay-laden, with few exchangeable bases, and thus cannot sustain intensive agriculture. However, volcanic ash enrichment has facilitated fertile soil development in Java, East Asia, Italy, South America, El Salvador, and other areas in Mesoamerica. These soil resources were intensively utilized by dense populations.

In comparison, the Arenal area was never densely populated. This situation raises other interesting and important questions. Were soils inferior, due to shorter weathering episodes between explosive eruptions? Was there less population pressure in adjoining regions, and thus less reason to recolonize the Arenal area with dense populations? The parent materials of the soils in the Arenal area vary from basaltic andesite to dacitic pumice. How might this have affectd soil development and fertility?

To resolve some of these problems soil samples from three sites (G–175, C–151C, and G–170) were analyzed in the Soils Laboratory, Agronomy, Universidad de Costa Rica. These sites were selected because they are representative of both the regional stratigraphy and the climatic variation within the Cuenca de Arenal. The three sites are also located in three topographically different areas. They thus reflect some of the environmental variability which affects soil development in the Arenal area.

G–175 and G–151C are the two sites at which the Silencio stratigraphic sequence is most clearly defined. Soil samples from these sites were from the main culture-bearing strata. G–175 is the only site thus far where we have found a soil zone between Units 40 and 41; sample 3 is from this poorly developed orange-brown soil. The most complete sampling of the soils of the Tilarán sequence was obtained at G–170.

G–151C is located on a ridge at 930 m in elevation, just west of the continental divide and 750 meters northwest of the El Silencio cemetery. G–175 and G–170 are both located on the southern shore of the Laguna de Arenal. G–175 is a large site on a ridge toward the eastern end of the area included in the shoreline survey. It is in the *Bosque muy húmedo Premontano* life zone, as is G–151C. Mean annual precipitation at nearby Arenal Viejo is 2800 mm, with 11 wet months and one month of excessive precipitation (Tosi 1980). G–170 is located on a piedmont slope near the western end of the lake where precipitation is approximately 2300 mm annually; the area has a dry season of 2 to 4 months, a wet season of 7 to 10 months, and at most one month of excessive rainfall (Tosi 1980). It is in the *Bosque húmedo Tropical, Transicion a Premontano* life zone. Soil erosion is considered to be moderate at the lakeshore sites and moderate to strong at G–151C (Tosi 1980).

Sample No.	Site	Provenience	pH (H20)	P	Fe
1	G175	Modern soil	6.60	19.00	50.00
2		Unit 20 topsoil	6.50	3.50	170.00
3		Unit 30 upper	7.10	3.00	150.00
4		Soil between Unit 40 and Unit 41	7.20	7.50	60.00
5		Unit 50	7.30	7.50	100.00
6		Unit 50 lower (darkest area)	7.20	3.00	50.00
7		Lot B6 "black soil"	7.30	3.50	30.00
8	G151C	Unit 30 middle	6.90	4.50	130.00
9		Unit 50 middle	7.00	1.00	90.00
10		Unit 54 upper	7.00	3.00	90.00
11		Unit 54 lower	7.00	1.50	80.00
12		Unit 55	6.80	6.50	70.00
13		Unit 60	7.00	2.50	90.00
14		Unit 65	7.00	3.50	50.00
15		Topsoil upper	6.50	1.50	110.00
16		Topsoil lower, sandy	6.80	2.00	100.00
17		Dark clayey	6.90	1.50	80.00
18		Light, fine sand	7.10	1.50	150.00
19		Dark	7.00	26.00	70.00
20		Light clayey	7.10	1.50	100.00
21		Black clayey	6.50	0.50	30.00
22		Top of Aguacate	6.60	1.00	70.00

* Se terminó la muestra.

Cu	Zn	Mn	Na	Ca	K	Mg
ug/ml soil					meg/100	
9.00	9.00	9.00	0.32	17.60	1.20	2.90
5.00	15.00	4.00	0.28	5.50	0.26	0.21
11.00	3.00	3.00	0.25	4.30	0.42	0.21
9.00	3.00	1.00	0.34	9.30	0.21	0.62
17.00	8.00	3.00	0.29	11.90	0.52	1.04
13.00	4.00	3.00	0.50	15.00	1.14	2.50
8.00	2.00	4.00	0.37	13.50	1.25	2.50
8.00	2.00	4.00	0.23	2.50	0.57	0.21
7.00	10.00	3.00	0.27	4.30	1.04	0.21
11.00	14.00	2.00	0.26	5.00	0.94	1.24
11.00	5.00	4.00	0.28	12.00	2.50	1.70
6.00	5.00	2.00	0.27	3.50	0.52	0.41
5.00	18.00	3.00	0.38	10.80	1.35	0.83
5.00	7.00	2.00	0.23	5.00	0.62	0.41
4.00	5.00	7.00	0.38	9.50	0.42	1.24
5.00	7.00	4.00	0.30	8.80	0.26	0.83
6.00	5.00	3.00	0.31	11.80	0.21	0.83
10.00	6.00	2.00	0.26	5.30	0.26	0.41
6.00	3.00	4.00	0.34	14.00	0.26	0.62
8.00	7.00	3.00	0.30	11.00	0.42	1.04
13.00	4.00	5.00	0.50	17.50	0.21	3.70
17.00	8.00	16.00	0.37	10.00	0.57	1.70

Acidity	O. M.		
	%		
0.30	17.10	0.60	9.51
0.40	5.09	0.30	7.91
0.30	2.01	0.30	11.10
0.30	0.80	0.40	5.36
0.40	2.01	0.40	11.10
0.30	3.22	0.50	10.31
0.30	4.15	0.30	6.70
0.40	2.55	0.40	3.08
0.30	4.02		
0.40	*		
0.30	6.83		
0.60	2.68		
0.50	9.25		
0.30	2.28		