GEOLOGY AND PETROLOGY OF ARENAL VOLCANO, COSTA RICA

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ABSTRACT

Arenal Volcano ($10^{o}27.8'$N, $84^{o}42.3'$W), a Quaternary conical stratovolcano (1633 m), is located in the Mesoamerican Volcanic Arc in northwestern Costa Rica.

The present study examines the field relations, stratigraphy and petrology of Arenal Volcano and its surrounding area covering an area of approximately 80 km^2. Four main rock units underlie Arenal Volcano. In order of increasing age, they are: (1) Arenal Volcanic Group consisting of historic and pre-historic lava flows, blocky ash flows, mudflows and lapilli and volcanic sand deposits ranging in composition from basalt to dacite but predominantly basaltic-andesite and andesite, (2) Volcanic ash-rich mudflows and lavas from the Quaternary Age Cerro Chato Volcanic Group, (3) Mudflows of unknown source, and (4) Upper Tertiary volcanic agglomerates and tuffaceous breccias of the Aguacate Volcanic Group.

Arenal Volcano began its first historic eruption in July 1968. Catastrophic explosions produced nuées ardentes that devastated 12 km^2 of jungle and deposited blocky ash flows, lapilli and volcanic sand layers, up to 5 km from Arenal summit. These violent explosions were followed by weaker eruptions of fine tephra, and fumarolic activity. Eruption of blocky lava flows began in September 1968 and has continued to present (6/79), interrupted only by short periods (1-2 weeks to 3-5 months) of strong fumarolic activity. Twenty-eight lava flows were erupted between 1968 and 1978 with a total volume of $0.107 \pm .036$ km^3. Three lava flows erupted from crater A (1050 m),

between 1968 and 1973. They represent 60 volume % of the lavas erupted between 1968 and 1978. Twenty-five lava flows were erupted from crater C (1450 m) between 1974 and 1978. They represent 40% volume of the 1968 to 1978 lavas. Lavas erupted from crater A, systematically vary in composition with time. The initial lavas were more differentiated than the later ones. Lavas erupted between 1974-1978 from crater C represented by six new chemical analyses do not follow this trend towards less differentiated lavas with time. Post-1973 lavas have minor chemical variations, but generally are very similar and fairly basic (SiO_2 54.05-55.05 wt. %) for calc-alkaline volcanic rocks. The post-1973 magmas may represent a new batch of magma intruded into a high level chamber underneath Arenal Volcano.

Two faults are apparently related with present volcanic activity. Three explosion craters which formed in 1968 delineate a fault trending N 80 W. One crater (A) was opened at the intersection of this fault with another fault, one with a 30 to 50 m fault-scarp, trending N 20 W.

Pre-historic and historic blocky ash flows and lava flows traveled flows traveled a maximum distance of 4.5 km from the summit of Arenal Volcano. Lapilli and volcanic sand layers produced by pre-historic initial eruptions of Arenal Volcano outcrop up to 12 km to the west of Arenal summit. The stratigraphic and lateral distribution of lapilli and volcanic sand layers suggests a preferred emplacement direction of Arenal initial explosions towards the NW and SW quadrants of Arenal Cone.

For blocky ash and lava flows, a zone of high potential volcanic risk is defined by the maximum traveled distances of pre-historic and historic blocky ash and lava flows. This zone extends 4.5 km from the summit of Arenal Volcano and covers an area of 63.6 km^2. This zone is of great potential volcanic risk for the remaining portion of the present active period.

A gross approximation of the age of Arenal Volcano can be made based on stratigraphic evidence, on calculations of released energy during the 1525 eruption and on two radio carbon dates. The data suggests a maximum age of Arenal Volcano ranging from 3,100 to 10,600 years old.

Monitoring of Arenal Volcano on a permanent basis is a necessity for the economic development of Costa Rica. A coordinated effort among the institutions already involved in studying this volcano and the funding of new research projects at the Volcanology Institute of Costa Rica are needed.

TABLE OF CONTENTS

Page

ACKNOWLEDGMENTS iii

FINANCIAL SUPPORT v

ABSTRACT vi

LIST OF TABLES xi

LIST OF FIGURES xii

INTRODUCTION 1

Purpose and Scope 1
Field Work 2
Previous Investigations 3

REGIONAL GEOLOGY AND LOCATION OF ARENAL VOLCANO 6

Geographic Location 6
Regional Geology 6
Regional Tectonics 12
Regional Geologic History 14
General Geology of Arenal Volcano Region 15
Geomorphology of Arenal Volcano Area 17

GEOLOGY OF ARENAL VOLCANO 20

Stratigraphy 20

Aguacate Volcanic Group 20
Cerro Chato Volcanic Group 21
Mudflow Deposits Unit 22
Arenal Volcanic Group 23
Pre-historic rock units of Arenal Volcano 23
Alternating layers of volcanic sand and angular lapilli 23
Pre-historic blocky ash flows and mudflows 27
Prehistoric lava flows 28
1525 ± 20 lava flows 28
Historic rock units of Arenal Volcano 30
1968 layers of volcanic sand and angular lapilli, and blocky ash flows 29
Historic lava flows 30
1975 blocky ash flow 31

Structure of Arenal Volcano 31

TABLE OF CONTENTS (Continued)

	Page
PETROLOGY OF ARENAL VOLCANO	34
Petrography of Arenal Volcano Rocks	34
Introduction	34
Description of 1968-1979 Lava Flows	35
Detailed Mode Calculations for 1968-1979 Lavas . . .	43
Petrographic Description of Pre-historic Lava Flows	44
Petrography of Lapilli Layers' Accidental Blocks . .	44
Petrography of Arenal Volcano Lapilli Layers	47
Petrochemistry of Arenal Volcanic Group	48
1968-1978 Lavas and Lapilli	56
MODEL OF ERUPTIVITY OF ARENAL VOLCANO	59
AGE AND GEOLOGIC HISTORY OF ARENAL VOLCANO	62
Initiation of Volcanism at Arenal Volcano	62
The Last Pre-historic Eruption of Arenal Volcano	64
1965-1968 Pre-eruption Events at Arenal Volcano	65
Historic Arenal Volcano Active Period	67
1975 Hot Avalanche Event (June 17-21, 1975)	70
VOLCANIC HAZARDS AND SURVEILLANCE	73
Potential Volcanic Hazards at Arenal Volcano	73
Permanent Volcanological Studies at Arenal Volcano . . .	76
CONCLUSIONS AND RECOMMENDATIONS	82
APPENDICES:	
Appendix A: Collection Place of Samples Mentioned in the Text	85
Appendix B: Summary of Analytical Methods	88
Appendix C: Petrographic Description and Modes for Pre-historic Lavas	91
Appendix D: Petrographic Description of Accidental Blocks from Arenal Volcano Lapilli Layers .	96
Appendix E: Petrographic Descriptions Juvenile Lapilli from Historic and Pre-historic Eruptions: El Tajo Site	100
Appendix F: Map of Arenal Volcano Lava Flows	105
Appendix G: Geologic Map of Arenal Volcano	106
LITERATURE CITED	107

LIST OF TABLES

Table		Page
1	Modes for Arenal Volcano Historic Lavas	36
2	Detailed Modes of Arenal Volcano Historic Lavas	45
3	Chemical Analyses, Normative Calculations and Differentiation Index for Arenal Rocks	49
4	Chronology of Historic Lavas	71
5	Modes for Pre-historic Lavas	94
6	Modes for Accidental Blocks	99

LIST OF FIGURES

Figure		Page
1	Geographical Location of Arenal Volcano	7
2	Geologic Map of Northern Costa Rica	9
3	Geologic Map of Arenal Volcano Region	16
4	Distribution of Lapilli and Volcanic Sand Alternating Layers Mantling Around Arenal Cone . . .	27
5	Harker Variations Diagrams for Arenal Rocks	52
6	AFM Diagram for Arenal Rocks	54
7	Plot of Total Iron as FeO versus the Ratio Total Iron as FeO/MgO	55
8	Variation in Composition versus Time in Arenal Volcano Historic Lavas	57
9	Areas of High and Greatest Volcanic Risk at Arenal Volcano for the Remaining Portion of Present Eruption	77
10	High Risk Area for Future Eruptions of Arenal Volcano	78

INTRODUCTION

Purpose and Scope

Arenal Volcano, located in northwestern Costa Rica was considered extinct prior to its violently explosive eruption of 1968. Nuées ardentes were produced during this eruption which killed 78 people and in a few hours transformed 12 km^2 of tropical rain forest into a fuming, tephra-covered desert. The volcanic activity that has continued from July 1968 to the present has brought worldwide scientific attention to this previously unknown or forgotten volcanic edifice.

The present study examines the field relations, stratigraphy and petrology of Arenal Volcano and its surrounding area in order to:

(a) Prepare a geologic map of Arenal Volcano, covering approximately 80 km^2.

(b) Reconstruct the volcanic history of the exposed portion of Arenal Volcano using the stratigraphic record.

(c) Study the petrologic evolution and chemical trends of exposed pre-historic and 1968-1978 volcanic rocks.

(d) Describe the evolution of Arenal's volcanic activity from 1973 to the present, which has not been previously documented.

(e) Evaluate the Melson and Saenz (1973) cyclic model using post-1973 eruptive units.

(f) Obtain basic criteria about potential volcanic hazards from Arenal Volcano.

(g) Evaluate the feasibility of establishing a permanent monitoring station in the vicinity of Arenal Volcano to be operated by the Volcanology Institute of Costa Rica at the National University.

Field Work

Field work was undertaken from June to August, 1978. Good access to Arenal Volcano is available on gravel roads from the Atlantic and from the Pacific sides of Costa Rica, but travel from one side of the volcano to the other is restricted to horseback or foot travel during the rainy season (May to October).

Weather conditions and vegetation at Arenal Volcano made field work difficult and challenging. Arenal Cone is covered by dense tropical rain forest. Annual precipitation in the area is approximately 3 m; most of this precipitation occurred during the field work.

Outcrops of pre-historic lava flows along streams form cliffs up to 20 m high making stream traverses very difficult or impossible.

Good topographic maps (1:50,000) and aerial photographs of Arenal Volcano were available for this study. In addition, photogeologic studies were conducted concurrently with the field work.

Field work concentrated on the west flank of the cone, because all the historic lava flows and their vents, some pre-historic flows, and the main explosion units are located on the west flank of the Cone. Furthermore, the vegetation on the west flank was devastated by 1968 nuées ardentes, thus facilitating field work.

Historic lava flows were sampled every 400 to 600 meters wherever possible. A total of 93 samples, representing historic, pre-historic and accidental blocks from lapilli layers, were collected during the field season.

Previous Investigations

Before the recent eruptive period began in July 1968, Arenal Volcano was not mentioned as a volcano in the Catalogue of Active Volcanoes of the World, Part 6, Central America by Mooser *et al.* (1959).

Although Arenal Volcano had been recognized as a Quaternary structure previous to 1968 (Dengo, 1962; Dondoli, 1965; and Dengo *et al.*, 1968), no research was conducted at the volcano before that year. Since 1968 Arenal has been studied using numerous methods by many scientists.

Physical volcanology: Simkin (1968), Waldrom (1968), Melson and Saenz (1968; 1973; 1977), Merino y Coronado (1968), Chavez (1969), Chavez and Saenz (1970), Saenz (1977) described the chronology of events and the devastative effects during the initial eruptions.

Minakami *et al.* (1969), Fudali and Melson (1972) and Melson and Saenz (1973), estimated physical parameters of the 1968 explosive phases (volume, energy and pressure released).

Parsons (1969) reported the current status of Central American volcanoes, including a brief summary on Arenal Volcano activity.

Melson and Saenz (1973), on the basis of field work and petrochemical information, postulated a cyclic model for Arenal eruptive periods.

Van der Bilt *et al*. (1976) and Matumoto and Umaña (1976) described the eruptive event of 1975 that produced a blocky ash flow from crater C.

Bennett and Raccichini (1977) reviewed the general theory for the processes related to an explosive eruption focused at Arenal Volcano. They also reported various aspects of the structure and dynamics of Arenal's lava flows, and the changes which have occurred on the west flank since 1968.

Avila (1978) reviewed all published information and included unpublished reports of Arenal pre-eruption behavior.

Geochemistry and petrography: Chavez (1969), Chavez and Saenz (1970) and Saenz (1977) described the general petrographic and chemical characteristics of erupted materials. Melson and Saenz (1973) studied petrochemical trends of materials erupted from 1968 to 1973; they dated the previous active period of Arenal Volcano at 1525 ± 20 A.D. by the radiocarbon method.

Cadle *et al*. (1969) compared physical and chemical properties of particles collected from the eruption fume of Kilauea, Mayon and Arenal volcanoes.

Allegre and Condomines (1976) reported uranium and thorium isotopic analyses of historic Arenal lavas and estimated, using internal isochrons, that the partial melting event that gave rise to a differentiating magma chamber beneath Arenal Volcano occurred 35,000 years ago.

Montigny et al. (1969) and Thorpe et al. (1979) reported strontium isotopic analyses of Arenal historic lavas. The former group proposed a mantle partial melting origin for Costa Rican andesites.

Geophysics: Minakami et al. (1969) reported seismological characteristics of the initial active period and made a geothermometric study at Arenal Cone. Simon et al. (1969) reported preliminary results from tiltmeter recording at Arenal Volcano. Matumoto (1968) and Matumoto and Umaña (1977) described seismic activity related with Arenal Volcano. Güendel (1978) studied the relation between earth tides, seismic and volcanic activity of Arenal Volcano during the emplacement of the 1975 blocky ash flow.

Avila (1978) summarized the progress obtained by Costa Rican Electricity Institute, ICE, in seismically monitoring Arenal Volcano since 1974.

Geography and Cartography: Cevo (1977) studied Arenal Volcano activity since 1968 from a geographic perspective. Taylor and Umaña (1978) prepared a map of Arenal historic lava flows (1:20,000), compiled at ICE. Bravo (1978) prepared a topographic map of Arenal Volcano (1:10,000) which is the base map used in this work.

REGIONAL GEOLOGY AND LOCATION OF ARENAL VOLCANO

Geographic Location

Arenal Volcano is located in northwestern Costa Rica, Central America (10°27.8'N-84°42.3'W). It is situated on the NW-SE trending continental divide, separating the Atlantic and the Pacific drainage systems, at the SE end of Cordillera Volcanica de Guanacaste as defined by Dengo (1962). Arenal Volcano is 90 kilometers NW of the Costa Rican capital, San Jose; it is presently the most active volcano in Costa Rica (see Figure 1).

Regional Geology

Arenal Volcano is located in the Mesoamerican Volcanic Arc, 150 km from the axis of the Mesoamerican Trench. The Cocos Plate is being subducted to the NE under Arenal Volcano which is part of the Caribbean Plate.

Five main lithologic belts parallel the Pacific coast (see Figure 2). They are described here from west to east. The first belt includes the Santa Elena peridotite, the Nicoya Complex, the Sabana Grande Formation, as defined by Dengo (1962). An angular unconformity separates these units from overlying Upper Campanian (Galli, 1979) to middle Tertiary clastic and carbonate sedimentary rocks. This sedimentary wedge includes the Quesera Limestone, the Rivas Formation, the San Buenaventura Limestone, the Barra Honda Limestone (Galli and Schmidt-Effing, 1977), and the Las Palmas Formation, the Brito Formation, the Masachapa Formation, the Montezuma Formation and the Punta Carballo Formation as described by Dengo (1962).

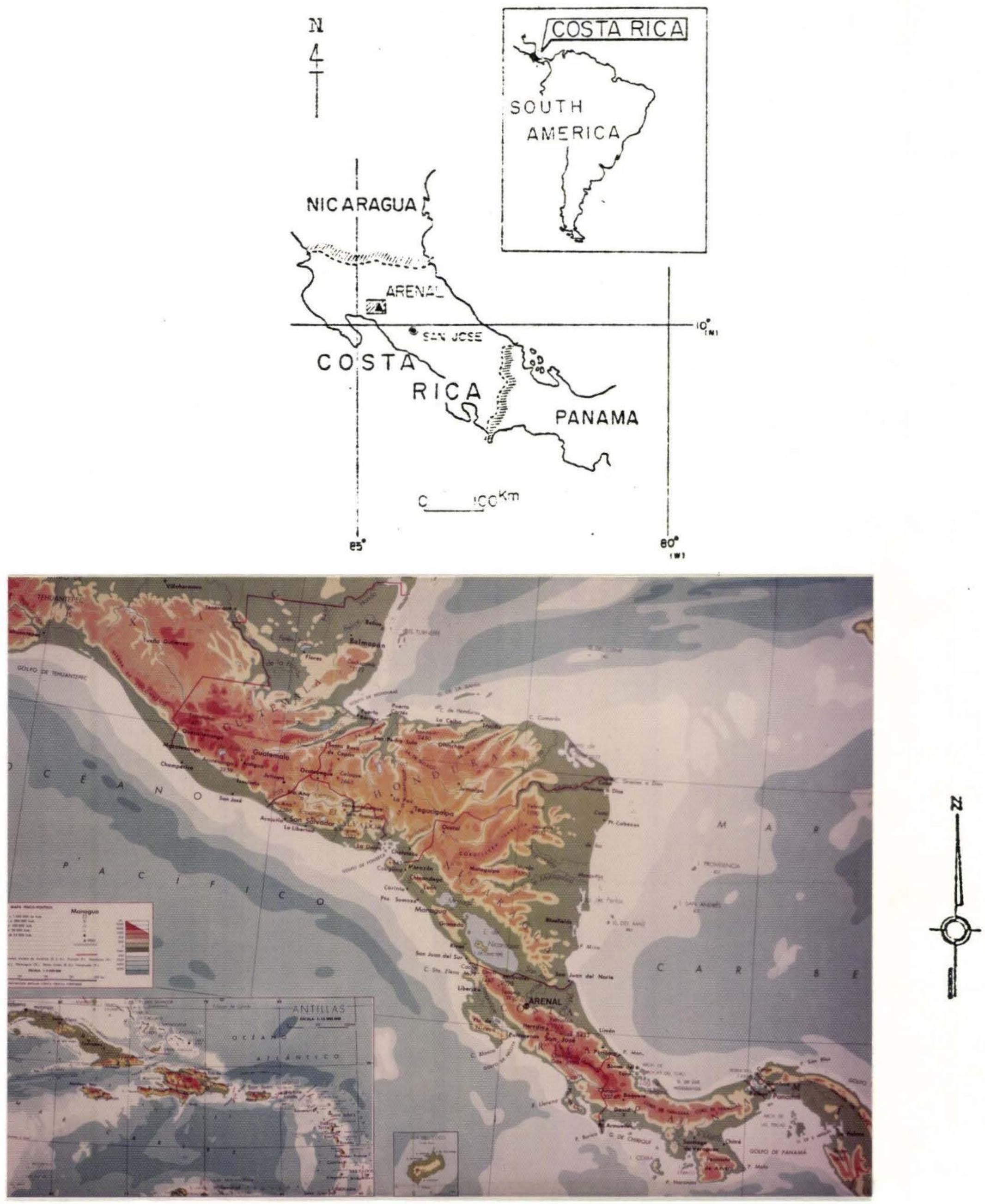


Figure 1. Geographical Location of Arenal Volcano

The Santa Elena peridotite, a serpentinized lherzolite (Tournon, 1970) with subordinated harzburgite as reported by Harrison (1953) and Dengo (1962), is considered part of Nicoya Complex, although relations of intrusive bodies suggest that Santa Elena peridotite might be older than the Nicoya Complex (Dengo, 1962). The Nicoya Complex of Cretaceous, pre-Santonian age (Galli and Schmidt-Effing, 1977) is comprised of cherts, graywackes, tholeiitic pillow lavas, basaltic agglomerates and is intruded by gabbroic, diabasic and dioritic rocks (Dengo, 1962).

The Nicoya Complex is considered to represent a raised block of oceanic crust (Dengo, 1962; Pitchler and Weyl, 1973; Pitchler, 1975). A similar interpretation is that the Nicoya Complex and overlying siliceous limestones of the Sabana Grande Formation is an ophiolitic suite, and to consider the sedimentary wedge of clastic and carbonate rocks overlying the ophiolite, due to their high content of volcaniclastic materials, as erosion products of an ancient island arc, probably as old as early Campanian (Galli and Schmidt-Effing, 1977; Galli, 1979) (see Figure 2).

The second belt inland from the trench is a block-faulted horst, the Sierra de Tilaran y Abangares, which parallels the NW-SE trend of the modern volcanic arc. This belt extends to the SE into Montes del Aguacate. The belt consists of andesitic and basaltic flows, volcanic agglomerates and tuffs and is part of the Aguacate Volcanic Group of late Miocene to early Pliocene age (Dengo, 1962). Rocks of the Aguacate Volcanic Group are not limited to Sierra de Tilaran y Abangares in northwestern Costa Rica, but also outcrop along the SW

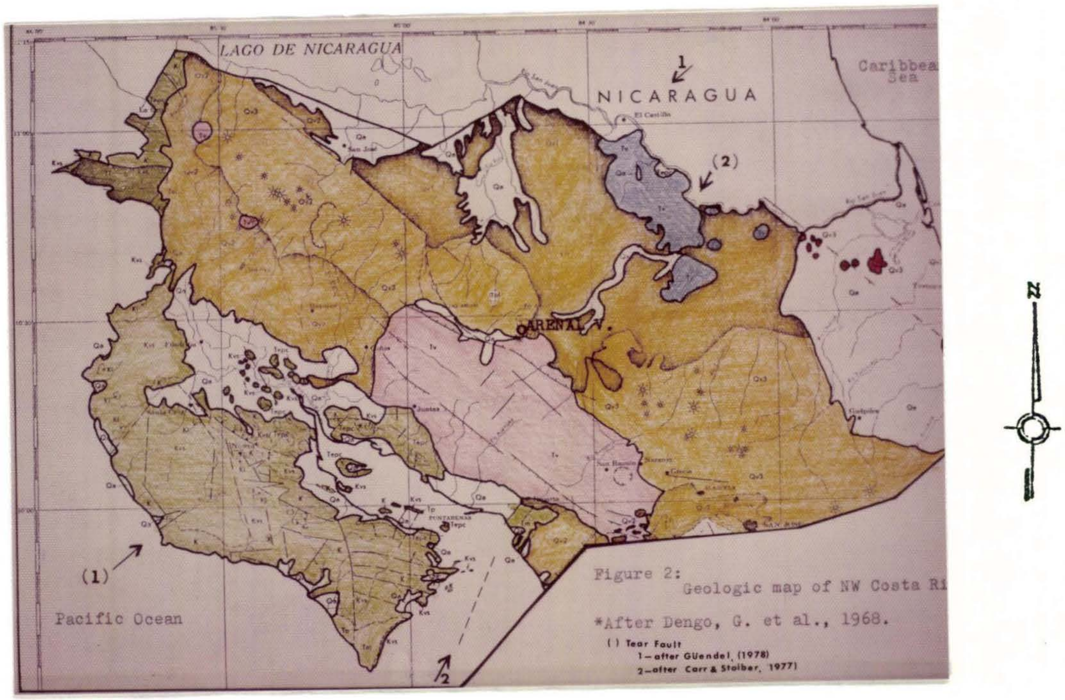


Figure 2. Lithological Belts Present in Northern Costa Rica

Green: First lithologic belt
Pink: Second lithologic belt
Yellow: Third lithologic belt
Blue: Fourth lithologic belt
White: Quaternary alluvium

Approximate scale: 1:4,000,000

flank of Cordillera Volcanica de Guanacaste, where they are partially buried under Quaternary tuffs, and to the north of Arenal Lake between Tenorio and Arenal volcanoes, where they are overlain by Quaternary layers of volcanic sand, lapilli and tuffs (Malavassi V. and Madrigal, 1970).

The Third belt from the trench is the Quaternary volcanic arc, the Cordillera Volcanica de Guanacaste. It is composed of five main stratovolcanoes. From the NW to SE they are: Orosi, Rincon de la Vieja, Miravalles, Tenorio and Arenal. Lavas from these Quaternary volcanoes range in composition from basaltic-andesite (Melson and Saenz, 1973) to lati-andesite (Dengo, 1962; Pitchler and Weyl, 1973), although petrochemical information about volcanoes other than Arenal is sparse. Mudflows are abundant in the NE flank of Cordillera Volcanica de Guanacaste and extensive rhyolitic and dacitic tuffs outcrop on the SW flank, overlying rocks from Aguacate Volcanic Group and the Nicoya Complex (Dengo, 1962).

Cordillera Volcanica Central, a continuation to the SE of the Quaternary Volcanic Arc is included in the present belt. It consists of four main stratovolcanoes; from NW to SE they are: Poas, Barba, Irazu and Turrialba. Lavas from this cordillera range from basalt to dacite and lati-andesite (Pitchler and Weyl, 1973). Extensive volcanic ash beds and mudflows are common and andesitic to quartz latitic tuffs outcrop in the SW flank of this cordillera (Williams, 1952).

The fourth belt, the Cureña Volcanic Formation consists of hypersthenic basalts, augite andesites, volcanic breccias (Malavassi V. and Madrigal, 1970) and dacites (Hayes, 1899). The Cureña Volcanic Formation discordantly overlies marine mudstones and sandstones of the Machuca Formation of Oligocene age (Hayes, 1899; Malavassi V. and Madrigal, 1970), suggesting a post-Oligocene age for this formation.

The Cureña Volcanic Formation outcrops near the Nicaraguan border, partially covered by Quaternary mudflows and alluvium; it represents a continuation of the Nicaraguan Sierra de Chontales, located east of Lake Nicaragua. These rocks may be equivalent in age to the Aguacate Volcanic Group (Malavassi V. and Madrigal, 1970).

The fifth belt consists of a group of Quaternary cinder cones known as Tortuguero Volcanic Formation; these cones rise approximately one hundred meters above the Caribbean alluvial plain in the NE corner of Costa Rica.

Tephras from these cones have mildly alkalic affinities with 0.44% normative nepheline; they were called alkalic basalts by Tournon (1972) and foid-bearing olivine hawaiites by Pitchler and Weyl (1976). This belt is located along the eastern border of the Nicaraguan tectonic depression (Dengo et al., 1968; 1970) (see Figure 2).

Quaternary alluvial deposits overlying pre-existing rocks are extensive along the Tempisque Valley and the Pacific coastal plain, near the coast of Lake Nicaraguan, and along the Caribbean coastal plain (see Figure 2).

Regional Tectonics

Active fault systems in northern Costa Rica are oriented trend either NW-SE or NE-SW (Matumoto et al., 1976), parallel and perpendicular respectively to the Mesoamerican trench (see Figure 2).

Studies of earthquake focal mechanisms indicate that north-south compression and east-west tension make up the prevailing pattern of tectonic stress in the region of Arenal Volcano (Latham and Matumoto, 1975). This stress system may be a consequence of differential movements between the Caribbean Plate, presently moving eastward, providing the east-west tensional feature, and the Cocos Plate which is moving northward, producing north-south compression (Güendel, 1978).

Two seismic profiles oriented NE-SW, perpendicular to the volcanic arc and located about 10 and 35 km NW of Arenal Volcano indicate different angles for the Benioff zone (Güendel, 1978). Stoiber and Carr (1973) proposed a model, supported as well by Güendel (1978), in which the subducted slab and the overlying non-subducted plate are broken by fractures traverse to the trench. One of these transverse fractures may be present (30 km ?) NW of Arenal Volcano (Güendel, 1978). Carr and Stoiber (1977) suggested that a tear fault is present slightly south of Arenal Volcano coinciding with the SE end of Nicoya Peninsula and an offset in the Middle America Trench (see Figure 2). According to Stoiber and Carr (1973), these transverse fractures are tear faults along which high seismic activity occurs including major earthquakes (e.g. Tilaran earthquake 1973, Ms = 6.5; Plafker, 1973);

cinder cones oriented perpendicular to the volcanic arc are common near or along these transverse fractures (e.g. Cerro Chopo; Mora, 1977).

Volcanoes associated with tear faults (Stoiber and Carr, 1973) frequently have small volumes (e.g. Cerro Chato and Arenal volcanoes), catastrophic historic eruptions (e.g. Arenal Volcano), and associated normal faulting (e.g. Arenal Lake graben; Dengo, 1962; Plafker, 1973). These features reinforce the idea of the presence of a tear fault near Arenal Volcano.

NW-SE faulting is more evident than is transverse faulting and best known in northern Costa Rica. Normal faulting associated with the Nicaraguan graben is present along the NE flank of Cordillera Volcanica de Guanacaste and in the NE corner of Costa Rica associated with the Quaternary Tortuguero Volcanic Formation (Dengo et al., 1968, 1970).

The Nicaraguan graben extends into northern Costa Rica where it is partially filled by Tertiary and Quaternary volcanic rocks and Tertiary, marine sediments. The presence of limestones, mudstones and sandstones of the Venado Formation of Miocenic age overlain by Aguacate Volcanic Group basalts somewhat supports this conclusion (Malavassi V. and Madrigal, 1970).

The Sierra de Tilaran y Abangares horst and Arenal Lake graben are formed by normal faults trending NW-SE, parallel to the volcanic arc. Some of the faults in the Nicoya Complex follow a trend parallel to the volcanic arc, but others trend N-S or E-W.

Regional Geologic History

Prior to Cretaceous Campanian time, Costa Rica was underlain by oceanic crust (Galli, 1979). The Nicoya Complex is a remanent of this basement (Pitchler and Weyl, 1973).

A volcanic arc was built on this oceanic crust in the early Campanian time (Galli, 1979) as the Cocos Plate began to be subducted under what is now the Caribbean Plate. Parallel with early stages of volcanic arc building, the Nicoya Peninsula ophiolitic suite was emplaced (Galli and Schmidt-Effing, 1977).

Vertical movements and deformation of the Nicoya Complex (ophiolitic suite; Galli and Schmidt-Effing, 1977) from Campanian to early Tertiary Period (Pitchler and Weyl, 1973) were accompanied by the deposition of a clastic sedimentary wedge of volcanogenic materials originating from a neighbor island arc (Galli and Schmidt-Effing, 1977).

Crustal deformation during the late Miocene caused uplift, accompanied by intensive volcanism along Sierra de Tilaran y Abangares in the south and Sierra de Chontales in the north (Malavassi V. and Madrigal, 1970) giving rise to Aguacate Volcanic Group and to the Cureña Volcanic Formation. Deformation and uplift continued during the Pliocene causing the linking of both Americas (Pitchler and Weyl, 1975). Pliocene tectonic events were characterized by great faults (e.g. Nicaraguan and Arenal grabens) and intense volcanism. The latter continued to the present (Dengo _et al_., 1970) along the modern Mesoamerican Volcanic Arc giving rise to Cordillera de Guanacaste and

Cordillera Volcanica Central along the SW margin of the Nicaraguan graben and to the Tortuguero Volcanic Formation near its NE margin.

General Geology of Arenal Volcano Region

Arenal is the youngest volcanic cone of a linear group of volcanoes in which volcanic activity has been migrating from SE to NW (Melson and Saenz, 1973; Bennett and Raccichini, 1977) that is, from Cerro Los Perdidos, a deeply eroded volcanic edifice, to Cerro Chato, a truncated cone, and to Arenal. This alignment of volcanic centers runs parallel to NW-SE trending faults that are clearly observed in aerial photographs SW of Cerro Chato and Cerro Los Perdidos, south of the study area. A fault present on the SW flank of Arenal Volcano parallels this general trend (see Appendix 6), but in general these faults are covered near Arenal Cone by pyroclastic debris from Arenal Volcano.

Arenal Volcano is located at the SE end of the Arenal Lake graben (see Figure 3), a regional tectonic feature with a NW-SE trend associated with the Quaternary volcanism.

Faults trending approximately N 75 E located south of the area of study (see Appendix G) are related to the Arenal Lake graben fault system (see Figure 3).

The geology and tectonics of the Arenal Volcano region is very poorly known and only one published work by Malavassi V. and Madrigal (1970) examines this region, but only in reconnaissance.

Venado Formation of Miocene age, the oldest lithologic unit in this region, consists of fossiliferous marine sedimentary deposits:

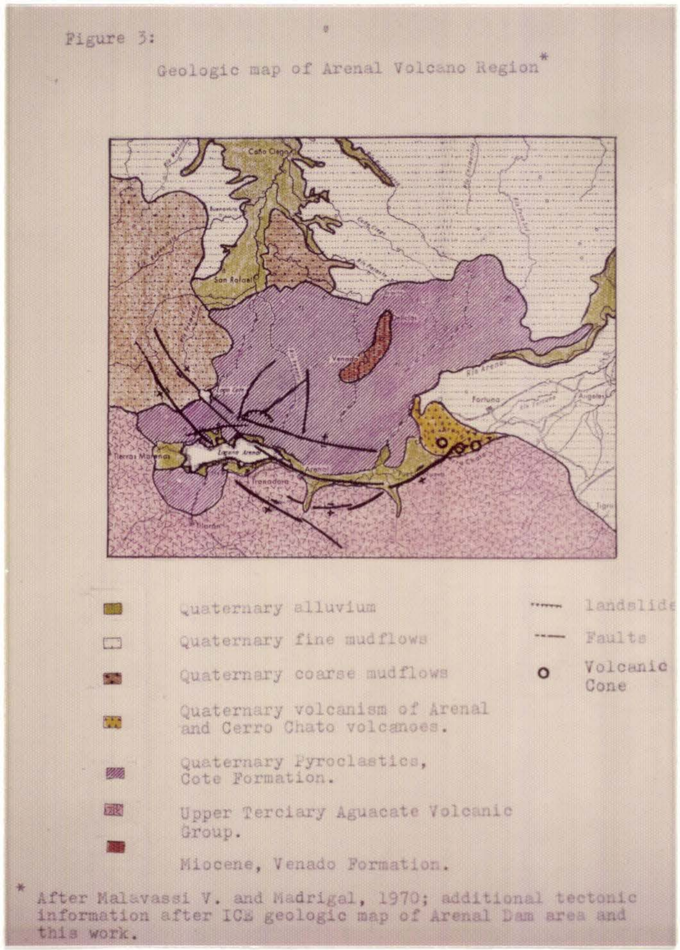


Figure 3. Geologic Map of Arenal Volcano Region*

Approximate scale: 1:400,000

limestones, mudstones and sandstones (Malavassi V. and Madrigal, 1970). These rocks outcrop 15 km NW of Arenal Volcano (see Figure 3) and are unconformably overlain by basalts of the Aguacate Volcanic Group of late Miocene to early Pliocene age (Dengo, 1968); which in the Arenal region consists of basalts and basaltic and tuffaceous agglomerates (Malavassi V. and Madrigal, 1970).

Quaternary volcanic materials overlie the Aguacate Volcanic Group. They consist of volcanic ash, volcanic sand and lapilli layers, tuffs of the Cote Formation that outcrop NW of Arenal Cone, mudflows that outcrop NE of Arenal Cone, and the Arenal and Cerro Chato Volcanic Groups. Quaternary alluvium is abundant along the main drainage channels and in the vicinity of Arenal Lake (Malavassi V. and Madrigal, 1970; see Figure 3).

Geomorphology of Arenal Volcano Area

Arenal Volcano is a cone-shaped, stratovolcano with a poorly developed radial drainage pattern; its shape has been somewhat modified by the pre-existing topography, in particular by neighboring Cerro Chato Volcano, against which the east flank of Arenal was built.

Four craters have been recognized on Arenal Volcano. Three craters (A, B and C) were opened during the explosions of July 1968 at the beginning of the present active period and the other crater (D) is the pre-historic summit crater (Melson and Saenz, 1973) (see Appendix F).

Arenal Volcano's pre-historic, circular-shaped summit crater D (elevation 1833 m) has shown intense fumarolic activity since 1968.

Crater C (elevation 1460 m) on the west flank erupted lava flows for the first time in 1974 and since then twenty-five lava flows have been erupted to 1978. This horseshoe-shaped crater has grown by collapse of its steep walls, in particular at the expenses of the west rim of the summit crater; this latter eventually may be transformed into a composite crater by coalescing with crater C. During the 1978 field season, this crater had two scoria cones, 15 to 20 m high, from which lava flows 26 and 27 had erupted.

Craters A and B (elevation 1050 m and 1170 m respectively) are now covered by blocky lava flows. The only indication remaining of crater A, which produced lava flows from 1968 to 1973 is a fuming scoria cone, 40 to 50 m high.

Other morphologically characteristic volcanic forms present at Arenal Volcano are those left by blocky lava flows. These include longitudinal hills, partially collapsed levees, fluidal lines (well observed in aerial photographs) transverse to the direction of movement and small lakes produced by filling of pre-existent drainage channels.

Erosion has formed steep, narrow, drainage channels commonly with cliffs up to 50 m high. Drainage channels at Arenal Cone contain running water during and just after heavy rains. Small alluvial fans and mudflows are commonly formed at the mouth of these channels.

The ridges located in the vicinity of crater A, which are less steep than the main cone, may represent the morphologic expression of an old rim (somma), on which the present Arenal Cone was built (Saenz, 1977). An alternative interpretation is that these ridges are topographic expressions of pre-historic lava flows and are now covered by posterior pre-historic tephras.

Cerro Chato Volcano, located 2.5 km to the SE of Arenal Volcano, is a truncated cone with a cold water crater lake and an imperfectly developed radial drainage pattern. Cerro Chato cone grew up from a pre-existent larger crater. The geomorphic expression of a former crater rim (somma) is present along the SE portion of Cerro Chato Volcano (Saenz, 1977).

GEOLOGY OF ARENAL VOLCANO

Stratigraphy

The exposed stratigraphy in the Arenal Volcano area consists of five main units. They are, in order of increasing age: historic and pre-historic Arenal Volcano volcanic rocks; mudflow deposits (source unknown); volcanic rocks from Cerro Chato Volcano; and late Tertiary agglomerates and tuffaceous breccias of the Aguacate Volcanic Group (see Appendix G).

In the following sections, each unit will be discussed in detail.

Aguacate Volcanic Group

The lowest stratigraphic unit exposed at Arenal Volcano area outcrops along Arenal River Gorge below an elevation of the 530 m and consists of volcanic agglomerates and tuffaceous breccias (Umaña *et al.*, 1973). A relatively well exposed section of these rocks is present 1 km NW of La Palma Village, on the trail to Santa Eulalia Village which crosses the Arenal River Gorge. The lower portion of the section consists of dark-gray to black, aphanitic volcanic agglomerates, 50 m thick. The matrix is silty to sandy, dark gray to yellow (when altered) and contains abundant volcanic ash. The upper portion, 20 m thick, consists of yellow-brown to cream color, porous, tuffaceous breccias. Angular fragments ranging from 0.2 to 6.4 cm float in an argillaceous, yellow to whitish in color matrix, that represents 10 to 15 percent of the total volume of the rock.

These rocks may be correlated, based on their lithological characteristics and stratigraphic position with the Aguacate Volcanic Group of late Miocene to early Pliocene age, which have been described by Dengo (1962) and studied in Arenal region by Malavassi V. and Madrigal (1970) and Umaña *et al.* (1973).

Cerro Chato Volcanic Group

Only a few outcrops of this group penetrate the dense jungle covering Cerro Chato Volcano. Where exposed, the rocks consist of lava flows and mudflows rich in volcanic ash. All rock units that appear from airphotos and field work to relate to this volcano are assigned to the Cerro Chato Volcanic Group.

Rocks from Cerro Chato Volcanic Group were examined in two areas. Along a stream that joins Calle de Arena Stream, on the north flank of Cerro Chato this group consists of outcrops mudflow deposits. These deposits are yellow-brown, altered, volcanic ash-rich mudflows in which the matrix comprises 80% of the total volume of the rock. Clasts, up to 10 cm in diameter are dark-gray aphanitic to porphyritic lavas. Outcrops of a very dense, dark-gray, aphanitic lava flows are present along the road to Chachagua, south of La Fortuna town, on the Fortuna River (southeast of the map area). Geomorphic evidence suggests that this lava flow originated from the SE flank of Cerro Chato Volcano.

Arenal Volcano pre-historic lavas overlie the Cerro Chato Volcanic Group on the NW flank of Cerro Chato Volcano. This plus, the lack of active fumaroles and the eroded morphology of Cerro Chato Cone suggests that Cerro Chato is older than Arenal Volcano.

Mudflow Deposits Unit

Mudflows are rarely well exposed since they are normally covered by poorly consolidated pyroclastic debris. Nevertheless, these deposits cover an extensive area and are not limited to the cone of Arenal Volcano. Mudflow deposits were observed at the base of the NE flank of the volcano, along streams that descend from Arenal Cone, along La Plama River and other secondary streams on the north flank, along the lower section of Tabacon River and Quebrada Lava on the NE flank and along a secondary stream that flows into Agua Caliente River on the south flank.

These mudflows consist of chaotic mixtures of angular to sub-angular clasts, up to 1.5 m in diameter, of gray to black, aphanitic to porphyritic lava with a gray to yellow-brown (when altered) matrix, of medium to coarse sand and abundant volcanic ash. Matrix to clasts ratios and the stage of matrix alteration vary between outcrops. Thicknesses of 20 to 40 m are exposed along a secondary stream between La Palma River and Laguna Cedeño, and of 25 m on the south bank of Tabacon River on the new road to Arenal Dam.

Mudflow deposits unconformably overlie tuffaceous breccias of the Aguacate Volcanic Group along Arenal River Gorge near La Palma Village. Arenal Volcano pre-historic lava flows cover mudflow deposits on the NE and SW flanks, and pyroclastic materials originating from Arenal pre-historic explosions overlie mudflows on the N, NW and W flanks of Arenal Volcano.

These mudflow deposits might be interpreted as representing portions of deeply dissected, pre-existent Quaternary volcanic cones on which Arenal and Cerro Chato volcanoes were built (Saenz, 1977).

Arenal Volcanic Group

The Arenal Volcanic Group includes all rock units genetically related to Arenal Volcano. This group consist of blocky lava flows, alternating layers of volcanic sand and angular lapilli, blocky ash flows and mudflows.

Pre-historic Rock Units of Arenal Volcano

Alternating layers of volcanic sand and angular lapilli: This stratigraphic unit outcrops at the base of Arenal Cone on the east, north, northwest and west flanks and midway up the cone (elevation 1,000 m) on the southwest flank of Arenal Volcano.

When exposed at the base of Arenal Cone these deposits consist of a gray to yellow-brown (when altered), coarse to very fine, angular volcanic sand layer that overlies a gray, angular lapilli layer. Both layers show a decrease in grain size upward. This alternating sequence is repeated as many as 15 times, but varies in number between localities. Thickness of the volcanic sand (upper) layer ranges from 0.15 m to 2.8 m and that of the angular lapilli (lower) layer ranges from 0.10 to 1.0 m among different outcrops.

Locally, lacustrine deposits, consisting of dark gray to yellow-brown, coarse to very fine sand, commonly argillized as a consequence of alteration and containing wood fragments, are interlayered within this unit, at the base of Arenal Cone. Two interlayered lacustrine deposits at Quebrada Lava, on the new road to Arenal Dam were 2 and 8 m thick. These lacustrine deposits represent small, local lagunas filled with volcanic sand similar to those forming the upper layer of a sequence.

On the SW flank of Arenal Cone, between 700 and 1,000 m of elevation, outcrops show a similar alternating sequence of a layer of coarse to very fine, angular, volcanic sand overlying a poorly defined layer, sometimes lenticular, of angular sand, lapilli and small blocks. The thickness of 10 layers exposed 500 m southwest of crater A is a total of approximately 9 m, individual layers ranging between 0.2 and 1.6 m. When outcrops located at the base of the cone are compared with those located at intermediate elevations on the SW flank, it becomes obvious that layers of this stratigraphic unit became coarser as the eruptive centers are approached.

The stratigraphic unit of alternating layers of volcanic sand and angular lapilli unconformably overlies the mudflow deposits unit; the contact between these two units is well exposed at Tabacon River, on the new road to Arenal Dam.

During the initiation of a typical Arenal Volcano active period, three phases can be differentiated, based on the 1968 chronology of events. An initial explosive phase in which the volcano opens and clears the conduit producing an angular lapilli layer at the base of Arenal Cone. This is followed by a pyroclastic phase in which the magma rising to the surface along the volcano conduits degases producing a layer of coarse to very fine, angular volcanic sand that is deposited over the previous layer. Finally, when the magma reaches the surface, blocky lava flows are erupted and in general are deposited on the higher and intermediate portions of the cone. Such a sequence of stages was reported by Melson and Saenz (1973) for the first seven weeks of the present active period.

Each active period records a similar sequence at the base of Arenal Cone, characterized by a layer of volcanic sand overlying a layer of angular lapilli, according to this explanation.

A detailed schematic section of an outcrop of this stratigraphic unit, studied by Melson (written communication, 1979), located at El Tajo Site, approximately 7 km SW of Arenal summit shows 10 consecutive units separated by soil zones of 0.1 to 0.2 m thick. Soil zones developed during long inter-eruptive periods, when Arenal Volcano was in a dormant state. All units except two consist of the previously noted pair of layers. The two other units have intercaled thin layers of angular volcanic sand in the lower layer of the sequence. However, they invariably show an upper layer of volcanic sand. This suggests that, in fact, each pair of layers as previously described, when limited by soil zones, are stratigraphic records of Arenal past eruptive periods, suitable to be used chronologically if dated radiometrically.

Based on the stratigraphy and lateral distribution of Arenal Volcano alternating layers of volcanic sand and angular lapilli (see Figure 4), it is possible to conclude that the preferential direction of Arenal explosions is toward the NW and SW quadrants of the cone

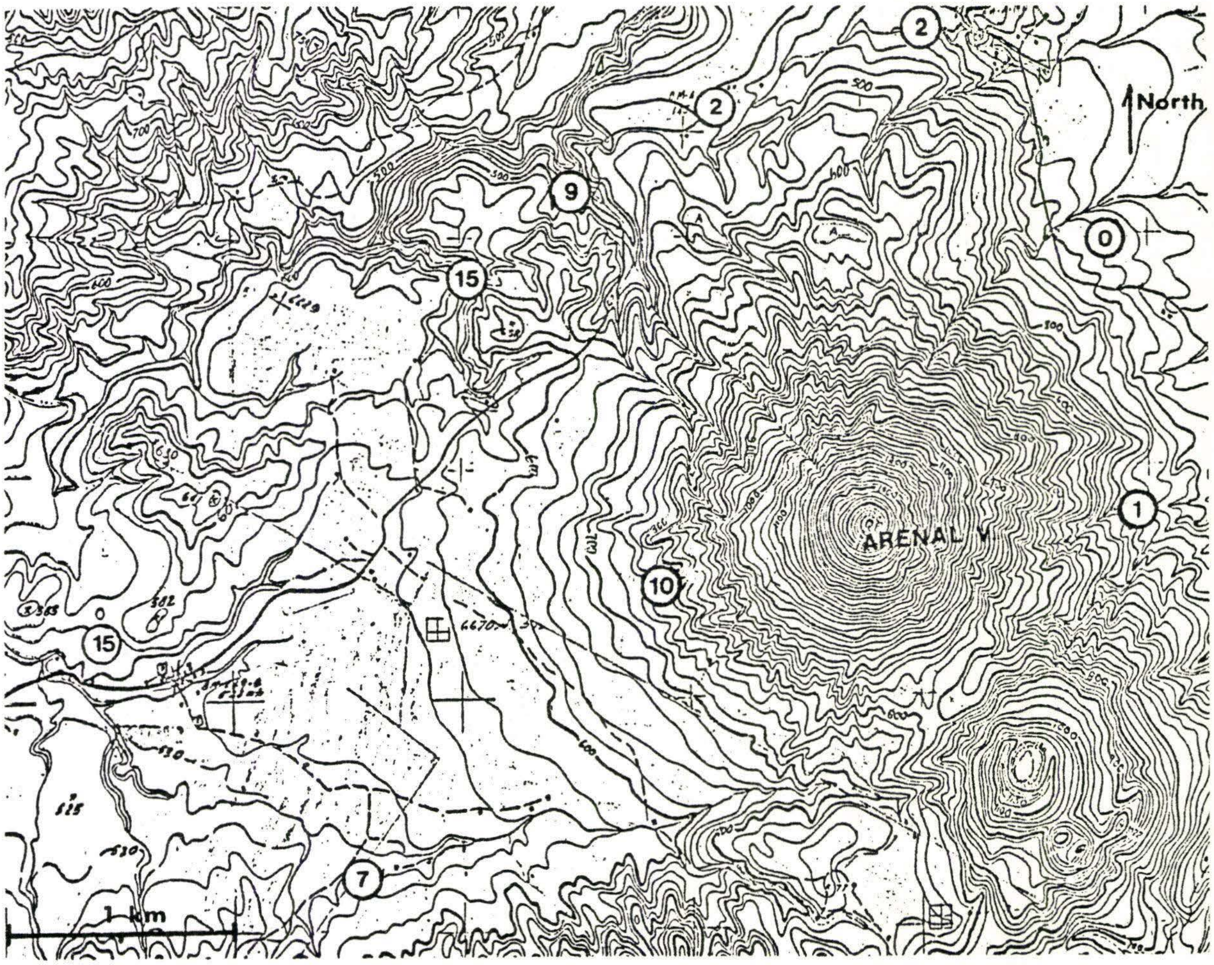


Figure 4. Distribution of lapilli and volcanic sand alternating layers mantling around Arenal Cone. Circles indicate the number of pairs of lapilli and volcanic sand layers outcropping at a given site, not necessarily separated by soil horizons.

where up to 15 paired sequences (not necessarily separated by soil zones), have been recorded.

Pre-historic Blocky Ash Flows and Mudflows

Pre-historic blocky ash flows were observed at three sites: on the north bank of Tabacon River, 300 m up stream from the ford on the new road to Arenal Dam (Melson and Saenz, 1973), on the lower portion of Calle de Arena stream, east flank of Arenal Cone (outside of the map area); and in the upper portion of a group of elongated hills located 500 m SW of crater A, southwest flank of Arenal Cone. Exposed thickness of these deposits ranges between 3 and 7 m.

These deposits consist of a chaotic mixture of angular blocks, up to 5 m in diameter, but normally less than 1 m, and a matrix of unaltered angular lapilli and volcanic sand matrix. The blocks are fragments of Arenal lavas and commonly are scoriaceous.

Blocks of the Calle de Arena Stream pre-historic blocky ash flow show well-developed bread crusts and pseudo-columnar jointing indicating that this flow was emplaced at very high temperatures.

The fact that blocky ash flows are normally exposed only in stream valleys with relatively poor exposure makes it difficult to differentiate the blocky ash flows from typical mudflows. Deposits with very similar characteristics as those described for the blocky ash flows, but lacking evidence of high temperature emplacement, are classified as mudflows and included in this unit.

Mudflows 3 to 5 m thick are interlayered with pre-historic lavas in the northeast flank of Arenal Cone. Another outcrop, 6 to 9 m thick, on the south flank, is overlain by pre-historic flows.

Pre-historic Lava Flows

All lava flows erupted before 1525 from Arenal Volcano are included within this unit. Pre-historic lava flows outcrop on all flanks of Arenal Cone, but on the west flank only one flow is exposed (see Appendix G).

Individual pre-historic flows are variable in thickness (8 to 40 m) and normally contain a denser core which is 1/4 to 1/2 of the total thickness of the flow. Constructional features of lava flows such as collapsed levees and longitudinal hills are common.

Heavy rains (3 m/year) and the friable nature of the levees cause them to collapse on the steep flanks of the volcano. Locally, the debris from collapsed levees reaches 12 m in thickness where it lies in depressions between lava flows and where the angle of the slope becomes low abruptly. This debris masks much of the interflow relationships. That is why detailed stratigraphic studies of this unit are not possible.

1525 ± 20 A. D. Lava Flows

These lavas have been delineated based on their topographic expression and the poorly developed vegetation cover, which contrasts with the surrounding jungle environment. They represent the oldest dated lava flows from Arenal Volcano. The age of this eruption based on C^{14} is 1525 ± 20 A. D. Cultural age studies on Indian ceramics found on a coarse lapilli layer erupted during the same eruptive period is 1200 to 1400 A. D. (Melson and Saenz, 1973).

These lavas issued from the summit crater covering an area of approximately 2.5 km^2 on the north flank of the cone and obtained a maximum thickness of 50 m. The flow that parallels Tabacon River traveled 5 km before it stopped at Arenal River Valley, after having partially filled the valley.

Two small lakes, Laguna La Palma and Laguna Cedeño, were produced after lava flows, issued during this eruption, filled a stream valley on the north slopes of Arenal Cone.

Lava flows from this eruption overly lava flows on the north flank, blocky ash flow at Tabacon River (Melson and Saenz, 1973) and sequences of volcanic ash and coarse lapilli near Laguna La Palma. These lavas, like other pre-historic lavas, are covered by colluvium up to 8 m thick.

Historic Rock Units of Arenal Volcano

1968 Layers of Volcanic Sand and Angular Lapilli, and Blocky Ash Flows

Arenal Volcano initiated its first historic active period on July 29, 1968 with the explosion of three craters devastating an area of over 12 km^2. Nuées ardentes from the explosion craters descended the steep west flank of Arenal Cone, traveling about 3 km from crater A. They desposited a 600 m long and from 20 to 40 m wide and the other was 500 m long and up to 60 m wide (Melson and Saenz, 1973).

The strong directional character shown by these flows suggests that they probably originated from an open crater (A) explosion by vertical discharge of incandescent ash and blocks.

Historic Lava Flows

Twenty-eight distinct lava flows, produced between 1968 and 1978 (Taylor and Umaña, 1978), outcrop on the NW, W and SW flanks of Arenal Cone (see Appendix G).

The first lava flow was issued on September 19, 1968, from crater A (1,050 m). Three lava flows were erupted from this crater (Taylor and Umana, 1978) between September 1968 and September 1973, covering an area of approximately 2.74 km^2 (Melson and Saenz, 1973) with blocky lava up to 60 m thick.

The volcano began a fumarolic phase in September 1973 which continued until March 1974. During March, a new flow was formed from crater C (1460 m). From March 1974 to August 1975, 11 lava flows originated from crater C.

On July 17, 1975, a blocky ash flow was emplaced along Tabacon River Valley, by avalanching of lava flow 14, while it was being erupted from crater C.

From August 1975 to December 1978, 14 lava flows were erupted from crater C. Total area covered by lavas from crater C is 2.16 km^2 with blocky lava up to 40 m thick.

Total area covered by historic lavas, until August 1978 was 4.9 km^2 with an estimated volume, including pore space, of 0.107 ±

.04 km^3, corresponding to an average thickness of 21.89 ± 7.3 m. Similar assumptions in thickness were used by Melson and Saenz (1973) to estimate a volume of 0.06 ± .02 km^3, including pore space, for lavas erupted during the period between 1968 to 1973.

1975 Blocky Ash Flow

On June 17 and 21, 1975, nuées ardentes were produced by the avalanching of lava flow #14 during its eruption from crater C. Hot avalanches descended and were deposited along the Tabacon River drainage on the NW flank of Arenal Volcano.

Hot avalanche deposits on the lower section of Tabacon River are 8 to 10 m thick (see Appendix G). This blocky ash flow consists of angular blocks up to 8 m in diameter, but normally less than 1 m, in a matrix made of a heterogeneous mixture of very coarse to fine grained angular sand with small clasts up to 5 cm in diameter. Blocks show bread crust, heat expansion joints with scoriaceous borders and evidence of flattening and breaking by impact, indicative of high temperature emplacement.

The 1975 blocky ash flow is overlain by subsequent historic flows along the upper and intermediate sections of Tabacon River.

Structure of Arenal Volcano

Arenal Volcano is located at the NW extreme of a linear group of volcanoes oriented NW-SE (Melson and Saenz, 1973; Bennett and Raccichini, 1977), following the general trend of the Cordillera Volcanica de Guanacaste. This linear group of volcanoes, separated from each other by less than 3 km. This closely spaced alignment of vents may result from a major fracture, following a similar trend, associated with the Quaternary volcanism in this portion of Cordillera Volcanica de Guanacaste.

Shallow epicenters (1-10 km depth) from seismograms obtained during September 1968 at Arenal Volcano were located on Cerro Chato's SW flank (Minakami et al., 1969). A path, having an initial angle of emission of 45° to 60° was assumed for the blocks produced during the July 1968 explosions (Saenz, 1977). These facts were interpreted by Bennett and Raccichini (1977) as evidence of an inclined conduit deepening toward Cerro Chato and that Cerro Chato and Arenal might have a common magma chamber.

Arenal Volcano is located on the downthrown block of a major normal fault related to the Arenal Lake graben. This fault trends N 75 W between Arenal and Cerro Chato Volcanoes (see Appendix G). Other faults to the SW of it are oriented following similar trends. A strong lineation having a similar trend (N 60 W) is present in aerial photographs at the NW flank of Arenal.

Two faults on the south and west flanks of the volcano are related to the present active period of Arenal. The first fault has a distinct scarp, 30 to 50 m high, trending N 20 W. The other fault trace includes three explosion craters formed during 1968 aligned along, N 80 W. One of the 1968 craters (A) is located at the intersection of these two faults (see Appendix G).

Lineations only observed on aerial photographs are probable indicators of fracture zones. Two orientations were noted; N 55 to 60 W and N 35 E on the northern section of the area of study, particularly near Bajo Tabacón. Lineations on Cerro Chato Volcano follow two orientations N 55 E and N 20 E. None of the mentioned aerial photo-lineations seem to be parallel with known faults directly related with Arenal activity (see Appendix G).

PETROLOGY OF ARENAL VOLCANO

Petrography of Arenal Volcano Rocks

Introduction

A total of 106 petrographic thin sections were studied. Sixty-four thin sections are from 1968-1978 lavas; twnety-five thin sections are from pre-historic lavas; five thin sections are from accidental blocks included into pre-historic angular lapilli layers.

Thin sections of fragments of angular lapilli (12) collected at El Tajo Site were provided by William G. Melson. All other thin sections are from 94 samples collected during the field work.

Modal calculations were obtained using either 500 point counts and a magnification of 80 or 1000 point counts and a magnification of 320 per sample. To evaluate minor variations in the groundmass and calculate volume percents of apatite inclusions in plagioclase 1000 points counts per sample, at 320 magnification, were counted on each of 17 thin sections from 1968-1978 lava flows. 500 points counts per sample at 80 magnification, were counted on all other modal calculations.

Since the main purpose of the present work is to determine the petrological character of Arenal Volcano rocks, only samples from Arenal Volcanic Group were considered for petrographical description, thereby excluding fragmental volcanic rocks from Aguacate Volcanic Group, Cerro Chato Volcanic Group and the mudflow units.

The sample numbering system for the 1968-1978 lava flows has three numbers separated by dashes. The first number refers to the flow number, the second number refers to the sample number within a particular flow and the third number is a field control number.

Pre-historic lava flows use only one number that corresponds to the field control numbers. A and B refer to different thin sections of the same sample.

Angular lapilli samples from El Tajo Site, are numbered from 1 to 9 in order of increasing age.

Description of 1968-1978 Lava Flows

The lava flows erupted from 1968 to 1978 are very similar petrographically. The characteristics of this group of lavas are outlined below. Phenocrysts are grains larger than 0.45 mm. All other grains are considered part of the groundmass. The 0.45 mm grain size boundary between groundmass and phenocrysts was empirically chosen based on the bimodal distribution shown by phenocrysts and groundmass grains from Arenal lava flows. Arenal historic lavas are dark gray, basaltic-andesites with porphyritic hyalopilitic texture and have a mean vesicularity of 22 vol. % (see Table 1).

Mineralogy: Phenocrysts: (27 vol. %; see Table 1) plagioclase, augite, hypersthene and, rarely, olivine. Groundmass: (50 vol. %; see Table 1) plagioclase, augite, hypersthene, magnetite and glass.

Plagioclase: Subhedral megaphenocrysts up to 3.5 x 2.0 cm are common. Plagioclase phenocrysts are subhedral to anhedral. Groundmass plagioclase is subhedral. Phenocrysts range in composition from 55 to 90% anorthite determined by the Michel-Levy method. Glass

Table 1. (Continued) Modes for Arenal Volcano Historic Lavas

	19-1-56	19-2-39	20-1-05	20-3-06	20-4-30	20-5-37	21-1-31	21-2-33	22-1-38A	24-1-42A
PHENOCRYSTS	23.6	28.4	23.6	30.0	27.0	24.4	22.0	30.8	34.4	28.2
Plagioclase	15.8	20.4	15.2	20.9	19.8	14.8	16.0	21.4	24.6	22.8
Augite	6.0	5.0	4.4	1.5	3.2	7.8	3.0	6.2	4.9	3.4
Hypersthene	1.8	3.0	4.0	5.8	3.8	1.8	2.8	3.2	3.7	2.0
Olivine	0.0	0.0	0.0	tr.	0.2	tr.	0.2	0.0	0.3	0.0
GROUNDMASS	55.2	53.6	54.6	48.6	49.0	51.0	46.0	51.0	39.1	46.8
Magnetite	2.8	2.0	1.6	1.0	2.4	1.6	2.6	1.4	1.5	4.0
VESICULARITY	21.2	18.0	21.8	21.4	24.0	24.6	32.0	18.2	26.5	25.0
Counts	500	500	500	1000	500	500	500	500	1000	500

Table 1. (Continued) Modes for Arenal Volcano Historic Lavas

	10-2-64	11-1-26	12-1-22	14-1-23	16-1-51	16-2-24	16-2-25	17-1-50	18-1-49	18-3-39
PHENOCRYSTS	29.6	21.6	25.4	24.6	29.4	25.4	25.9	27.4	28.8	28.3
Plagioclase	19.2	15.0	15.1	16.4	23.0	15.8	14.7	19.8	19.2	19.8
Augite	6.6	3.0	4.8	3.4	1.8	4.4	6.6	4.4	5.4	1.7
Hypersthene	3.8	3.4	3.7	4.8	2.6	5.2	2.7	3.0	4.0	5.2
Olivine	0.0	0.2	0.0	0.0	0.0	tr.	0.1	0.2	0.2	0.0
GROUNDMASS	48.2	47.0	47.4	51.8	54.0	54.0	50.9	47.0	43.4	55.2
Magnetite	2.8	3.0	2.1	7.8	2.6	3.6	2.7	1.6	2.2	2.4
VESICULARITY	22.2	31.4	27.2	23.6	16.6	20.6	23.2	25.6	27.8	16.5
Counts	500	500	1000	500	1000	500	1000	500	500	1000

Table 1. (Continued) Modes for Arenal Volcano Historic Lavas

	5-1-59A	5-2-44	6-1-58	7-1-62	8-1-67	8-2-66	8-3-61B	8-4-46A	9-1-63	10-1-84
PHENOCRYSTS	26.4	26.6	24.6	22.8	26.8	26.6	20.2	31.5	18.6	25.4
Plagioclase	18.4	17.0	17.2	13.8	15.4	14.0	13.2	18.7	10.0	15.1
Augite	3.2	6.4	4.6	4.8	8.0	9.6	5.2	5.4	4.8	4.8
Hypersthene	3.3	3.2	2.6	4.2	3.4	3.0	1.8	5.7	3.6	3.7
Olivine	0.0	0.0	0.2	0.0	tr.	0.0	tr.	0.0	0.2	0.0
GROUNDMASS	54.1	55.6	52.0	60.4	46.8	46.0	42.4	51.2	38.8	47.4
Magnetite	1.1	4.2	1.6	2.2	1.8	2.2	2.8	3.6	3.6	2.1
VESICULARITY	19.5	17.8	23.4	16.8	26.4	27.4	37.4	17.3	42.6	27.2
Counts	1000	500	500	500	500	500	500	1000	500	1000

Table 1. Modes for Arenal Volcano Historic Lavas

	1-1-82	1-2-83	1-3-15	1-4-20B	1-5-16B	1-6-17B	2-1-07	2-2-34	3-1-19B	3-2-18
PHENOCRYSTS	22.4	35.2	23.6	314	25.1	30.2	27.0	31.4	23.8	30.4
Plagioclase	19.0	23.8	17.4	25.8	14.9	20.4	16.2	17.2	19.8	21.2
Augite	2.8	6.6	4.0	3.8	3.7	6.0	7.0	11.0	1.8	3.6
Hypersthene	0.6	4.2	2.2	1.8	5.6	3.8	3.8	3.0	2.2	4.5
Olivine	0.0	0.6	0.0	0.0	0.2	0.0	0.0	0.2	tr.	0.0
GROUNDMASS	48.0	52.2	56.8	53.6	54.5	54.6	46.4	48.4	49.8	50.6
Magnetite	1.6	2.6	3.0	3.8	3.2	8.8	2.4	3.4	2.8	1.8
VESICULARITY	29.6	12.6	19.6	15.0	20.4	15.2	26.6	20.2	26.4	19.0
Counts	500	500	500	500	1000	500	500	500	500	1000

Table 1. (Continued) Modes for Arenal Volcano Historic Lavas

	25-1-48	26-1-52	26-2-77	26-3-68B	26-4-69	26-5-70	27-1-87	27-3-45	27-2-40B	27-1-87
PHENOCRYSTS	27.3	35.6	24.4	31.3	28.0	20.0	27.9	27.4	37.3	23.0
Plagioclase	18.4	24.0	19.2	21.3	20.8	16.2	20.8	19.2	25.7	18.0
Augite	2.8	7.8	1.8	4.1	1.1	2.4	2.4	2.6	5.1	3.0
Hypersthene	5.0	3.8	3.4	4.0	4.1	1.4	3.0	4.0	5.0	2.0
Olivine	0.0	0.0	0.0	0.0	0.4	0.0	0.1	0.2	0.2	0.0
GROUNDMASS	45.9	44.8	58.8	41.2	49.6	50.8	52.7	49.4	39.0	58.6
Magnetite	2.0	2.4	2.6	2.0	1.7	2.2	2.9	2.3	0.3	1.4
VESICULARITY	26.3	19.6	16.8	27.5	22.4	29.2	19.4	23.2	23.7	18.4
Counts	1000	500	500	1000	1000	500	500	1000	1000	1000

Table 1. (Continued) Modes for Arenal Volcano Historic Lavas

	88M	#Samples	Mean*	Standard Deviation
PHENOCRYSTS	25.4	51	26.9	3.8
Plagioclase	22.2	51	18.3	3.7
Augite	2.8	51	4.5	2.1
Hypersthene	0.4	51	3.6	4.2
Olivine	0.0	51	--	--
GROUNDMASS	57.2	51	50.0	5.1
Magnetite	4.0	51	2.4	1.6
VESICULARITY	17.4	51	21.7	6.6
Counts	500			

*Difference to 100% account for apatite and olivine.

inclusions form honeycomb structures which are common in both plagioclase phenocrysts and groundmass grains. Most phenocrysts show normal zoning, but inverse and oscillatory zoning are present. Polysynthetic, pericline twinning, and combined albite and carlsbad twinning are locally present in phenocrysts. Polysynthetic and carlsbad twinning are common in groundmass plagioclase. The mean value for phenocrystic plagioclase is 18.3 vol. % and for groundmass plagioclase is 19.9 vol. % (see Tables 1 and 2).

Augite: Euhedral to subhedral augite phenocrysts up to 1 cm in diameter are common. Augite phenocrysts, normally subhedral to anhedral constitute 4.5 vol. % and groundmass, subhedral augite constitutes 4.4 vol. % (see Tables 1 and 2). Augite is pale yellow-green to colorless and shows slight pale yellow-green to light green pleochroism. Zoning is common in phenocrysts, but absent in groundmass augites. Rare grains are twinned, $2\ V_z = 50^o$.

Hypersthene: Subhedral to anhedral phenocrysts constitute 3.6 vol. %. Subhedral groundmass hypersthene constitutes 1.7 vol. %. Hypersthene is pale green to colorless and slightly pleochroic (light green to light yellow-green); $r > v$, $2V_x = 60^o$, zoning is common.

Olivine: Anhedral olivine crystals, partially resorbed by reaction with the magma are rarely present as phenocrysts. Olivine is normally surrounded by hypersthene phenocrysts with a corona of vermicular magnetite. It was not possible to determine the 2V of the olivine grains because of this reaction. Olivine rarely contains picotite inclusions (see Table 1).

Magnetite: Commonly present in the groundmass and as inclusion in pyroxene phenocrysts. Mean value for magnetite is 2.4 vol. % but unusually high contents of magnetite, up to 8.8 vol. % are possible. Magnetites are cubic or aggregates of cubic microcrysts. Rounded or irregular aggregates are also present.

Glass: Color ranges from pale brownish gray in the glass-poor samples to dark brown to orange-brown in the glass-rich samples. Mean volume is 21% (see Table 2).

Apatite: Present as inclusions in phenocrystic and groundmass plagioclase with composition generally between 45 and 60% anorthite. Mean value is 1.5 vol. % (see Table 2). Normal grain is less than 0.2 mm in diameter.

Detailed Mode Calculations for 1968-1978 Lavas

Detailed mode determinations of phenocrysts and groundmass components, using 1,000 point counts at a magnification of 320 were made to evaluate minor variations in the mineralogy of the 1968-1978 lava flows, particularly of groundmass components and apatite variations.

Arenal lavas from 1968 to 1978 appear to maintain nearly constant modes (see Table 2). Observed differences in mineral proportions are probably more related to different grades of crystallinity and vesicularity, than with differences in rock chemical composition.

Apatite modal calculations (mean value 1.5 vol. %) disagree with apatite norm calculations (0.3-0.5 vol. %) (see Tables 2 and 4).

Apatite grains are so fine (< 0.2 mm) that in order to differentiate them from other inclusions present in plagioclases, it is necessary to focus the inclusions very carefully. This may have caused an overestimation of apatite since grains that were not in the thin section plane (out of focus) were counted.

Petrographic Descriptions of Pre-historic Lava Flows

Arenal pre-historic lavas are dark gray to gray, hyalopilitic to pilotaxitic, basaltic-andesites.

The 1525 pre-historic lavas and other pre-historic lavas outcropping in the northeast and east flanks of the volcano show very similar petrographic characteristics to the 1968-1978 lava flows (see Appendix E for petrographic descriptions and modal calculations).

Southwest flank basaltic andesite flows are less glassy (< 2%) than 1968-1978 lavas, and have pilotaxitic texture. These lavas have higher modal plagioclase phenocrysts and lower modal pyroxene phenocrysts than 1968-1978 lava flows (see Appendix E for petrographic descriptions and modal calculations).

Petrography of Lapilli Layers' Accidental Blocks

Accidental blocks are common features in layers of angular lapilli on the north and northeast flanks of Arenal Cone. These blocks were emplaced by nuées ardentes during the initial events of pre-historic active periods.

Accidental blocks are pale to dark gray, hornblende, two pyroxene gabbros, with phaneritic, subhedral granular to poikilitic texture.

Table 2. Detailed Modes for Arenal Volcano Historic Lavas

	1-5-16	3-2-18	5-1-59A	8-4-46A	10-1-84	12-1-22	16-1-51	16-2-85	18-3-22	20-3-06
PHENOCRYSTS	25.1	30.4	26.4	31.5	25.4	30.7	29.4	25.90	28.3	30.0
Plagioclase	14.9	21.2	18.4	18.7	15.1	23.8	23.0	14.7	19.8	20.9
Augite	3.7	3.6	3.2	5.4	4.8	1.7	1.8	6.6	1.7	1.5
Hypersthene	5.6	4.5	3.3	5.7	3.7	4.1	2.6	2.7	5.2	5.8
Olivine	0.2	0.0	0.0	0.0	0.0	tr.	0.0	0.1	0.0	tr.
Apatite	0.7	1.1	1.5	1.7	1.8	1.1	2.0	1.8	1.6	1.8
GROUNDMASS	54.5	50.6	54.1	51.2	47.4	49.4	54.0	50.9	55.2	48.6
Plagioclase	25.6	22.7	19.8	26.0	21.8	21.7	21.7	19.3	19.6	18.1
Augite		6.8	6.1	2.8	2.0	5.1	8.5	0.6	6.6	
Pyroxenes	6.3									3.2
Hypersthene		1.5	0.9	3.9	3.2	1.2	1.1	1.8	1.6	
Glass	19.4	17.8	26.2	14.9	18.3	17.8	20.1	26.5	25.0	26.3
Magnetite	3.2	1.8	1.1	3.6	2.1	3.6	2.6	2.7	2.4	1.0
VESICULARITY	20.4	19.0	19.5	17.3	27.2	19.9	16.8	23.2	16.5	21.4
Points	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000

*Including subdivided groundmass and apatite volume percentages

Table 2. (Continued) Detailed Modes for Arenal Volcano Historic Lavas

	22-1-38A	25-1-48	26-3-68B	26-4-69	27-1-87	27-2-40B	27-3-45	#Samples	Mean	Standard Deviation
PHENOCRYSTS	34.4	27.8	31.3	28.0	27.9	37.3	27.4			
Plagioclase	24.6	18.4	21.3	20.8	20.8	25.7	19.2			
Augite	4.9	2.8	4.1	1.1	2.4	5.1	2.6			
Hypersthene	3.7	5.0	4.0	4.1	3.0	5.0	4.0			
Olivine	0.3	0.0	0.0	0.4	0.1	0.2	0.2			
Apatite	0.9	1.6	1.9	1.6	1.6	1.3	1.4	17	1.5	0.4
GROUNDMASS	39.1	45.9	41.2	49.6	52.7	39.0	49.4			
Plagioclase	14.0	16.5	14.9	18.7	22.0	14.4	20.9	17	19.9	3.5
Augite	3.0	6.2	4.7	0.4				12	4.4	2.6
Pyroxenes					4.8	1.5	2.8			
Hypersthene	0.7	1.2	1.9	2.8				12	1.7	1.0
Glass	19.9	20.0	17.7	26.0	23.0	22.8	23.4	17	20.9	7.00
Magnetite	1.5	2.0	2.0	1.7	2.9	0.3	2.3			
VESICULARITY	26.5	26.3	27.5	22.4	19.4	23.7	23.2			
Points	1000	1000	1000	1000	1000	1000	1000			

Sample 92 is a hornblende gabbro with felty texture. These blocks probably represent magma cumulates crystallized at shallow depths (see Appendix E for petrographic descriptions and modal calculations).

Petrography of Arenal Volcano Lapilli Layers

Twelve microprobe polished sections of juvenile lapilli collected from 9 different layers at El Tajo Site were petrographically described. Modes were visually estimated since the area of the polished sections is very small.

El Tajo lapilli layers have the most contrasting chemical composition variations present in Arenal Rocks (see Table 4). These compositional variations are evidenced in the mineralogy and mineral proportions of El Tajo samples.

Lapilli layer rock types and general mineralogical characteristics are summarized as follow: Sample 6 is a two pyroxene, basalt; samples 1, 3 and 8 are two pyroxene, basaltic-andesites; sample 4 is an andesite without phenocrystic or groundmass pyroxenes; sample 9 is a hornblende, pyroxene andesite and samples 2, 5 and 7 are hornblende-dacites without phenocrystic or groundmass pyroxenes. Texture ranges from hyalopilitic to trachytic. Phenocryst volume % ranges from 25 to 30% in the basalt and basaltic-andesites, and from 1 to 7% in the acid andesites and dacites. Glass volume % range from 25 to 30 in the basalt and basaltic-andesites, and increases up to 50 volume % in the dacites. (See Appendix E for petrographic descriptions and modal estimations.)

Petrochemistry of Arenal Volcanic Group

Twenty one new chemical analyses of rocks from Arenal Volcano are presented in this work with nine other earlier chemical analyses from Melson and Saenz (1973) (see Appendices A and B for information about each sample and analytical information). In addition to chemical analyses, CIPW norms and differentiation indexes are given in Table 3.

The compositions of Arenal Volcano rocks are similar to volcanic rocks from other continental margins of the circum-Pacific region, that is, orogenic andesite and related rocks. The MgO, CaO, TiO_2 and total Fe contents decrease, and alkalis increase in these rocks with increasing SiO_2 (see Figure 5).

Arenal Volcano magmas show typical calc-alkalic trends in the AFM diagram with neither enrichment nor empoverishment in total Fe relative to MgO and total alkalis (see Figure 6).

Compositions of rocks from Arenal Volcano plot in the calc-alkalic field in the total Fe versus total Fe/MgO, which differentiate between the calc-alkalic and the tholeiitic volcanic series of island arcs and active continental margins (Miyashiro, 1974) (see Figure 7).

Based on chemical analyses most volcanic rocks from Arenal Volcano are basaltic-andesite or andesites. The exceptions are three dacitic lapilli layers (lapilli 02, 05 and 07), a basalt (lapilli 06) and several gabbroic accidental blocks (see Table 3).

Table 3. Chemical Analyses, CIPW Norms and Differentiation Index for Arenal Rocks

HISTORIC LAVAS	1+	2+	3+	4+	5-1-59	10-1-84	16-1-51	20-4-30	25-1-48	22-1-87
Symbol	A	B	C	D	E	F	G	H	I	J
SiO_2	56.31	55.91	54.02	54.43	54.05	54.25	55.15	54.90	54.65	55.05
Al_2O_3	20.38	20.24	20.08	19.36	18.72	18.56	18.33	18.34	17.96	18.67
Fe_2O_3	2.66	3.81	4.38	3.00	3.10	2.78	4.25	3.57	3.21	3.07
FeO	3.96	3.06	3.31	4.72	5.04	5.20	3.68	4.52	4.88	4.68
MgO	2.91	3.10	4.25	4.82	4.88	5.28	4.77	4.37	5.25	4.83
CaO	9.09	9.09	9.64	9.28	9.18	9.34	8.90	8.83	9.30	8.75
Na_2O	3.42	3.35	3.06	3.02	2.80	2.73	2.89	2.77	2.77	2.85
K_2O	0.66	0.66	0.60	0.52	0.64	0.63	0.64	0.66	0.65	0.63
H_2O^+	0.00	0.00	0.00	$<$ 0.10	--	--	--	--	--	--
H_2O^-	0.03	0.05	0.05	0.06	--	--	--	--	--	--
H_2O	--	--	--	--	0.22	0.18	0.18	0.15	0.18	0.18
TiO_2	0.54	0.56	0.61	0.72	0.62	0.65	0.61	0.65	0.61	0.61
P_2O_5	0.16	0.17	0.12	0.14	0.19	0.19	0.19	0.17	0.17	0.19
MnO	0.14	0.14	0.20	0.16	0.16	0.16	0.16	0.16	0.17	0.16
CO_2	--	--	--	--	0.06	0.04	0.03	0.03	0.05	0.05
Total	100.23	100.09	100.27	100.17	99.66	99.99	99.78	99.62	99.85	99.72
Q	9.7	10.7	8.1	7.4	7.9	7.5	10.8	10.1	8.5	9.5
OR	3.9	3.9	3.5	3.1	3.8	3.7	3.8	3.9	3.9	3.7
AB	28.9	28.3	25.8	25.5	23.8	23.2	24.6	23.6	23.5	24.2
AN	38.9	38.2	39.2	37.7	36.8	36.6	35.3	35.9	34.8	36.5
WO	2.4	2.4	3.2	3.1	3.2	3.6	3.3	3.0	4.3	2.5
EN	7.2	7.7	10.6	12.0	12.2	13.2	11.9	12.2	13.1	12.1
FS	4.4	1.8	1.8	5.8	6.0	6.5	2.5	4.6	5.6	5.4
MT	3.8	5.5	6.3	4.3	4.5	4.0	6.2	5.2	4.7	4.5
IL	1.0	1.1	1.2	1.4	1.2	1.2	1.2	1.2	1.2	1.2
AP	0.4	0.4	0.3	0.3	0.5	0.5	0.5	0.4	0.4	0.5
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Salic	80.7	81.1	76.6	73.6	72.4	71.0	74.5	73.4	70.7	74.0
Femic	19.3	18.9	23.4	26.4	27.6	29.0	25.5	26.6	29.4	26.0
D. In.	42.5	42.9	37.5	35.9	35.5	34.4	39.2	37.5	35.9	37.5
Erupted	9/68	11/68	6/70	8/73	5/74	?/75	?/76	?/77	12/77	8/78
Analyzed at	S.I.	S.I.	S.I.	S.I.	U.M.	U.M.	U.M.	U.M.	U.M.	U.M.

+After Melson and Saenz (1973)

S.I. = Smithsonian Institution
U.M. = University of Manitoba

Table 3. (Continued) Chemical Analyses, CIPW Norms and Differentiation Index for Arenal Rocks

PRE-HISTORIC LAVAS AND ACCIDENTAL BLOCKS

	5+	6+	7+	8+	09	10	65	86	9+
SiO_2	53.61	54.85	59.27	55.97	53.60	54.60	55.65	52.40	51.52
Al_2O_3	19.91	21.07	18.49	20.80	18.74	18.48	19.62	17.84	20.15
Fe_2O_3	3.95	1.87	3.02	2.36	2.82	3.42	2.94	3.54	2.89
FeO	4.17	4.73	3.76	4.25	5.60	4.68	4.01	5.62	5.64
MgO	4.42	2.93	2.53	2.85	5.05	4.75	2.92	6.05	4.98
CaO	9.39	9.37	7.21	8.87	9.44	8.96	9.16	9.74	10.30
Na_2O	2.98	3.37	3.61	3.36	2.64	2.72	3.12	2.46	2.51
K_2O	0.56	0.65	0.71	0.67	0.46	0.58	0.69	0.48	0.29
H_2O^+	0.17	0.00	0.58	$<$ 0.10	--	--	--	--	0.45
H_2O^-	0.05	0.06	0.09	0.00	--	--	--	--	0.09
H_2O	--	--	--	--	0.41	0.39	0.46	0.53	--
TiO_2	0.47	0.54	0.39	0.45	0.62	0.59	0.61	0.69	0.75
P_2O_5	0.15	0.14	0.17	0.16	0.20	0.20	0.23	0.20	0.14
MnO	0.16	0.12	0.20	0.14	0.17	0.19	0.14	0.18	0.12
CO_2	--	--	--	--	0.03	0.08	0.43	0.02	--
Total	99.99	99.70	100.03	99.88	99.78	99.68	99.98	99.75	99.88
Q		6.9	15.6	9.3	7.7	9.8	11.1	6.3	5.2
OR	3.3	3.9	4.2	4.0	2.7	3.5	4.1	2.9	1.7
AB	25.3	28.6	30.7	28.5	22.5	23.5	26.6	21.0	21.4
AN	39.4	40.6	32.4	39.7	38.2	36.6	37.8	36.5	43.2
WO	2.6	2.1	1.1	1.4	3.2	2.9	2.7	4.5	3.1
EN	11.0	7.3	6.3	7.1	12.7	11.9	7.3	15.2	12.5
FS	3.9	6.5	4.2	5.4	7.3	5.2	4.2	6.6	6.9
MT	5.7	2.7	4.4	3.4	4.1	5.0	4.3	5.2	4.2
IL	0.9	1.0	0.7	0.9	1.2	1.1	1.2	1.3	1.4
AP	0.4	0.3	0.4	0.4	0.5	0.5	0.5	0.5	0.3
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Salic	75.4	80.0	82.9	81.5	71.1	73.4	79.7	66.7	71.6
Femic	24.6	20.1	17.1	18.5	28.9	26.6	20.3	33.3	28.5
D. Ind.	36.0	39.4	50.5	41.8	32.9	36.8	41.9	30.2	28.4
Erupted	1525			1968					
				*					*
Analyzed at	S.I.	S.I.	S.I.	S.I.	U.M.	U.M.	U.M.	U.M.	S.I.

+After Melson and Saenz (1973)
*Accidental blocks.

S.I. = Smithsonian Institution
U.M. = University of Manitoba

Table 3. (Continued) Chemical Analyses, CIPW Norms and Differentiation Index for Arenal Rocks

JUVENILE LAPILLI FROM EL TAJO SITE

Layer	1	2	3	3	4	5	5	6	7	8	9
Symbol											
SiO_2	56.15	62.32	52.40	52.88	60.14	58.83	63.24	51.44	63.57	54.29	56.50
Al_2O_3	20.75	18.18	20.11	19.42	17.95	18.43	17.64	18.18	17.34	19.13	18.67
FeO*	6.19	5.45	8.14	8.10	6.62	7.13	5.44	9.09	5.44	7.79	7.94
MgO	2.56	1.99	4.74	4.73	2.43	2.68	1.83	6.48	1.85	4.06	3.20
CaO	8.98	6.52	10.38	9.67	6.68	7.50	5.97	9.89	6.35	9.40	8.12
Na_2O	3.45	3.83	2.69	2.86	4.08	3.55	4.05	2.02	3.41	2.69	3.11
K_2O	0.68	0.78	0.42	0.49	0.82	0.65	0.89	0.31	0.72	0.56	0.52
TiO_2	0.52	0.38	0.58	0.60	0.49	0.46	0.38	0.56	0.33	0.53	0.48
P_2O_5	0.14	0.19	0.14	0.14	0.21	0.17	0.22	0.12	0.17	0.14	0.15
Total	99.42	99.63	99.59	98.89	99.43	99.80	99.66	98.08	99.17	98.59	98.70
Q	9.9	19.2	5.7	6.3	14.7	14.7	19.9	7.0	23.6	9.9	13.1
OR	4.0	4.6	2.5	2.9	4.9	3.9	5.3	1.9	4.3	3.4	3.1
AB	29.4	32.5	22.8	24.5	34.7	30.2	34.4	17.4	29.1	23.1	26.7
AN	39.4	30.2	41.7	39.1	28.4	32.6	27.4	40.4	30.1	39.0	35.9
WO	1.9	0.4	3.8	3.5	1.5	1.5	0.4	3.7	0.2	3.1	1.6
EN	6.4	5.0	11.8	11.9	6.1	6.7	4.6	16.5	4.6	10.3	8.1
FS	4.3	3.9	5.8	5.7	4.7	5.1	3.9	6.7	4.0	5.6	5.8
MT	3.4	3.0	4.5	4.5	3.7	4.0	3.0	5.1	3.0	4.4	4.4
IL	1.0	0.7	1.1	1.2	0.9	0.9	0.7	1.1	0.6	1.0	0.9
AP	0.3	0.5	0.3	0.3	0.5	0.4	0.5	0.3	0.4	0.3	0.4
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Salic	82.7	86.5	72.7	72.8	82.7	81.4	87.0	66.7	87.1	75.3	78.8
Femic	17.3	13.5	27.3	27.2	17.3	18.6	13.1	33.3	12.9	24.7	21.3
D. Ind.	43.3	56.3	31.0	33.7	54.3	48.7	59.5	26.3	57.0	36.3	42.8
Erupted	1968	1525							220 B.C.		
Analyzed at	S.I.	S.I.	S.I.	S.I.	S.I.	S.I.	S.I.	S.I.	S.I.	S.I.	S.I.

*All Fe calculated as FeO.
$Fe_2O_3/FeO = 0.677$ = Ave 18 Arenal Volcano Rocks.

S.I. = Smithsonian Institution

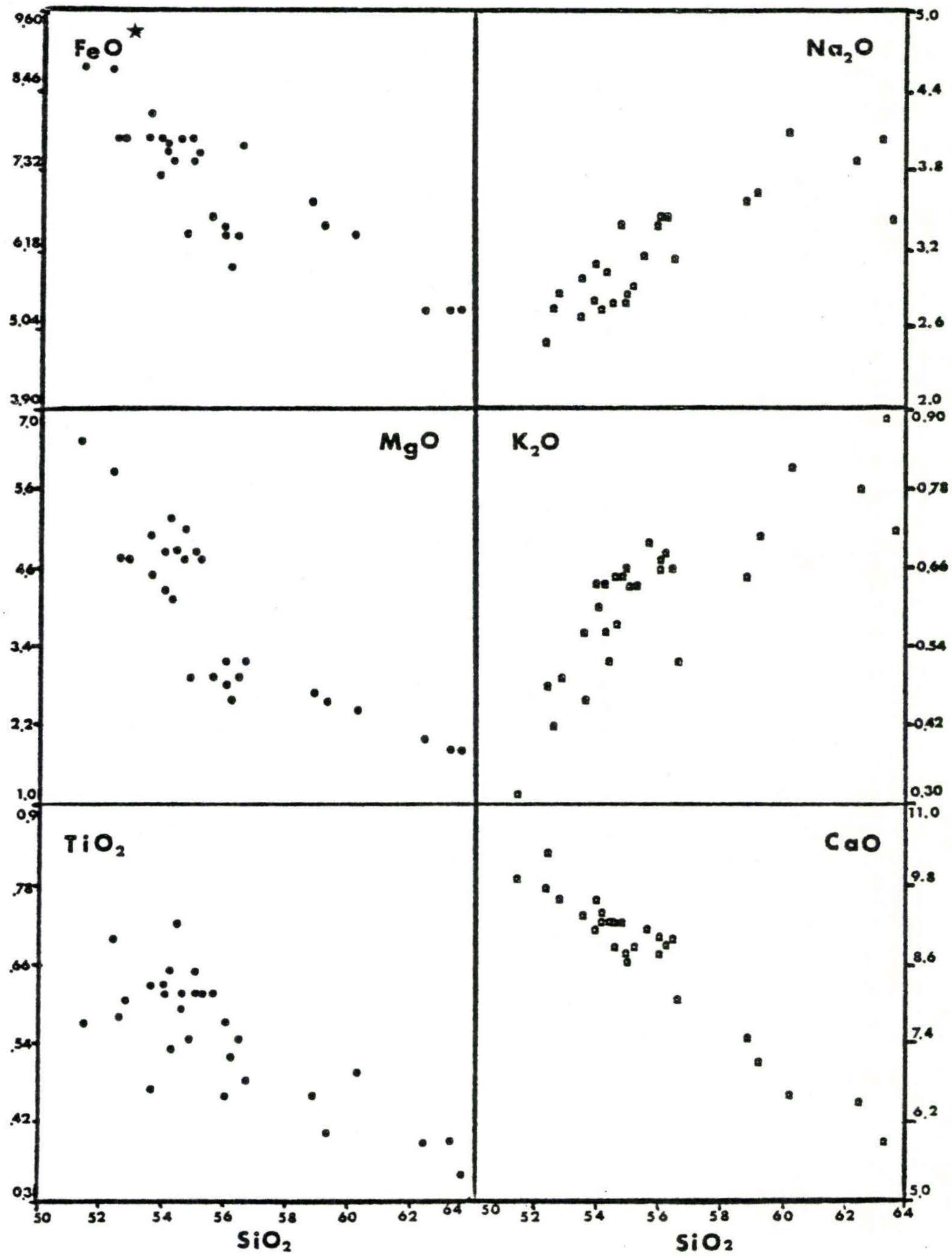
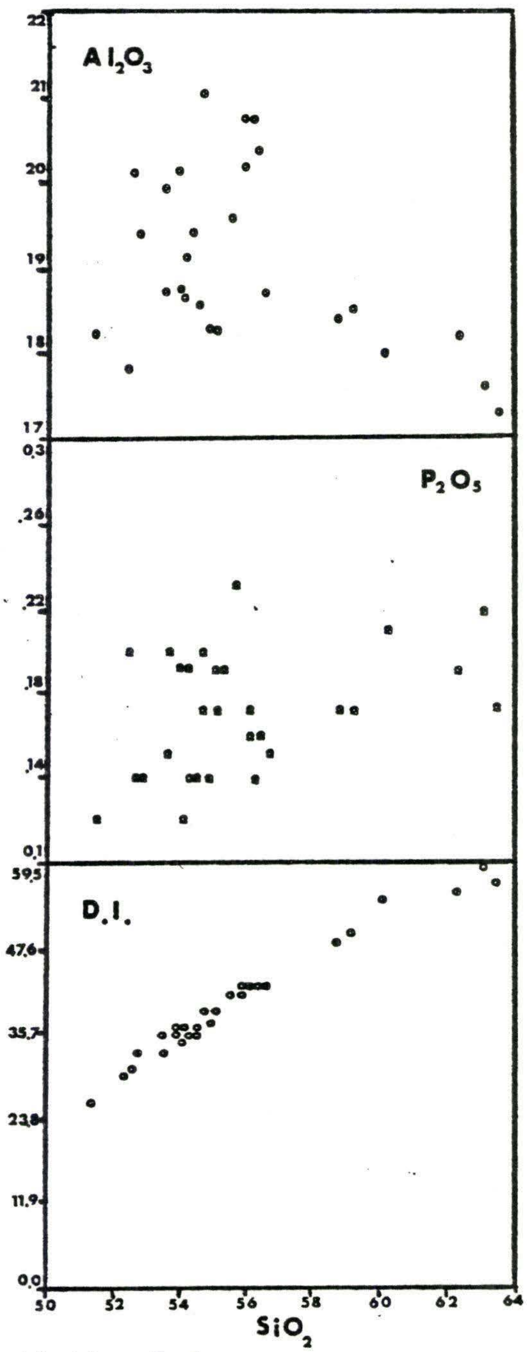
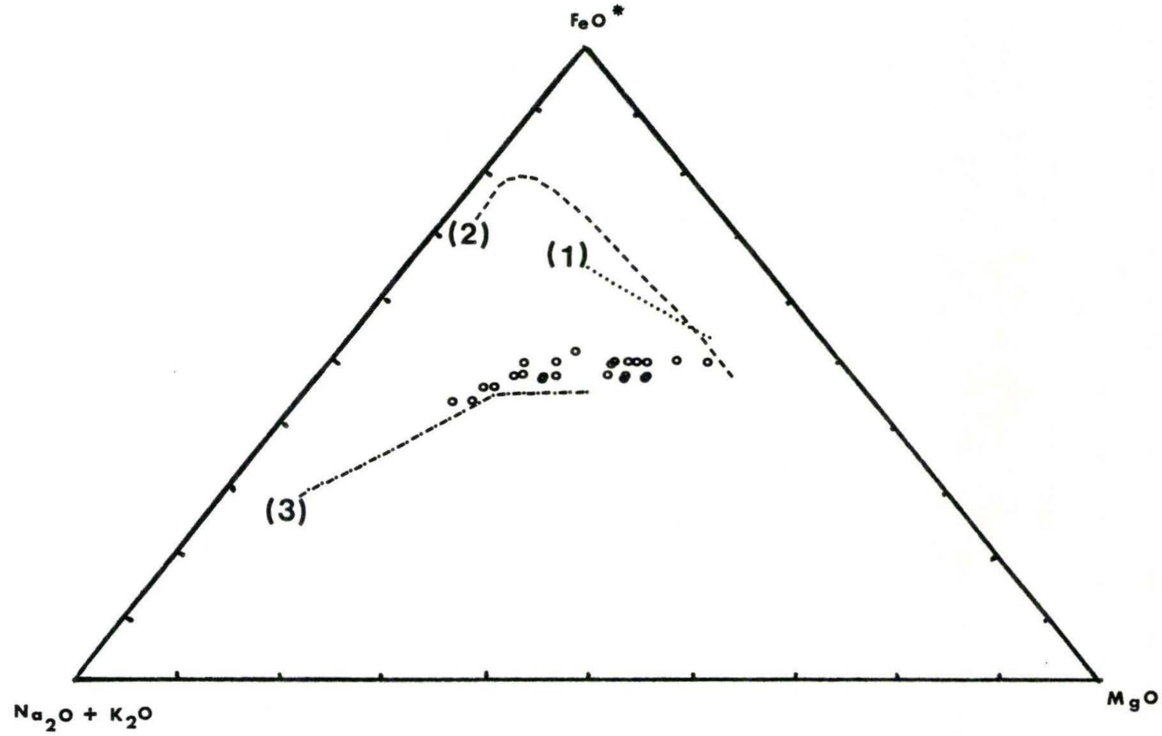


Figure 5. Harker variation diagrams for Arenal Rocks.
FeO* = total iron as FeO



D.I. = Differentiation Index

Figure 5. (Continuation) Harker variation diagrams for Arenal Rocks. FeO* = Total iron as FeO



°° = Arenal Volcano Rocks

1 = Tofua trend, Tholeiitic Series of Island Arcs and Active continental margins environment

2 = Skaergaard Intrusion (liquid) trend Continental Tholeiitic Province

3 = Asama Volcano trend, Calc-Alkalic Series of Island Arc and active Continental Margins environment

FeO^* = Total iron as FeO

Figure 6. AFM Diagram for Arenal Rocks

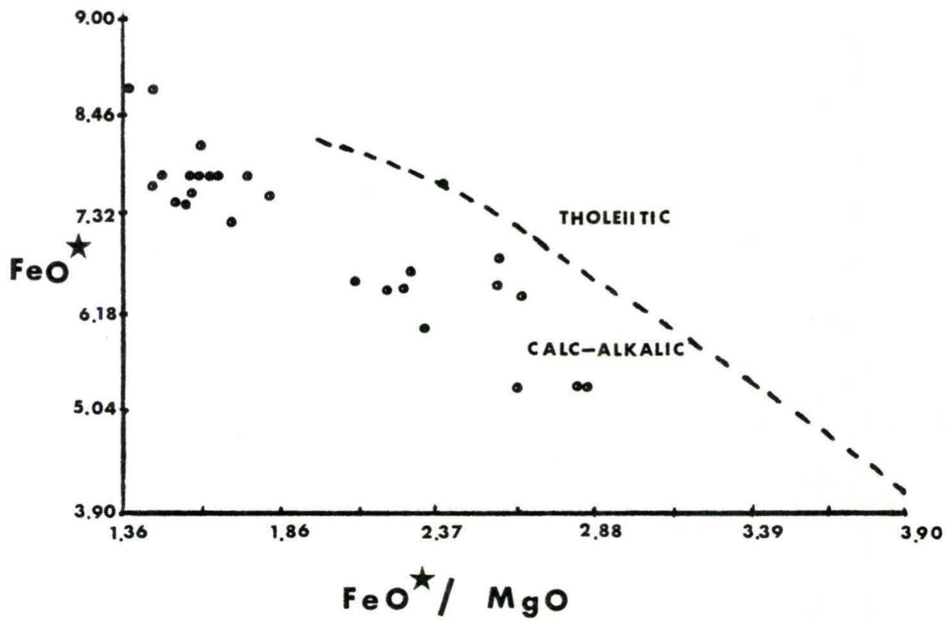


Figure 7. Plot of total iron as FeO versus the ratio total iron as FeO/MgO. Line after Miyashiro, A. (1974).

1968-1978 Lavas and Lapilli

There are eleven chemical analyses of historic lavas and essential ejecta from Arenal Volcano. Chemical analyses of four of the samples were reported by Melson and Saenz (1973). Seven new chemical analyses are presented here (see Table 3 and Appendix A for information about each sample). Symbols are used in the following plots. They are in chronological order. A is the oldest sample (1968); J is the youngest (1978). Sample 1 is equivalent to sample A in age.

A small but significant decrease in Na_2O and K_2O, and increase in total Fe, MgO, and TiO_2 is obvious in the 1968 to 1973 lava flows. Melson and Saenz (1973) interpreted this trend as reflecting the extrusion of less differentiated lava with time (see Figure 8).

Six new chemical analyses of Arenal lavas presented in this study are from samples erupted from 1974 to 1978 from crater C.

Lavas from 1973 (sample D), erupted from crater A, when compared with lavas from 1974 (sample E), erupted from crater C, show the following characteristics: an increase in total Fe, FeO, MgO and K_2O accompanied by decrease in CaO, Na_2O and TiO_2 (see Figure 8).

Lavas erupted after 1974 show a small and irregular increase in total Fe and MgO, constant level or slight increase in TiO_2 and a small decrease in Na_2O when compared with previously erupted lavas. Nevertheless, chemical changes are very small when compared with pre-1974 lavas and they do not follow a singular obvious trend as is evident for pre-1974 lavas (see Figure 8).

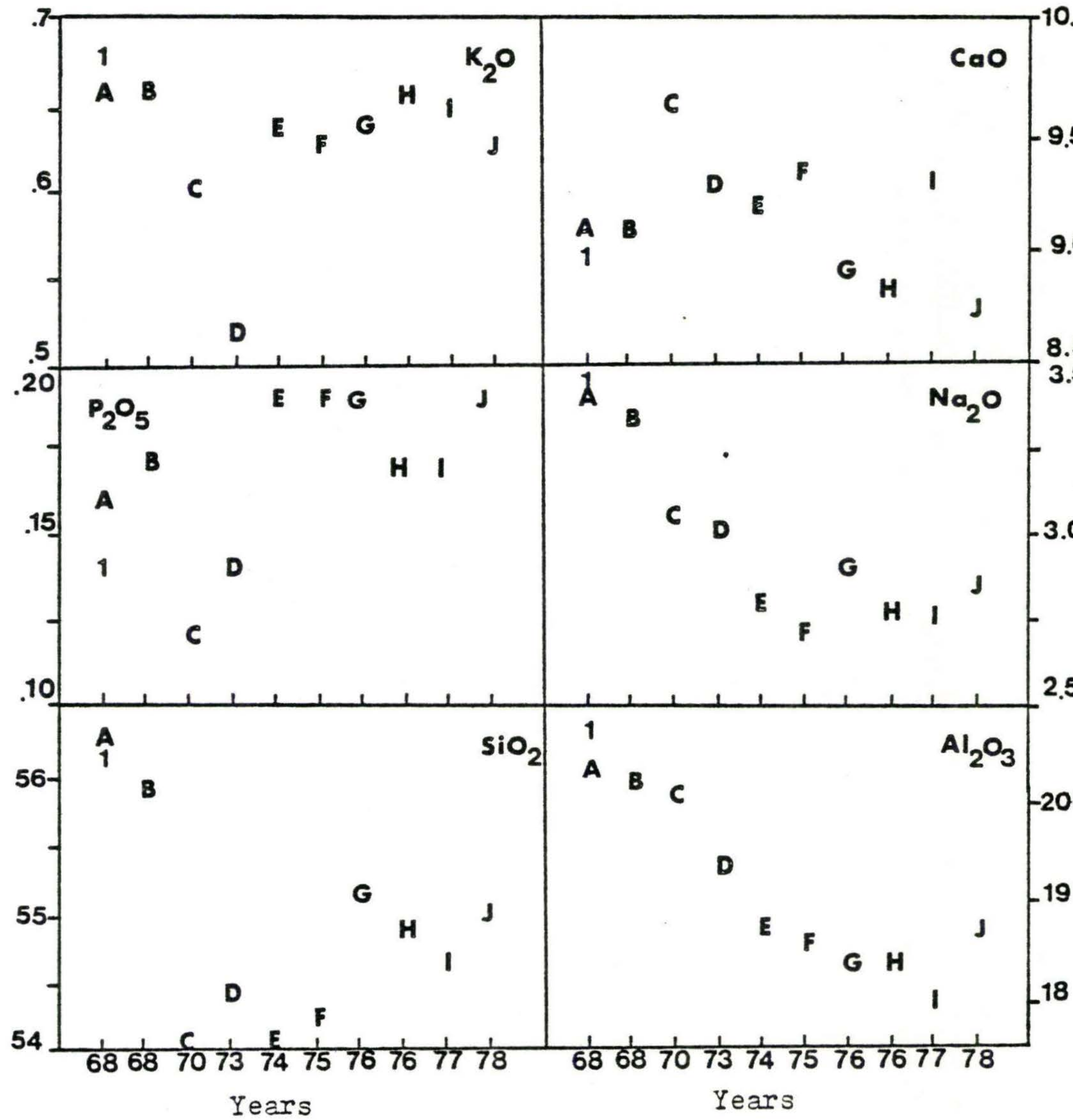


Figure 8. Variation in composition versus time in Arenal Volcano historic lavas.

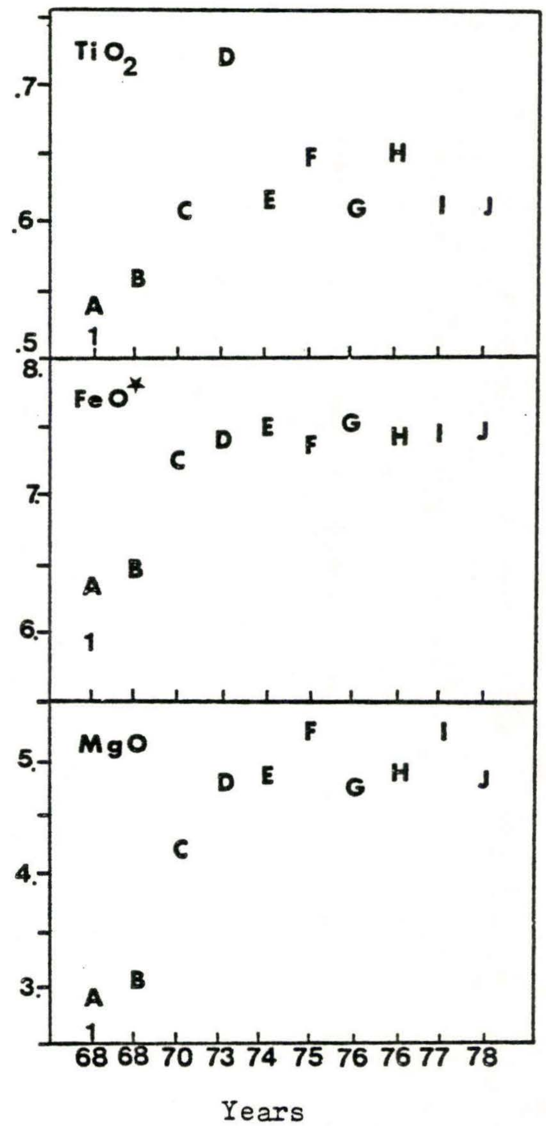


Figure 8. (Continuation) Variation in composition versus time in Arenal Volcano historic lavas.

MODEL OF ERUPTIVITY OF ARENAL VOLCANO

A cyclic model of eruption for Arenal Volcano was proposed by Melson and Saenz (1973) based on the characteristics of the present eruption up to 1973 and on information from pre-historic eruptions.

Melson and Saenz (1973) characterized Arenal Volcano eruptive cycles as follows: Eruptions begin with an upsurge of magma after a period of repose. The pulsating rise of magma clears conduits, becomes degassed and erupts blocky lava flows. Initial explosions are explained as a result of explosive degassing of magma super-saturated with volatiles. Volatile super-saturated magma could be produced by either crystallization of anhydrous phases, probably plagioclase and pyroxene, or by isothermal displacement of deep seated volatile saturated magma to near the surface. Another possible explanation is that over-pressures are produced by low volatile magma moving through water-saturated rocks. Small explosions and volcanic ash emission are interpreted as products of degassing of successive zones of magma, as each approaches the surface until, finally, a blocky lava flow is erupted. The magma column is not only zoned in regard to volatile content, but in major and minor elements as well, with more-differentiated, volatile-rich, magmas at the top and less-differentiated, volatile-poor magmas at the bottom.

The process of eruption of such a magma column will produce successively less differentiated lavas through time. During a repose period the magma remaining in the conduit and magma chamber would become successively more differentiated until new uprising magma produces a new eruption.

New chemical analyses do not support a simple evolution toward less differentiated lavas at Arenal Volcano, after 1974, which is 40% of the volume of the 1968-1978 lavas. During 1974 lavas began to erupt from crater C. The difference in chemical parameters between 1973 and 1974 could be explained by a zoned magma chamber. The vent fro crater C tapped a higher level of the magma chamber.

Tiltmeter records from Arenal Volcano early eruptive period (1969-1970) indicate several episodes of uplifting and subsidence on the scale of the order of 10 microradians. The uplift may be the result of addition of new magma to the reservoir. Subsidence may be the result of loading extensive lava flows (Simon et al., 1969). The multiple periods of uplifting suggest that magma was intruded into Arenal Volcano in pulses. This new magma may have been less differentiated. This is consistent with the chemical analyses for post-1973 lavas which have minor variations, but generally are very similar and basic for calc-alkaline volcanoes.

Correlation of the chronology and the chemistry of Arenal lavas and unpublished tilt and seismic information will be very valuable in understanding the mechanisms governing magma movement underneath Arenal Volcano.

Chemical analyses of essential ejecta collected from historic and pre-historic lapilli show diverse chemical compositions, ranging from basaltic to dacitic. Since stratigraphic evidence and the chronology of the present active period suggest that these deposits were emplaced during the initial explosive events of an eruption, the presence of lapilli layers with SiO_2 content of less than 52% (see Table 4) suggests that the production of more differentiated lavas at the early events of Arenal eruptions might not necessarily be a consistent feature of Arenal Volcano active periods.

The presence of basaltic andesitic to dacitic lapilli in different layers, suggest that if differentiation is the factor responsible for the differences in composition, more differentiated lapilli layers are indicators of longer periods of repose since the previous eruption. This possibility should be evaluated using radiometric dating of material in lapilli layers.

AGE AND GEOLOGIC HISTORY OF ARENAL VOLCANO

Initiation of Volcanism at Arenal Volcano

There are few unambiguous age dates for Arenal Volcano. Geomorphologically, Arenal Cone is a recent geological feature. Absolute estimations of the age of Arenal encounter many limitations.

Total energy required to built up Arenal Cone from 500 m to 1833 m, using equations from Hedervari (1963), is 6.6×10^{25} ergs. Calculation of total energy released by the 1525 eruption is 1.8×10^{24} ergs (Melson and Saenz, 1973). Dividing the total energy required to built up Arenal Cone by the energy released during the 1525 active period will provide the number of eruptions of similar energy needed to built up the Arenal Cone. Twenty-four to thirty-seven eruptions similar to the 1525 are required to build up Arenal Cone. The real number is probably smaller since only the Tabacon River Lava Flow was included in the calculations, excluding other 1525 lava flows, and early eruptions were on the average more voluminous (energetic) than the current one, perhaps 5 to 10 times according to the relative thickness of their volcanic sand and lapilli layers (Melson and Saenz, 1973).

Stratigraphy of the volcanic sand and lapilli layers could be used to evaluate Arenal Volcano age. A stratigraphic section of El Tajo Site, 20 m thick (10°27.8'N, 84°46.0'W) consists of 10 eruptive units separated by soil horizons (Melson, 1978, written communication). A very similar section was studied during my field work at Quebrada

Lava ($10^{o}29.14$'N, $84^{o}44.14$'W). A minimum of 10 major eruptions occurred at Arenal Volcano according to the stratigraphic record.

The number of eruptions necessary to built up Arenal Cone is more likely a number between 10 and 24 eruptions (17 ± 7) according to above mentioned arguments.

C^{14} age dates from three wood samples collected during field work in 1978 are not yet available. However two other radiocarbon dates have been made on Arenal pre-historic eruptions. The last pre-historic eruptions (unit 2 at El Tajo Site) were dated at 1525 ± 20 (Melson and Saenz, 1973), and eruptive unit 8 at El Tajo Site was dated at 2170 ± 65 B.P. (Melson, 1978, written communication). From these age dates it is possible to estimate the dormancy period between the last pre-historic eruption and the 1968 eruption at 443 ± 40 years. An average period of 310 ± 9 years is estimated from the last 7 dormancy periods. These facts suggest that Arenal dormancy periods are irregular in duration. Similar irregular dormancy periods have been reported for other volcanoes (e.g. Mt. Saint Helens (Crandell _et al_., 1975), Vesuvius (Lirer _et al_., 1973), Fuji (Tsuya, 1955)).

Nonetheless, it is possible to estimate the age of Arenal Volcano. Let's assume that the number of eruptions necessary to built up Arenal Cone is 17 ± 7 eruptions. The age of Arenal Volcano is estimated at 5270 ± 2170 years, if the average dormancy period of approximately 310 years is used; and at 7531 ± 3101 years, if the dormancy period between the last two eruptions is used.

Further research using radio-carbon methods combined with detailed stratigraphy of Arenal volcanic sand and angular lapilli layers, will provide a better estimation of Arenal Volcano absolute age and periodicity.

The Last Pre-historic Eruption of Arenal Volcano

The last pre-historic eruption of Arenal Volcano was dated using radio-carbon at A.D. 1525 ± 20 (Melson and Saenz, 1973). The fact that Indian ceramic objects, culturally dated between 1200 and 1400 A.D. (Melson and Saenz, 1973), were excavated from airfall ash from this eruption ($10^{o}30.0$'N, $84^{o}42.5$'W), suggests that Arenal Volcano area was populated by Indians when the last pre-historic eruption occurred. Undoubtedly, these Indians were victims of explosions and nuées ardentes from Arenal Volcano.

Blocky lava flows and a blocky ash flow produced during this eruption are exposed on the north and northwest flank of Arenal Cone.

Initial events during the 1525 eruption produced a sequency of two layers of airfall materials at the base of Arenal Cone. These layers consist of a layer, 75 cm thick, of coarse angular lapilli, overlaid by a layer of angular volcanic sand, 100 cm thick, at approximately 7 km south-southwest of Arenal summit. These layers are notably thicker than the overlying 1968 eruption layers, which are 25 cm for the angular lapilli layer and 12 cm for the volcanic sand layer. Assuming comparable wind directions and intensity during 1525 and 1968 eruptions, the 1525 eruption was about 5 times more voluminous during its explosive phase (Melson and Saenz, 1973).

The 1525 group of lavas includes the largest exposed pre-historic flow (Tabacon River Flow). This flow traveled for five kilometers, before terminating at the Arenal River Valley, which was at least partially dammed by this flow (see Appendix G).

According to field and aerial photograph observations, the 1525 flows originated from the summit crater or close to its northern rim. They produced two lakes on the northern slopes of Arenal Cone by filling and damming pre-existent channels (see Appendix G).

After the 1525 active period, Arenal entered a fumarolic stage for more than four centuries. Reports from 1937 and 1963 from hikers established the existence of small fumaroles in Arenal's summit crater rim (Saenz, 1977). Farmers of the area reported that Tabacon River had thermal waters before 1968.

1965-1968 Pre-eruption Events at Arenal Volcano

A series of changes occurred in the vicinity of Arenal Volcano from 1965 to 1968, which were registered by H. Taylor, a topographer working in the area for ICE, and reported by Avila (1978). Taylor registered the appearance of fumaroles near Venado Village, 12 km north-northwest of Arenal summit and 2.3 km northeast from the summit crater (map coordinates: 2737-4607). Gases liberated in these areas asphyxiated small animals. These fumaroles disappeared after the volcano entered eruption, but information about their evolution is missing. At the same time, the water level of the lakes was reported to be unusually low. In 1967, Taylor reported a rise in temperature of Tabacon River, to a point that cattle could no longer drink the water. In May 1968, seismic activity was felt near Tabacon and Pueblo Nuevo Villages. The amount of seismic activity increased during the week before the initial explosion. A seismic storm with increasing frequency and intensity affected Arenal Volcano and surroundings for 8.5 hours before the initiation of the explosive activity; 20 to 100 earthquakes were felt by La Palma Village and La Fortuna Town residents, with intensities of IV and V in the modified Mercalli scale (Matumoto, 1968).

Farmers near La Plama Village reported unusual travertine deposition previous to 1968 and during the first years of activity along Quebrada Guillermina, a cold water stream in the northeast flank of the volcano, located about 0.5 km from one of the fumaroles described by Taylor in 1965. These deposits, 1 to 3 cm thick, were observed covering the stream gravel during the field season. A hot spring, located 700 m SW from quebrada Guillermina ford on the road to La Palma Village, was visited too, however this hot spring did not show any travertine deposits.

Previous to July 1968, local changes in the water table, rising in hot springs temperatures, fumarolic activity, deposition of travertine along stream beds and a drastic increase in seismic activity were obvious manifestations that an eruption was imminent at Arenal Volcano. However these facts were probably never known or were looked upon with skepticism by people who would be able to interpret them correctly.

Historic Arenal Volcano Active Period

On July 29, 1968, Arenal Volcano initiated its first historic active period which still continues today. According to the descriptions of Melson and Saenz (1968; 1973); it is possible to recognize the following eruptive phases: I. Explosive (July 29-31, 1968); II. Fine pyroclastic (August 1-10, 1968); III. Fumarolic (August 10-September 14, 1968); IV. Strombolian (September 14-19, 1968); and V. Effusive (September 19, 1968 to present).

I. Explosive phase (July 29-31, 1968)

Three new explosion craters were opened along an approximately east-west line on the west flank of Arenal Volcano. The largest crater (a), the one from which the major explosions originated, is located at an elevation of 1050 m. Two major explosions from crater A which produced nuées ardentes were registered, one on July 29, 1968, and the other on July 31, 1968. The diameter of the material expelled by the explosions ranged from fine ash to large blocks (2 x 3 x 6 m). Numerous large blocks were expelled at low angles (60^{o} or less; Saenz, 1977) to distances of up to 5 km from crater A.

Fall back of explosively ejected materials created hot avalanches which coalesced and descended the west and northwest flanks of Arenal Volcano, reaching about 5.0 km from crater A and devastating 12 km^2. Nuées ardentes reached large average ejection velocities estimated at 300 m/sec (Melson and Saenz, 1973), and temperatures that charred and totally defoliated the forest in just a few minutes. At Tabacon and

Pueblo Nuevo, 3-5 km from crater A, air temperatures were estimated at 300-500^{o}C (Melson and Saenz, 1973).

The first blocky ash flows which erupted on July 29, 1968, had an almost elliptical distribution around the explosion craters. They were relatively poor in juvenile ejecta and graded down-slope into an angular lapilli layer at the base of the cone. The second blocky ash flows erupted on July 31, 1968, were produced from an open crater (A) explosion by vertical discharge of incandescent ash and blocks. The blocky ash flows were deposited along drainage channels trending N 35 W from the lower explosion crater A.

During this phase 78 people were killed by nuées ardentes and a volume of 0.03 ± .02 km^2 of tephra was emitted.

II. Fine Pyroclastics Phase (August 1 to 10, 1968)

Emission of volcanic ash, first from crater A, and later from crater C, was accompanied by fumarolic activity. Nuées ardentes were not erupted during this phase. On August 3, 1968 crater A entered fumarolic activity and ash began to be erupted for the first time from crater C. Moderate explosive activity during this phase was characterized by the emission of dark clouds with volcanic ash, 2 to 3 km above Arenal Cone, which were blown to the west. Numerous ash falls were reported within an area of 1052 km^2 extending from Arenal Volcano to the Pacific coast (Saenz, 1977).

III. Fumarolic Phase (August 10 to September 14, 1968)

There was strong to moderate fumarolic activity from craters A, C, and D, with the most intensive activity from crater C.

IV. Strombolian Phase (September 14 to 19, 1968)

This phase was characterized by mild eruptions of a small volume of scoriaceous to pumiceous basaltic-andesite bombs, volcanic ash and vapor from the lower crater A. This phase marked the first time that ejecta were mainly juvenile.

V. Effusive Phase (September 19, 1968 to present)

Twenty-eight lava flows were erupted from September 1968 to December 1978, covering an area of 4.9 km^2 (see Appendix F). Three large flows were erupted from the lower explosion crater A, from September 1968 to 1973, and twenty-five flows, from the upper explosion crater C from 1973 to December 1978. Lava flow 1 is a composite flow which was emplaced from September 1968 to late 1971 or early 1972. Druing this period a scoria cone formed around crater A. Aerial photographs taken September 5, 1972 show lava flows 2 and 3 already emplaced and minor fumarolic activity in craters A, C, and D. Sometime in early 1974, probably in March or April, the upper explosion crater C began to erupt lavas. On May 3, 1974, when the author visited Arenal Volcano, a lava flow from crater C was moving downslope near the south rim of crater A. This is probably lava flow 5 of Taylor and Umaña (1978). By April 23, 1975 when aerial photographs were taken, lava flow 13 had been erupted. Aerial photos were taken again on

December 28, 1976. They show the eruption of lava flow 18. Late May 1978 when the field work for this study began, lava flow #26 had been flowing for more than five weeks. This flow continued moving until late July, approximately two weeks after its source stopped activity. Between July 20 and 25, 1978, a new lava flow (#27) began along the W flank of Arenal Volcano and when the field season ended in mid-August it was still moving. Flow #28 began to erupt, following a direction similar to flow 26 (towards NW), in late November 1978, and was still flowing in late January 1979 (see Table 4).

1968 to 1973 lava flows covered an area of 2.74 km^2 with 21.9 ± 7.3 m of blocky lava flows which represent a volume of 0.060 ± .020 km^3 including empty spaces (Melson and Saenz, 1973). An area of 2.16 km^2 is covered by 1973 to 1978 lava flows. A volume of 0.047 ± .016 km^3 including empty spaces is estimated for this period and a total volume of lava, including pore spaces, is estimated for the period of 1968 to 1978 of 0.107 ± .0036 km^3, using the same thickness parameters as Melson and Saenz (1973).

During the field season, the eruption of lava flow #26 continued for 10 weeks. The eruption of lava #27 required four to five weeks.

1975 Hot Avalanche Event (June 17-21, 1975)

On June 17, 1975 between 9:00 and 10:30 a.m., four nuées ardentes were produced by avalanching of lava flow #14 while it was being erupted from crater C. The steepness of the NW flank of Arenal Cone near crater C favored the production of these avalanches, which descended the drainage of Tabacon River.

Table 4. Chronology of 1968-1978 Lava Flows*

Lava Flow #	Erupted from Crater	Reported Flowing	Last Reported Flowing
1	A	9/14/68	late 71
2	A	9/71	8/72
3	A	9/72	late 73
5	C	5/3/74	----
13	C	4/23/75	----
14	C	6/17/75	7/75
18	C	12/28/76	----
26	C	4/78	7/78
27	C	7/78	8/78
28	C	11/78	2/79
29	C	4/79	----

*Based on data from Taylor and Umaña (1978), Melson and Saenz (1973), Van der Bilt et al. (1976) and this work.

The hot avalanches were composed largely of juvenile ejecta, accompanied all along their course of descent by the production of large quantities of fine, airborne tephra. A similar, but smaller hot avalanche was produced on July 21, 1975 (Van der Bilt et al., 1976).

Ash falls were intense within an area 5.5 km long and 3 km wide in a direction NE-SW from Tabacon River. Thicknesses ranging from 0.5 cm (Matumoto and Umaña, 1976) to 2.5 cm (Van der Bilt, 1976) were reported in the vicinity of Arenal Dam.

Temperatures between 200° to 400° C were reported 15 cm underground on these hot avalanche deposit 5 days after their emplacement (Van der Bilt et al., 1976).

During this period, drastic changes occurred in crater C. Hot avalanches eroded the NW rim of crater C and were accompanied by landslides. Materials from the hot avalanches and landslides probably mixed. This would account for the mixture of juvenile and accidental materials found in the blocky ash flows. These blocky ash flows were part of the effusive phase, having formed as the result of collapse of a lava flow.

VOLCANIC HAZARDS AND SURVEILLANCE

Potential Volcanic Hazards at Arenal Volcano

Major active periods of volcanoes tend to be relatively short when compared with periods of dormancy. Therefore, it is reasonable to expect that in the near future lava flow eruption will stop and Arenal Volcano will return to a dormant stage with gradually decreasing fumarolic activity.

Available data upon which future predictions of Arenal Volcano can be based are meager. It does not permit one to answer for example, how many more months or years this volcano is going to continue to be active, nor how long the transition is going to be between an effusive stage and a dormant stage.

Dry tilt measurements on Arenal Volcano west flank indicate that Arenal has continued to deflate since 1977 with a net deflation of around 93 millimeters/km at station C (740 m elevation) (Melson, written communication, 1979). This fact supports the idea that the present active period is going to come to an end if the volcano continues following the same tendency in the future.

Knowledge of Arenal Volcano obtained from the descriptions of the current active period and from the stratigraphic record allow a possible evaluation of the potential volcanic hazards. Using the maximum distance traveled by erupted materials in the past, it is possible to predict potential volcanic risks for Arenal Volcano.

Areas up to 3.5 km from Arenal's summit may be subjected to future hot avalanches of directional character, similar to those produced in 1975 and on August 31, 1968. This areal definition does not consider topographic irregularities (see Figure 4).

The maximum distances of deposition of layers of volcanic sand and angular lapilli produced by nuées ardentes during the initial explosion of Arenal active periods is difficult to estimate; layers of volcanic sand and angular lapilli are reported as far away as 12 km west of Arenal Volcano at the intersection of the roads to Venado Village and Arenal Dam (Aguilar, personal communication, 1978) (outside the area of study). Layers of volcanic sand and angular lapilli outcrop in the vicinity of Arenal Dam about 7 km west of the summit crater.

Layers of volcanic sand and angular lapilli are only produced during the initiation of an Arenal active period. Therefore, during the remaining portion of the present active period, potential volcanic hazards are reduced. They consist of the emplacement of lava flows and blocky ash flows produced by collapse of erupting flows. This fact reduces the area potentially exposed to volcanic hazards to 5 km from Arenal summit.

Arenal Volcano produced fine pyroclastics, mainly volcanic ashes, in appreciable amounts only during fine pyroclastic phase from August 1 to 10, 1968. During this phase ash falls were reported within an area of 1052 km^2 to the west of Arenal Volcano (Saenz, 1977). Damages caused by these ash falls were probably very limited, since they are not mentioned in the literature and heavy rains probably contributed to washing away the ash rapidly. Fine pyroclastics, produced during the emplacement of 1975 hot avalanches, affected areas close to Arenal Cone west flank, up to 7 km from the summit crater. Most of the area affected by these ash falls was previously devastated by 1968 nuées ardentes, so that they caused little economic damage.

Considerable damage could be caused to the Arenal Hydroelectric Complex if very heavy fine pyroclastic eruptions, such as occurred at Irazu Volcano in 1963-1965 (Murata et al., 1966), were to be produced by Arenal Volcano. Such eruptions would accelerate erosive processes producing considerable sedimentation and pollution in Arenal Dam reservoir. The stratigraphic record and present active period chronology suggest that fine pyroclastic eruptions occur at Arenal Volcano only during the initiation of an active period, although the 1968 initial events produced very mild deposition of fine pyroclastics in the area presently occupied by Arenal Dam reservoir.

The morphology and location of the present day main active vent (crater C) define an area of highest potential volcanic hazards at Arenal Volcano for the current eruption. This area of semi-circular shape is located between N 15 W and S 15 W of Arenal Cone with its center located at crater C and radius defined by the previously mentioned maximum distances traveled of lava flows and blocky ash flows (see Figures 9 and 10).

Possible morphological changes produced by collapse of crater C walls might eventually increase the area of highest potential hazards. Crater C morphological evolution should be carefully followed since small modifications by landsliding of crater C northern wall will expose farms in the northern flank of the volcano to possible danger from lava and blocky ash flows.

The stratigraphic and lateral distribution of volcanic sand and angular lapilli layers, already mentioned in the stratigraphy section, suggests that preferential direction of Arenal initial explosions is toward the NW and SW quadrants of the Cone. This preference and the already reported distances greater than 7 km reported for pre-historic layers of volcanic sand and angular lapilli define a high risk area for future active periods. Further studies should provide a better definition of the spatial distribution of pre-historic volcanic sand and angular lapilli layers. Such studies are needed before any accurate evaluation can be made of potential volcanic hazards within this area which includes Arenal Dam and a portion of Arenal Dam reservoir.

Another topic that deserves future investigation is the duration of dormancy stages between active periods. Detailed studies on volcanic sand and lapilli layers using radio-carbon dating of wood samples collected from different layers will provide a better understanding of the periodicity of activity at Arenal Volcano and probably a better estimation of the age of the volcano.

Permanent Volcanological Studies at Arenal Volcano

Fifty-three volcanic edifices are present in Costa Rica (Saenz, 1971) and in historic times, 5 of the edifices have been active: Turrialba, Poas, Irazu, Rincón de la Vieja and Arenal.

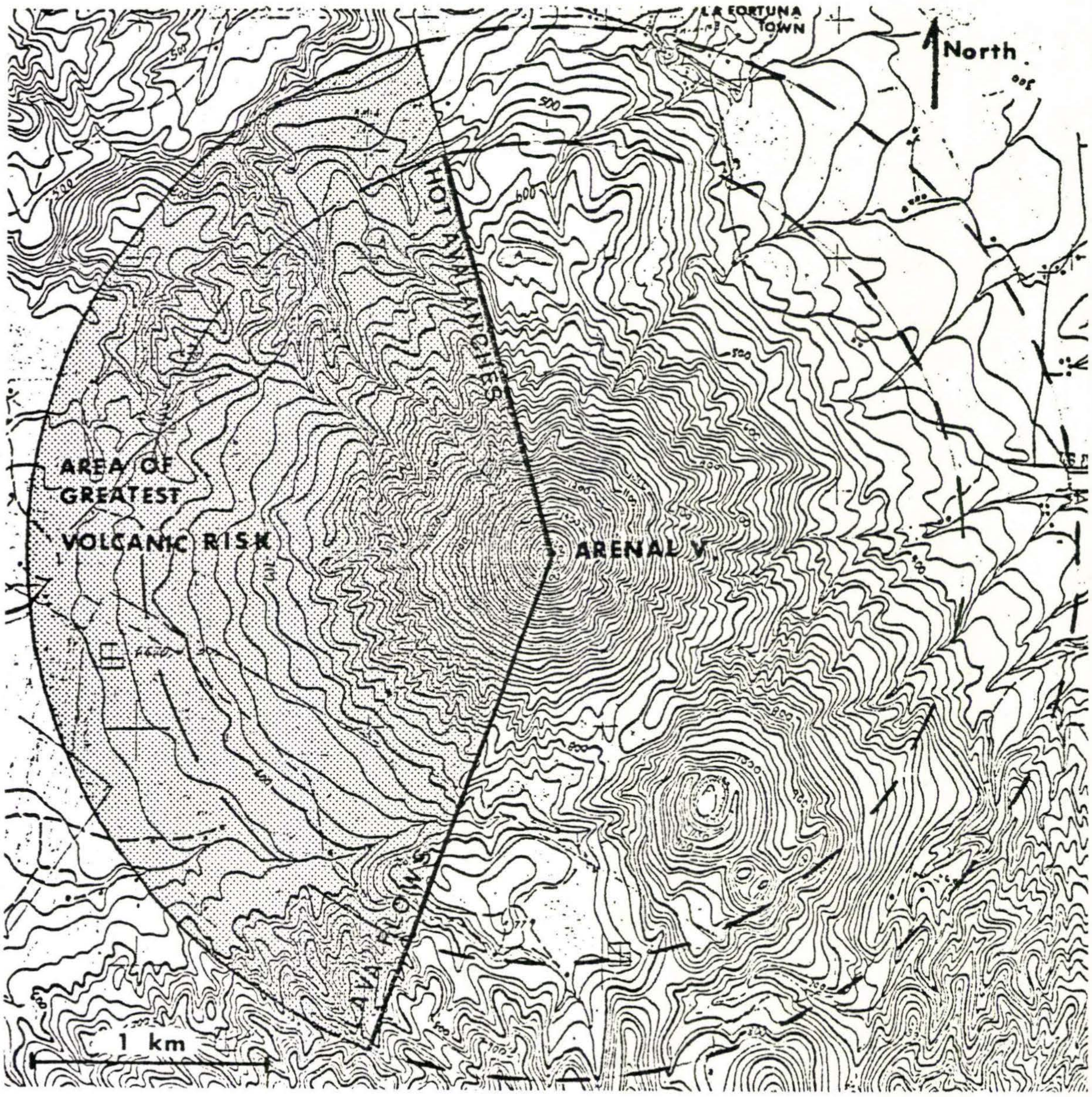


Figure 9. Areas of high and greatest volcanic risk at Arenal Volcano for the remaining portion of the present eruption.

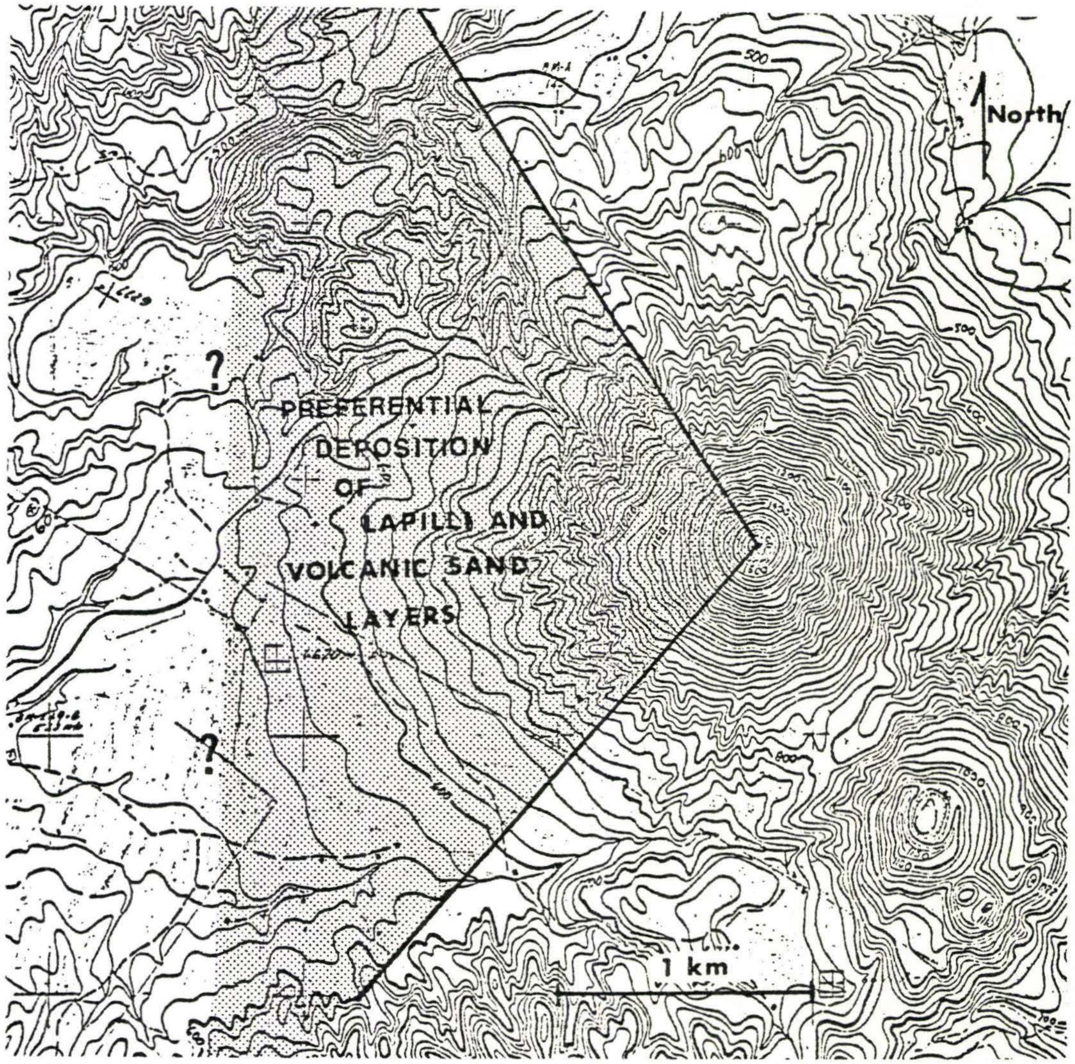


Figure 10. Area of high risk for future eruptions of Arenal Volcano.

The last two major volcanic eruptions, Irazu, 1963-1965, and Arenal 1968 to present, were exceptionally violent, causing approximately 90 human fatalities and millions of dollars of damage.

A detailed study of Costa Rican volcanoes is necessary for several reasons: the increasing trend to use fertile soils on the flanks of volcanic edifices for agriculture as a consequence of demographic pressures; the existence of many towns and villages potentially exposed to volcanic eruptions; the need that planners and legislators have of technical assistance in the planning of the economic development of the country in the hope of being able to prevent future disasters.

Volcanoes with long periods of dormancy during the recent geologic past are common in island arc volcanism. Just a few examples reported in the literature are: Arenal Volcano with one period of 443 years (Melson and Saenz, 1973), Mt. Fuji with one period of 428 years (Tsuya, 1955), Vesuvius with one period of 492 years (Lirer *et al.*, 1973), and Mt. Saint Helens with 3 periods of 120-150 years and 4 periods of 400 to 500 years (Crandell *et al.*, 1975).

Many Costa Rican volcanoes that have not been active during historic times may simply be dormant. These Quaternary volcanoes need to be examined geologically and geophysically to determine whether they are likely to erupt in the near future.

The Costa Rican Electricity Institute (ICE) recently inaugurated a hydroelectric project with an investment of approximately 250 million dollars, consisting of an earthfill dam, 75 m high, on Arenal

River. The dam will produce a reservoir that is used to generate electricity and irrigate a portion of Guanacaste Province. Arenal Dam is located 7 km to the west of Arenal Volcano summit and within the meizoseismal area of the 1973 Tilaran 6.5 m earthquake (Plafker, 1973). These facts have justified an ICE investment in seismic studies since 1974. In addition, a dry tilt line has been constructed on the west flank of Arenal Volcano in order to evaluate the safety of the Dam. Valuable data have been collected by ICE about regional and Arenal Volcano seismicity. Unfortunately, most of the seismic and dry tilt information compiled by ICE remains unpublished.

During 1974, staff from National University initiated periodical visits to Arenal Volcano in an attempt to study and describe its activity. Some of the results of this work have been reported by Cevo (1976); and Bennett and Raccichini (1977). A periodical bulletin initiated in 1978 by National University reports on the state of Costa Rican volcanoes. A british expedition visited Arenal Volcano during 1978 with sponsorship of National University; part of the information collected was included in a paper by Thorpe _et al_. (1979).

In response to the growing necessity for the study and monitoring of Costa Rican volcanoes, the National University recently founded the Volcanology Institute of Costa Rica. This Institute has the task of developing a long term research program on Costa Rican volcanoes which should give an important contribution during the coming years to a better understanding and knowledge of them.

The Costa Rican Civil Defense Office, an organization created to assist the population in the event of natural disasters by evacuating and providing shelter to the victims, established a station on the north flank of Arenal in 1968. The purpose of this station is to broadcast to a central office in San Jose any catastrophic event occurring at Arenal Volcano. Although this station is not scientifically oriented it has played an important role in the past by providing radio communication and playing host to scientists studying Arenal Volcano. This station has had more than 10 years of permanent operation.

Monitoring of Arenal Volcano on a permanent basis should be accomplished in the near future by an effective coordination of efforts among the institutions already involved in studying this volcano, and by the funding of new research projects at the Volcanology Institute of Costa Rica.

CONCLUSIONS AND RECOMMENDATIONS

Stratigraphy of Arenal Volcano area consists of five basic units. They are in order of increasing age: (1) historic Arenal Volcano lavas, blocky ash flows and fine tephras, (2) pre-historic Arenal Volcano lavas, blocky ash flows and mudflows, and fine tephras, (3) volcanic ash rich mudflows and lavas of Cerro Chato Volcanic Group, (4) mudflow deposits of unknown source, and (5) Upper Tertiary agglomerates and tuffaceous breccias of the Aguacate Volcanic Group.

Arenal Volcanic Group consisting of historic and pre-historic volcanic rocks contains coarse lapilli and volcanic sand deposits, blocky ash flows, mudflows and blocky lava flows. Arenal Volcano rocks range from basalts to dacites but are predominantly basaltic andesites and andesites. The 1968 to 1978 lavas are porphyritic, two-pyroxene basaltic-andesites. Small but significant decreases in Na_2O, and K_2O, and increases in total Fe, MgO and TiO_2 support the idea that lavas from 1968 to 1973 are less-differentiated with time. Post-1973 lavas do not support a simple evolution toward less differentiation with time. Chemical analyses have minor variations, but generally are very similar and basic (54.05-55.05 wt. % SiO_2) for calc-alkaline volcanoes. They may represent a new batch of magma intruded into Arenal Volcano from the main magma chamber to a higher-level magma chamber. Future work should be concentrated on new bulk chemical analyses of lavas and electron microprobe chemical analyses of the mineral phases present in the lavas to provide a better understanding of the petrochemical evolution of Arenal lavas.

Two faults on the south and west flanks of Arenal Volcano are apparently related to the present eruption. The first fault has a distinct scarp trending N 20 W. Along the other fault, trending N 80 W, three explosion craters were formed during 1968. One of the 1968 craters (A) is located at the intersection of these two faults.

The location of present active vents, the maximum distances traveled by Arenal Volcano erupted materials during the past and the stratigraphic and lateral distribution of Arenal Volcano layers of lapilli and volcanic sand support the idea that the preferential explosions are towards the northwest and southwest quadrants of the cone and within a distance of 5 kilometers from the summit craters. Human activity should be reduced to a minimum within this area in order to avoid future fatalities. The lateral distribution of lapilli and volcanic sand layers to the west of the area of study is unknown. Lapilli and volcanic sand layers have been reported up to 12 km to the west of Arenal summit. Delimitation of lapilli and volcanic sand layers is important to evaluate volcanic risk during future eruptions. Zones of expected high economic development in the future are located to the west of the area of study.

Indirect calculations of the age of Arenal Volcano are only gross approximations and are made in the absence of radiometric age dates. These estimates are based on stratigraphy, energy release calculations during eruptions and two radio carbon dates. The age of Arenal Volcano according to these estimates ranges from 3,100 to 10,000 years old. Future work should be concentrated on locating samples for C^{14}

age dating and documenting the detailed stratigraphic relations of tephra levels. Such a study would allow us to not only determine the age of Arenal Volcano, but also to evaluate how often the volcano erupts.

Monitoring of Arenal Volcano on a permanent basis should be accomplished in the near future by a coordinated effort among the institutions already involved in studying this volcano, and by funding of new projects at the Volcanology Institute of Costa Rica at National University.

APPENDIX A

Collection Place of Samples Mentioned in the Text

Arenal Volcano Regional topographic maps, prepared by Instituto Geografico Nacional de Costa Rica (IGN) and the base topographic map used in this work use the Lambert's Projection grid. This grid consists of principal lines called map or quadrangle coordinates which are vertical (N-S) or horizontal (E-W), and are spaced every kilometer. Each line has a number (i.e. 430 or 291). The location of a sampling site is given by a horizontal coordinate number and a vertical coordinate number (comparable with latitude and longitude), fractions being used if necessary. A site with coordinates 291.3-431.8 is a point on the map located 300 m from the horizontal coordinate 291 and 800 m from the vertical coordinate 431.

Sample Number	Collection Site Coordinates	
1-1-82	273.3	455.8
1-2-83	273.0	456.5
1-3-15	273.4	457.2
1-4-20B	272.2	456.3
1-5-16B	272.7	457.3
1-6-17B	272.0	457.4
2-1-07	272.9	458.0
2-2-34	273.3	457.7
3-1-19B	272.1	456.4
3-2-18	271.7	457.6
5-1-59A	270.0	458.1
5-2-44	271.4	458.6
6-1-58	271.0	457.8
7-1-62	270.9	458.2
8-1-67	270.5	457.6
8-2-66	270.8	458.0
8-3-61B	270.9	458.5
8-4-46A	271.4	458.9
9-1-63	270.8	458.7
10-1-84	270.1	458.7
10-2-64	270.7	458.9

Sample Number	Collection Site Coordinates	
11-1-26	272.8	458.3
12-1-22	272.7	458.3
14-1-23	272.7	458.5
16-1-51	273.4	458.5
16-2-24	272.7	458.7
16-2-25	277.6	458.7
17-1-50	273.2	458.7
18-1-49	273.1	458.8
18-3-39	272.2	458.8
19-1-56	271.3	457.7
19-2-39	271.4	458.1
20-1-05	273.2	458.1
20-3-06	272.8	458.1
20-4-30	272.5	458.3
20-5-37	271.7	459.0
21-1-31	272.0	458.2
21-2-33	272.3	458.5
22-1-38A	271.6	459.0
24-1-42A	271.6	459.0
25-1-48	272.8	458.8
26-1-52	273.3	458.4
26-2-77	272.9	458.4
26-3-68B	272.8	458.7
26-4-69	272.5	458.2
26-5-70	271.8	459.2
27-1-87	271.1	457.7
27-3-45	271.4	458.7
27-2-40B	271.4	458.5
88M	271.4	458.0
01	273.7	458.9
02	273.7	459.0
12	271.8	459.4
13	272.9	459.3
14	274.9	457.5
28	272.8	458.5
53	274.2	457.9
55	275.8	457.7
71	272.4	458.9
85	270.5	459.2
09	273.5	460.8
10	273.3	461.4
11	273.8	460.8
72	273.5	460.6
73	271.6	462.2
74	271.4	461.4
76	272.0	461.7
77	271.1	461.0
78	271.4	461.4
79	271.6	461.7

Sample Number	Collection Site Coordinates	
86	271.0	462.3
41	271.4	458.3
57	271.0	457.7
60	270.9	458.1
65	271.0	471.6
21	273.7	457.1
89	275.0	458.0
89A	275.0	458.0
90	271.6	462.6
92	274.6	461.1

APPENDIX B

Summary of Analytical Methods

Three sets of chemical analyses obtained by different methods were used in this work. The first set was published by Melson and Saenz (1973). Analyses were done at the Smithsonian Institution by E. Jarosewich using classical methods.

The second set was analyzed at the Department of Earth Sciences of the University of Manitoba, Canada. A review of the analytical method used by Manitoba University is the following:

Summary of Methods Used in the Analytical Laboratory, Department of Earth Sciences, University of Manitoba*

Element	Method
Si Al Fe(Total) Mg(High) Ca K Ti Mn Zr	X-ray Fluorescence Spectrometry. Weighted sample plus $La_2B_4O_7$ plus La_2O_3 heated in a graphite crucible at about 1100^{o} for a half hour. Resulting glass bead with H_3BO_3 (total weighted, 2.1000 grams) ground to -200 mesh and then compressed to 50,000 p.s.i. Elements then simultaneously analyzed on multi-channel ARL X-ray Spectrometer.
Na_2O, MgO(Low) and Trace Metals	Atomic Absorption Spectrophotometry. Rock dissolved with HF, H_2SO_4, and HNO_3 in platinum curcibles. Perkin-Elmer 303 A.A.S. used for determinations.
P_2O_5	Colorimetry. Solution as for Na_2O above. The absorption at 430 m of molybdivanadophosphoric acid complex. Unicam sp 500 spectrophotometer.
FeO	Rock decomposed with HF and 1:4 H_2SO_4 solution titrated with $K_2Cr_2O_7$ using Sodium Diphenylamine sulfonate as indicator.

Element	Method
H_2O^-	Determined by heating sample to constant weight at 1100°.
H_2O(Total)	Determined by heating sample in a stream of dry oxygen in an induction furnace (Temp. 1100°C). H_2O collected on Anhydrone and weighted.
H_2O^+	H_2O (Total - H_2O^-.
S	Determined by heating samples in an induction furnace with oxygen flowing through combustion chamber. SO_2 evolved is then titrated. Leco Induction Furnace and automatic Titrator.
CO_2	Sample decomposed by HCL and heat. CO_2 evolved passed through drying train and collected on Ascarite.
CO_2(Low S samples)	Determined simultaneously with H_2O(Total). CO_2 collected on Ascarite; small amounts of SO_2 removed on MnO (act).

*written communication by Ramlal, K. (1978)

Constituents, Concentration, Precision, and Accuracy
of Major Element Determinations,
Department of Earth Sciences, University of Manitoba*

Constituent	Concentration %	Instrument Precision,	Accuracy of Replicates,
SiO_2	59.60	.12	.20
Al_2O_3	9.34	.05	.13
Fe_2O_3(Total)	10.08	.017	.03
MgO	.404	.04	.10
CaO	10.22	.02	.07
K_2O	2.69	.01	.01
MnO	.41	.01	.01
TiO_2	.48	.02	.02
Na_2O	4.20	.01	.05
H_2O(Total)	1.60	.03	.06
CO_2	1.15	.05	.12
P_2O_5	0.20	.01	.01
FeO	10.92	---	.04
S	0.185	.003	.005

*written communication by Ramlal, K. (1978)

The third set, provided by William G. Melson, was analyzed at the Smithsonian Institution. Visual homogeneity was the criteria to choose the juvenile lapilli. Samples were fused and the glasses analyzed by electron microprobe.

APPENDIX C

Petrographic Description of Pre-historic Lavas

Samples 41-57-60-65:

Gray, basaltic-andesites from Arenal SW flank (see Appendix 1 for collection sites). Texture: Pilotaxitic, but hialopilitic in sample 41. Phenocrysts: Plagioclase: An 46-82%, subhedral to anhedral, normal, inverse and oscillatory zoning. Polysynthetic, combined albite and carlsbad, and pericline twinning. Honeycomb structure. Green apatite inclusions. Augite: Slightly pleochroic, pale yellow-green to pale green, subhedral to anhedral with magnetite inclusions. Hypersthene: Slightly pleochroic, pale yellow-green to light green, subhedral to anhedral with magnetite inclusions. Groundmass: Plagioclase, subhedral to anhedral, An 46-60%. Polysynthetic and albite twinning. Green apatite inclusions. Augite and hypersthene: Subhedral to anhedral crystal and irregular aggregates. Glass is gray-brown. Sample 41 has more glass than the other samples, producing a different texture (see Table 5 for modal calculations).

Samples 09-10-11-72-73-74-76-77-78-79-86:

Gray, basaltic-andesites, outcrop on the northeast and east flank of Arenal Cone (see Appendix 1 for collection sites). Texture: Hialopilitic. Phenocrysts: Plagioclase: An 55 to 86%, subhedral to anhedral, normal, inverse and oscillatory zoning. Polysynthetic, combined albite and carlsbad, and pericline twinning. Honeycomb structure and green apatite inclusions. Augite: Slightly pleochroic, pale yellow-green to pale green. Subhedral to anhedral, rarely euhedral. Zoned, 2V = 50 with subhedral to anhedral magnetite inclusions. Hypersthene: Slightly pleochroic, pale yellow-green to light green. Subhedral to anhedral, 2V = 60, $r > v$. Normal zoned with subhedral to anhedral magnetite inclusions. Groundmass: Plagioclase: An 36-55%, subhedral to anhedral. Polysynthetic, albite and carlsbad twinning. Augite and hypersthene: subhedral to anhedral. Magnetite: subhedral to anhedral crystals and irregular aggregates. Glass is gray-brown. Sample 09 contains small amounts of glass (2.0 vol. %) producing a pilotaxitic texture. (See Table 5 for modal calculations.)

Samples 01-02-12-13-14-28-53-55-71-85:

Dark gray, basaltic-andesites from 1525 eruption, except for sample 85 which has unknown age. Texture: Hialopilitic. Phenocrysts: Plagioclase: An 55-90%, subhedral to anhedral. Normal, inverse and oscillatory zoning. Polysynthetic, combined albite and carlsbad, and pericline twinning. Honeycomb structure and green apatite inclusions. Augite: Slightly pleochroic, pale yellow-green to pale green. Subhedral to anhedral magnetite inclusions. Hypersthene: Slightly pleochroic, pale yellow-green to light green. Subhedral to anhedral magnetite inclusions. Olivine: rarely present. Anhedral, embayed, surrounded by hypersthene and with a corona of vermicular magnetite. Groundmass: Plagioclase: An 40-60%, subhedral to anhedral. Albite and carlsbad twinning. Apatite inclusions. Augite and hypersthene: Subhedral to anhedral. Magnetite: Subhedral to anhedral crystals and irregular aggregates. Xenoliths: Rare in some lavas. Sample 55 has two xenoliths. One is gabbroic containing subhedral to anhedral grains of plagioclase (53-55% An), augite, hypersthene, olivine and magnetite. The other xenoliths is a very fine grain foliated rock containing an abundant opaque mineral (see Table 5 for modal calculations).

Table 5. (Continued) Modes for Pre-historic Lava Flows: SW, E and NE Flanks

	09	10	11	72	73	74	76	77	78	79	86	41	57	60	65
PHENOCRYST	38.8	23.8	26.8	22.2	26.6	37.6	37.2	39.8	33.4	31.2	36.4	19.2	35.6	35.0	36.4
Plagioclase	23.8	19.2	22.0	17.8	25.4	31.4	29.8	30.8	32.6	29.8	19.2	17.4	33.6	32.2	33.6
Augite	11.0	1.6	2.0	1.8	0.6	3.0	3.6	5.4	0.6	1.2	6.2	0.8	1.4	1.8	1.2
Hypersthene	4.0	2.0	2.8	2.6	0.6	2.2	3.8	3.6	0.2	0.2	10.0	0.8	0.6	1.0	1.6
Olivine	0.0	0.0	0.0	0.0	0.0	tr.	0.0	0.0	0.0	tr.	0.0	0.0	0.0	0.0	0.0
Oxy-hornblende												0.2	0.0	0.0	0.0
GROUNDMASS	60.4	76.0	45.4	45.4	58.4	63.0	50.2	52.0	65.4	59.2	56.8	65.2	63.4	64.2	63.0
Magnetite	4.4	2.8	2.2	1.2	6.2	3.6	3.2	3.4	1.6	1.6	3.0	5.2	4.0	2.8	2.0
VESICULARITY	0.8	0.4	27.8	32.4	15.0	0.4	12.6	8.2	1.2	9.6	7.8	15.6	1.0	0.8	0.6
Counts	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500
Flank	NE	NE	NE	NE	E	E	E	E	E	E	E	SW	SW	SW	SW

Table 5. Modes for Pre-historic Lava Flows: 1525 A.D.

	01	02	12	13	14	28	53	55	71	85*	#Samples	Mean	Standard Deviation
PHENOCRYSTS	29.8	37.2	32.8	34.0	29.2	29.2	34.4	36.4	28.2	33.8	10	32.5	3.3
Plagioclase	26.0	34.8	27.0	30.8	23.6	24.6	25.4	30.0	26.2	28.0	10	27.6	3.4
Augite	0.8	0.8	3.8	1.8	3.8	2.8	7.0	5.0	1.2	4.6	10	3.2	2.1
Hypersthene	3.0	1.4	2.0	1.4	1.8	1.8	2.0	1.4	0.8	1.2	10	1.7	0.6
Olivine	0.0	0.2	0.0	tr.	tr.	0.0	0.0	tr.	tr.	tr.	10	--	--
GROUNDMASS	48.8	57.4	49.2	48.4	53.4	50.4	45.4	61.0	50.0	60.2	10	52.4	5.4
Magnetite	1.4	3.8	1.2	2.4	3.4	11.2	5.0	5.2	3.4	2.8	10	4.0	2.9
VESICULARITY	21.4	5.4	18.0	17.6	17.4	20.4	20.2	2.6	21.8	6.0	10	15.1	7.4

*Unknown age, but very similar to 1525 lava flows (S flank)

APPENDIX D

Petrographic Description of Accidental Blocks from Arenal Volcano Lapilli Layers

Sample 21:

Pale gray, hornblende, two pyroxenes gabbro (see Appendix 1 for collection site). Texture: Phaneritic, holocrystalline, subhedral granular to poikilitic. Phenocrysts: 0.45 to 4 mm. Plagioclase: Mostly An 50-70%, anhedral to subhedral, rarely euhedral. Rare grains of oligoclase and andesine (An 18-50%), bytownite and anorthite (An 70-94%). Normal, inverse and oscillatory zoning. Polysynthetic, albite and pericline twinning. Green apatite inclusions. Hornblende: pargasitic, slightly pleochroic, pale green to pale greenish-yellow. Anhedral, (+), $2V_x = 60$. Occurs as oikocrysts, surrounding plagioclase, augite, hypersthene and magnetite poikicrysts. Arranged in patches with well-developed poikilitic texture. Biotite: Pleochroic in brown shades, anhedral. Hypersthene: Pleochroic, pale yellow-green to light green. Anhedral, $2V_x = 60$, $r > v$. Augite: anhedral. Magnetite: subhedral to anhedral. Chlorite: fibrous, secondary replacement (see Table 6 for modal calculation).

Samples 89 and 89A:

Gray, hornblende, two pyroxene gabbro (see Appendix 1 for collecting site). Texture: Holocrystalline phaneritic, subhedral granular to poikilitic. Phenocrysts: Plagioclase: An 40-70%, subhedral to anhedral. Normal, inverted and oscillatory zoning. Polysynthetic, albite and pericline twinning; green apatite inclusions. Rare plagioclase megaphenocrysts up to 1.5 cm in diameter. Hornblende: Pleochroic, light green, greenish-brown, yellow-brown. Anhedral, oikocrystic, surrounding plagioclase, augite, hypersthene and magnetite poikicrysts. Augite: Pleochroic, pale green to yellow-green. Anhedral, $2V_z = 50$. Hypersthene: Pleochroic, light brownish yellow to greenish-yellow. Euhedral to subhedral, $2V_x = 60$, $r > v$. Magnetite: anhedral, rarely interstitial (see Table 6 for modal calculations).

Sample 90:

Pale gray, hornblende, magnetite gabbro (see Appendix 1 for collection site). Texture: Holocrystalline, phaneritic, poikilitic. Phenocrysts: Plagioclase: An 50-70%, but minor An 70-80% phenocrysts are present. Anhedral, zoning is absent. Polysynthetic, albite twinning. Hornblende: Pleochroic, greenish-yellow to light green; anhedral; oikocrystic surrounding plagioclase, magnetite, augite and olivine poikicrysts. Magnetite anhedral, rarely interstitial. Augite and olivine: anhedral (see Table 6 for modal calculation).

Sample 92:

Pale gray, hornblende gabbro (see Appendix 1 for collecting site). Texture: Felty to poikilitic. Phenocrysts: Plagioclase: An 50-90%, subhedral to anhedral. Normal, inverse and oscillatory zoning. Polysynthetic, albite and pericline twinning. Hornblende: Pleochroic, greenish-yellow to light green. Anhedral. Oikocrystic surrounding plagioclase and magnetite poikicrysts, rarely olivine. Biotite, magnetite and olivine: minor, anhedral. Hand specimen has banded arrangement of ferromagnesian minerals, although this is not obvious in thin section (see Table 6 for modal calculations).

Table 6. Modes for Accidental Blocks from Lapilli Layers

	21	89	89A	90
Plagioclase	67.8	57.2	54.4	71.2
Augite	1.2	10.4	1.8	0.6
Hypersthene	2.6	8.0	1.8	0.0
Hornblende	17.6	15.2	17.2	11.8
Biotite	3.4	0.0	0.0	0.0
Olivine	0.0	0.4	0.0	0.2
Magnetite	1.8	6.8	3.0	9.2
Chlorite	1.0	0.0	0.0	0.0
Apatite	tr.	tr.	tr.	tr.
Vesicularity	4.6	2.0	21.8	7.2
Counts	500	500	500	500

APPENDIX E

Petrographic Descriptions of Juvenile Lapilli from Historic and Pre-historic Eruptions: El Tajo Site

A detailed stratigraphic section of El Tajo Site was prepared by William G. Melson. The section, located approximately 7 km SW of Arenal summit ($10^{o}27.8'N$, $84^{o}46.0'W$) consists of 10 consecutive pairs of alternating layers of volcanic sand and coarse lapilli. These pairs are separated by soil zones of 0.1 to 0.2 m (Melson, written communication, 1979). Petrographic descriptions of juvenile lapilli collected from these pairs, presented in this appendix, was done on small microprobe thin sections with approximately 1/3 or 1/4 the area of a standard petrographic thin section.

Juvenile lapilli samples from El Tajo Site are numbered from 1 to 9 in order of increasing age.

Sample 1:

Basaltic-andesite juvenile lapilli ejected during 1968 initial explosions. Texture: Hyalopilitic. Vesicularity: 20 vol. %. Phenocrysts: (24 vol. %). Plagioclase: (18 vol. %), An 57-74%, subhedral to anhedral; normal, inverse and oscillatory zoning; polysynthetic, combined albite and carlsbad, and pericline twinning; honeycomb structure; green apatite inclusions. Augite: (4 vol. %), slightly pleochroic, pale yellow-green to pale green, subhedral to anhedral, zoned, $2V_z = 50$. Hypersthene: (2 vol. %), slightly pleochroic, pale yellow-green to light green, subhedral to anhedral with magnetite inclusions. Groundmass: (56 vol. %). Plagioclase: (14 vol. %), An 48-55%, subhedral to anhedral; polysynthetic and albite twinning. Augite and hypersthene: (4 vol. %) subhedral to anhedral. Magnetite: (3 vol. %) subhedral to anhedral crystals and irregular aggregates, rarely rounded. Glass: (35 vol. %) brown.

Sample 2:

Hornblende dacite lapilli ejected during the 1525 eruption. Texture: Hyalopilitic. Vesicularity: 25 vol. %. Phenocrysts: (7 vol. %). Plagioclase: Subhedral to anhedral, grains present do not allow to estimate An %, honeycomb structure, normal and inverse (4 vol. %). Hornblende: (3 vol. %) pleochroic, olive green to light green, 2V not measured because grain size too small. Augite: (0-2 vol. %). Groundmass: (68 vol. %). Magnetite: (3 vol. %), subhedral to anhedral crystals. Glass: (50 vol. %), pale gray.

Sample 3:

Basaltic-andesite, unknown age. Texture: Hyalopilitic. Vesicularity: 20-25 vol. %. Phenocrysts: (25 vol. %). Plagioclase: (22 vol. %) An 46-78%, subhedral to anhedral, normal, inverse and oscillatory zoning, honeycomb structure common, green apatite inclusions. Augite: (1-4 vol. %), slightly pleochroic, pale yellow-green to pale green, subhedral to anhedral, rarely zoned. Hypersthene: (3 vol. %), slightly pleochroic, pale yellow-green to light green, subhedral to anhedral with magnetite inclusions. Groundmass:

(40 vol. %). Magnetite: (3 vol. %), anhedral to subhedral. Plagioclase: (10 vol. %) subhedral to anhedral, albite twinning. Augite and hypersthene: (3 vol. %) anhedral to subhedral. Glass: (25 vol. %), dark-brown.

Sample 4:

Andesite, unknown age. Texture: Trachytic. Vesicularity: 30 vol. %. Phenocrysts: (1 vol. %). Plagioclase, subhedral to anhedral, honeycomb structure. Groundmass: (69 vol. %). Plagioclase: (20 vol. %), subhedral to anhedral, tabular. Glass: (45 vol. %), brown. Magnetite: (4 vol. %), subhedral to anhedral.

Sample 5:

Hornblende dacite, unknown age. Texture: Trachytic. Vesicularity: 25 vol. %. Phenocrysts: (3 vol. %). Plagioclase: Subhedral to anhedral, honeycomb structure. Groundmass: (72 vol. %). Plagioclase: (18 vol. %), subhedral to anhedral, commonly tabular, An 56-60%, normal and oscillatory zoning, albite and polysynthetic twinning. Hornblende: (4 vol. %), euhedral to subhedral, pleochroic, olive green to pale green, rarely zoned. Magnetite: (2 vol. %), brownish-gray.

Sample 6:

Basalt, unknown age. Texture: Hyalopilitic. Vesicularity: 20 vol. %. Phenocrysts: (30 vol. %). Plagioclase: (20 vol. %), An 56-74%, subhedral to anhedral, normal, inverse and oscillatory zoning, honeycomb structure, polysynthetic, combined albite and carlsbad, and pericline twinning. Augite: (8 vol. %) slightly pleochroic, pale yellow-green to colorless, subhedral to anhedral, rarely euhedral, zoning is common, $2V_z = 50^o$, with magnetite inclusions. Hypersthene: (2 vol. %), subhedral to anhedral, slightly pleochroic, light green to light yellow-green, $r > v$, $2V_x = 55^o$, with magnetite inclusions. Groundmass: (50 vol. %). Plagioclase: (12 vol. %), An 45-60%, common albite twinning. Augite: (4 vol. %), subhedral to anhedral. Hypersthene: (1 vol. %) subhedral to anhedral. Magnetite: (3 vol. %), subhedral to anhedral crystals and irregular aggregates. Glass: (30 vol. %), brownish-gray.

Sample 7:

Hornblende dacite, erupted 220 B. C. Texture: Hyalopilitic. Vesicularity: 20 vol. %. Phenocrysts: (6 vol. %). Plagioclase: (5 vol. %), subhedral to anhedral, honeycomb structure, inverse, normal and oscillatory zoning, impossible to obtain compositional range by Michael-Levy method. Hornblende: (1 vol. %), subhedral, pleochroic, olive green to pale green. Groundmass: (74 vol. %). Plagioclase: (8 vol. %), subhedral to anhedral, common tabular, An 50%, albite twinning is common, normal, inverse and oscillatory zoning. Hornblende: (4 vol. %), pleochroic, olive green to light green, anhedral to subhedral. Magnetite: (4 vol. %), anhedral crystals and irregular aggregates. Glass: (48 vol. %), gray-brown.

Sample 8:

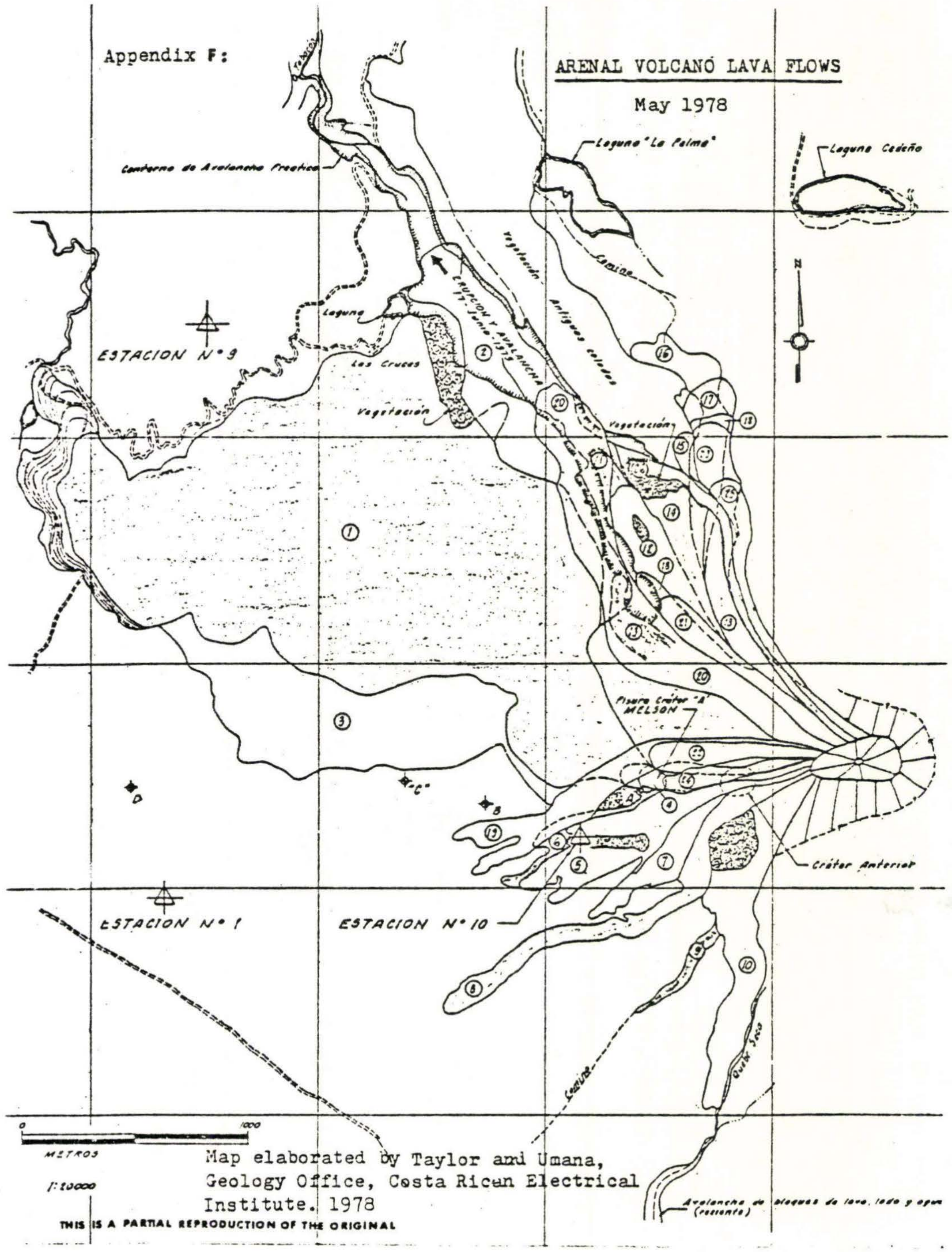
Basaltic-andesite. Unknown age. Texture: Hyalopilitic. Vesicularity: 18 vol. %. Phenocrysts: (30 vol. %). Plagioclase: (24 vol. %), An 55-84%, subhedral to anhedral, normal, inverse and oscillatory zoning, polysynthetic, albite and periclase twinning, honeycomb structure. Hypersthene: (4 vol. %), subhedral to anhedral, slightly pleochroic, yellow-green to colorless, $r > v$, $2V_x = 60^{\circ}$. Hornblende: (1 vol. %), subhedral to anhedral, pleochroic, olive green to light green. Augite: (2 vol. %), subhedral, colorless. Groundmass: (52 vol. %). Plagioclase: (12 vol. %), subhedral to euhedral. Augite and hypersthene: (4 vol. %), subhedral to anhedral. Magnetite: (2 vol. %), anhedral. Glass: (34 vol. %), grayish-brown.

Sample 9:

Hornblende andesite, unknown age. Texture: Hyalopilitic. Vesicularity: 18 vol. %. Phenocrysts: (7 vol. %). Plagioclase: (4 vol. %), subhedral, normal, inverse and oscillatory zoning. Hornblende: (2 vol. %), subhedral to anhedral, pleochroic, olive green to yellow green. Hypersthene: (1 vol. %), subhedral, slightly pleochroic, pale yellow green to very light green. Groundmass: (75 vol. %). Plagioclase: (20 vol. %), subhedral to anhedral, An 48-60%, albite twinning, normal, inverse and oscillatory zoning. Augite: (1 vol. %), anhedral. Hypersthene: (2 vol. %), subhedral to anhedral. Hornblende: (3 vol. %), subhedral to anhedral. Magnetite: (4 vol. %), anhedral to subhedral crystal with irregular aggregates. Glass: (45 vol. %), greenish-brown.

APPENDIX F

Map of Arenal Volcano Lava Flows



APPENDIX G

Geologic Map of Arenal Volcano

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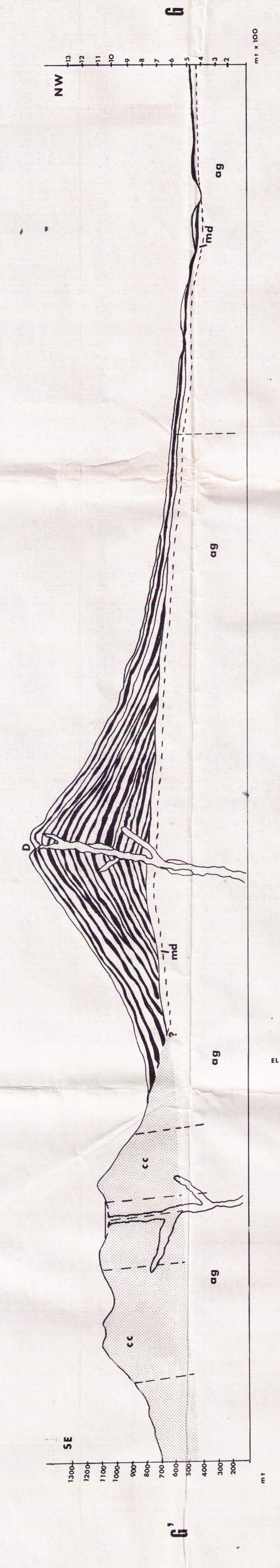
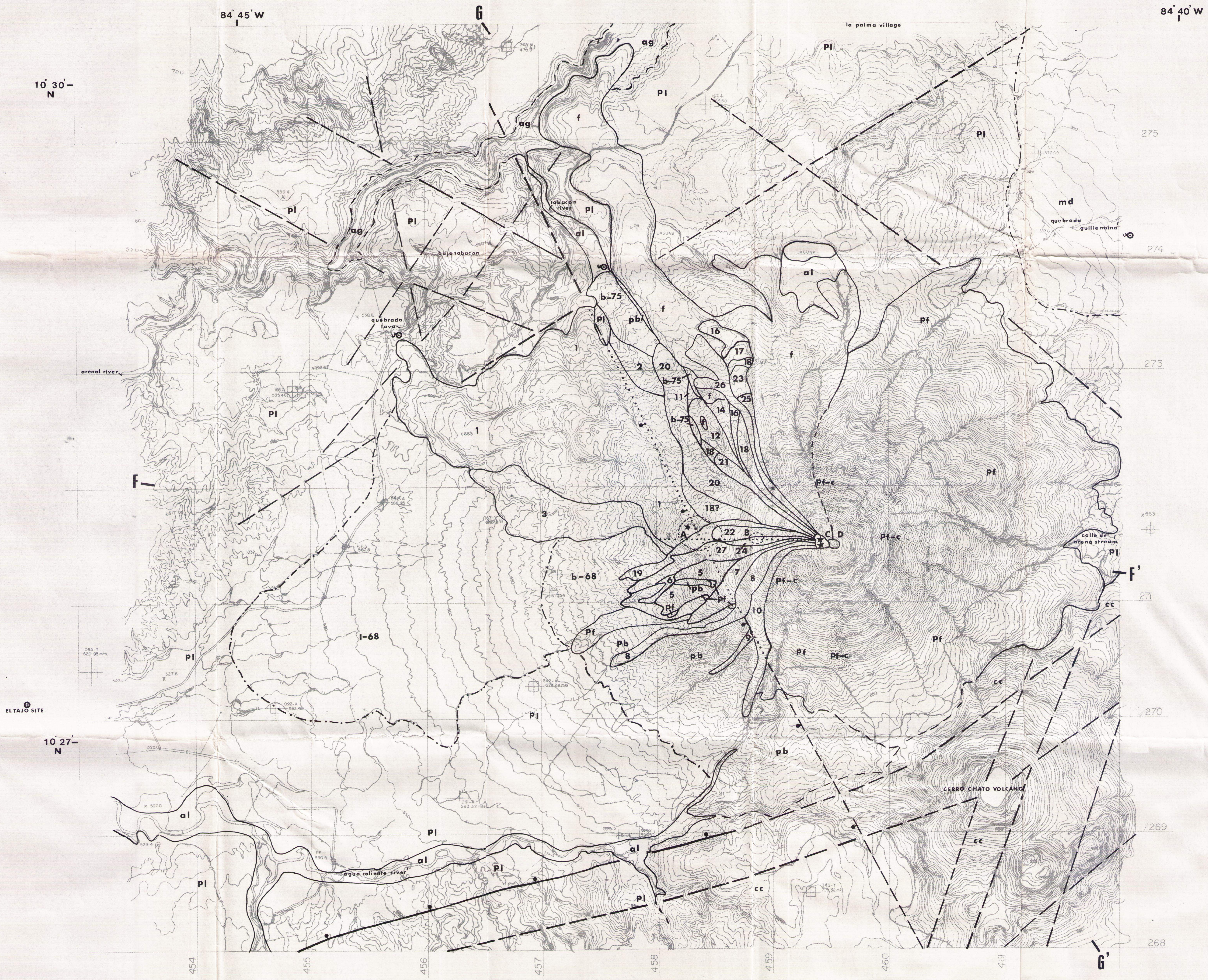
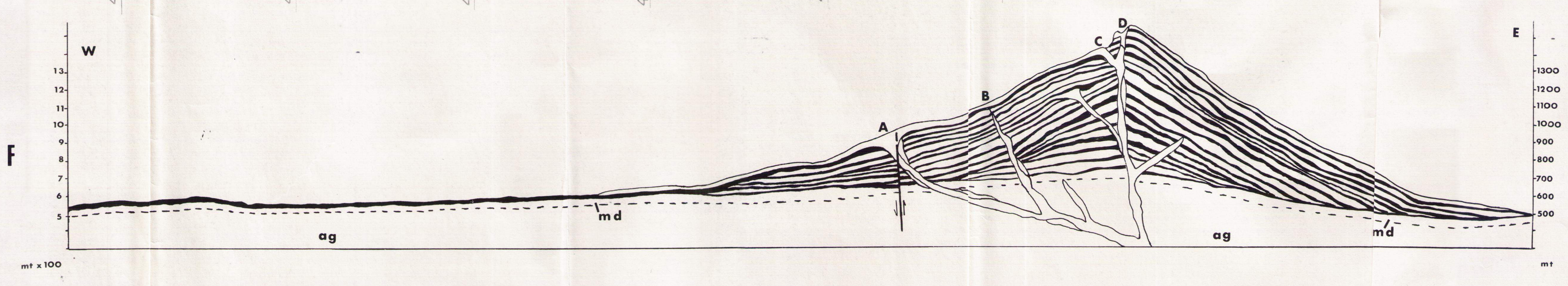
GEOLOGIC MAP OF ARENAL VOLCANO
COSTA RICA







GEOLOGIC MAP OF ARENAL VOLCANO
COSTA RICA

by

EDUARDO MALAVASSI R.

1979

Scale 1:20,000

CONTOUR INTERVAL 20 METERS

geologic field work 1978

EXPLANATION

ARENAL VOLCANIC GROUP — QUATERNARY

al	RECENT ALLUVION AND COLLUVIUM
b-75	1975 BLOCKY ASH FLOW
	1968–1978 LAVA FLOWS
1-3	ERUPTED 1968–1973
4-27	ERUPTED 1974–1976
b-68	1968 BLOCKY ASH FLOW
l-68	1968 LAPILLI AND VOLCANIC SAND LAYERS
f	1525 LAVA FLOWS
Pf	PRE-HISTORIC LAVA FLOWS
Pf-c	PRE-HISTORIC LAVA FLOWS COVERED BY COLLUVION
pb	PRE-HISTORIC BLOCKY ASH FLOWS
Pl	PRE-HISTORIC LAPILLI AND VOLCANIC SAND LAYERS
cc	CERRO CHATO VOLCANIC GROUP
md	MUDFLOW DEPOSITS UNIT
ag	AGUACATE VOLCANIC GROUP (MIO-PLIOCENE)

? TERTIARY

CRATERS A-B-C-D

FAULT

DASHED WHERE AERIAL PHOTO-LINEATIONS; DOTTED WHERE CONCEALED BALL ON DOWNTHROWN SIDE.

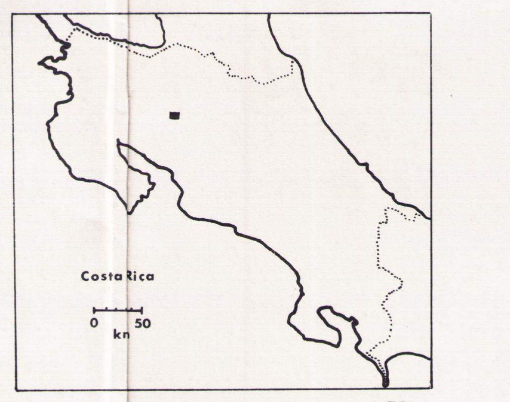
SCORIA CONE ☆

CONTACT

DASHED WHERE APROXIMATELY LOCATED; DASHED AND DOTTED WHERE GRADATIONAL

HOTSPRING

index map



BASE MAP ELABORATED BY BRAVO, J. (1978)

CROSS SECTIONS

VERTICAL AND HORIZONTAL SCALE 1:20,000

contacts of the 1968-1978 lava flows after Taylor and Umaña (1973), unpublished Photogrametric data by Bravo, J. (1978), and this work