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**LA THÈSE A ÉTÉ
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The Mina El Limon Area
and
the Telica Complex:
Two Examples of Cenozoic Volcanism
in
Northwestern Nicaragua, Central America

by

David V. Lefebure

A thesis submitted to the Faculty of
Graduate Studies and Research in partial
fulfilment of the requirements for the degree of
Doctor of Philosophy

Department of Geology

Carleton University

Ottawa, Canada

1986

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The undersigned hereby recommend to the Faculty of Graduate Studies acceptance of this thesis, submitted by David Victor Lefebure, B.Sc. and M.Sc., in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Leif Lefebure

Thesis Supervisor

Richard L. Bann

Chairman, Department of Geology

Leif Lefebure

Abstract

Two volcanic successions from northwestern Nicaragua are described in detail. These rocks form part of the Middle American island arc.

The Mina El Limon area is underlain by a Miocene volcanic succession at least 400 m thick. These subaerial volcanic rocks consist of tholeiitic plagioclase phyric mafic lahars and flows overlain by calc-alkaline rocks consisting of two-pyroxene andesite porphyry flows, dacite domes with associated volcaniclastic rocks and andesite and dacite flows. Dacite dikes and stocks intrude the volcanic sequence and are considered hypabyssal equivalents of the dacite domes.

Northerly-trending and east-striking faults divide the Mina El Limon area into fault-bounded blocks of shallowly-dipping homoclines. Epigenetic, gold- and silver-bearing quartz veins follow the northerly-trending faults. Four major vein systems have produced approximately 750,000 ounces of gold. Hydrothermal alteration envelopes the quartz veins. In the mafic wall rock a proximal sericite-adularia zone grades outward into an argillic zone. The latter zone changes away from the vein into a distal propylitic zone. Other types of alteration in the Mina El Limon area are silicification and potassium metasomatism.

The second area, the Telica Complex, consists of six composite volcanoes of Pleistocene to Recent age. These are Cerro Los Portillos, La Ceiba, San Jacinto, Cerro de Aguero, Santa Clara and Telica. They are made up of tholeiitic rocks which vary from high-alumina basalts to basic andesites. There are no systematic chemical variations from one volcano to another.

Telica, the youngest volcano, has erupted minor amounts of ash three times over the last ten years and exhibits continuous solfateric activity. The distribution and composition of Telica rocks can best be explained by tapping a vertically-zoned magma chamber produced by crystal fractionation of plagioclase, clinopyroxene, olivine, orthopyroxene, ilmenite and magnetite from a basaltic parent magma.

All groundwater in northwestern Nicaragua appears to be derived from local, meteoric sources.

A comparison of volcanic rocks from northwestern Nicaragua shows that all mafic volcanic rocks are generally similar in composition. The Nicaraguan Depression appears to separate an easterly calc-alkalic succession (Coyol Group) from the westerly tholeiitic rocks forming the Tamarindo Group and Marrabios Range volcanoes.

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1. Introduction

1.1 General Statement

This thesis presents the results of a study of Cenozoic volcanic rocks in northwestern Nicaragua. Detailed examination of two areas, Mina El Limon and the Telica Complex, forms the basis for this study.

The objectives are to:

- i) describe the geology and stratigraphy of the Mina El Limon area and Telica Complex;
- ii) determine the petrogenesis of the Cenozoic volcanic rocks in the study area;
- iii) provide exploration criteria for auriferous quartz veins at Mina El Limon;
- iv) compare the Tamarindo Group with the Coyol Group; and
- v) document the composition of groundwater in northwestern Nicaragua.

1.2 Location and Access

The study area lies within northwestern Nicaragua between the latitudes 12°30' and 13°00' N and longitudes 86°15' and 87°30' W (Figure

1.1). The two areas mapped are centred on the town of Mina El Limon (12°45' N, 86°45' W) and Volcan Telica (12°36' N, 86°52' W). Leon, Corinto and Chinandega are the major towns within the study area.

The field area is accessible by highway #12 from the south, highway #24 from the north and highway #26 to the east (Figure 1.1).

Dirt roads provide good access to most parts of the study area except in

Figure 1.1 Location of study areas, Northwestern Nicaragua.

the rainy season. An all-weather gravel road connects Mina El Limon to highway #26.

1.3 Methods of Study

The field work was carried out over a total of 5 months during the summers of 1976 and 1977. A geological map (1:16,250) of the Mina El Limon area was made and 150 rock and 8 groundwater samples were collected for analysis (Figure III-1). The gold-bearing quartz veins were sampled and core from 9 diamond drill holes logged. The Telica Complex was mapped at a scale of 1:25,000 and 204 rock and 11 groundwater samples were taken (Figure III-2). In both areas the geology was initially plotted on air photos and then subsequently transferred to base maps. In addition, seventy samples of Cenozoic rocks were collected from other parts of northwestern Nicaragua for petrographic and geochemical study (Map 1).

Petrographic work included examination of 275 thin and polished thin sections (Appendix 1). One hundred rock samples were analysed for major and minor oxides, trace elements and volatiles (Appendix 2). Carleton University's electron microprobe was used to determine phenocryst compositions from Telica lavas and tephra deposits (Appendix V). Oxygen and hydrogen isotopic compositions were determined for groundwater from 23 sites in northwestern Nicaragua.

1.4 Physiography, Climate and Vegetation

Nicaragua is composed of four physiographic regions (Figure 1.2; McBirney and Williams, 1965):

- i) the Pacific Coastal Plain,
- ii) the Nicaraguan Depression,
- iii) the Interior Highlands, and
- iv) the Atlantic Coastal Plain.

PHYSIOGRAPHIC PROVINCES OF NICARAGUA

Figure 1.2 The physiographic provinces of Nicaragua (modified from McBirney and Williams, 1965).

Figure 1.3 Generalized geological section through southwestern Nicaragua (from Weyl, 1980 after McBirney and Williams, 1965).

The study area encompasses parts of the first three regions. The Pacific Coastal Plain is a narrow strip of low-lying hills and plains underlain by sedimentary and volcanic rocks (Figure 1.3). It is bounded to the west by the Pacific Ocean and the east by the Marrabios Range volcanoes. The volcanoes lie along the western margin of the Nicaraguan Depression, a northwest-trending trough filled with alluvium, sediments and volcanic ash. Further to the east, the Interior Highlands rise abruptly from the Nicaraguan Depression and reach a maximum elevation of 1700 metres. The Interior Highlands grade eastward into the flat Atlantic Coastal Plain that extends to the Caribbean Sea.

Landforms within the Telica Complex reflect both constructional and erosional processes and have a maximum relief of 800 m. The older volcanoes are dissected, while the younger volcanic cones and flows are largely intact. In the Mina El Limon area erosion has been far more important, producing a terrain of small hills and mesas with a maximum relief of 300 m (Plate 1.1). The small hills and ridges commonly have cores or spines of stocks or dikes that are more resistant to erosion than the host volcanic rocks. Generally the flat-topped mesas are underlain by the youngest volcanic flows which are more resistant to erosion than the underlying units.

Western Nicaragua has a tropical savanna climate with a dry season during the winter months and only minimal rainfall in July and August. Average annual rainfall is 164.5 cm (Leon, National Inventory of Resources, 1966) and the temperature varies between 22° and 32° C.

Vegetation in the area varies with elevation and relief. Much of

Plate 1.1. Typical countryside around Mina El Limon.
Telica Complex is visible on the horizon. The volcano erupting ash in the centre of the picture is Telica. Photograph taken by W. Chapman from outside the Mina El Limon geology office in the fall of 1977.

the Pacific Coastal Plain is covered with fields of maize, cotton, sugar cane, tobacco, beans and other crops. The higher regions of the Coastal Plain, the Nicaraguan Depression and the Interior Highlands are grassland areas intermixed with cultivated plots, forests and bush. On the upper flanks of the volcanoes, fields give way to dense deciduous forests; some pine trees are found on the upper slopes.

1.5 Previous Work

The earliest scientific descriptions of Nicaragua were written in the nineteenth century by explorers and naturalists. Squier (1851, 1860), Oviedo and Valdes (1855), Belcher (1843) and Belt (1888) produced the first reports on the volcanoes of Nicaragua. A proposed route for the Panama Canal in southern Nicaragua was mapped by Hayes (1899).

Crawford (1891; 1892, 1895; 1902a; 1902b) published several short articles on the volcanic activity of San Cristobal (also known as El Viejo) and other Nicaraguan volcanoes. Brief articles by Bertrand (1901), Chamberlain (1903) and Zies (1942) also describe Nicaraguan volcanoes.

The first volcanological studies in Nicaragua were carried out by Karl Sapper (1899; 1905; 1913a) who travelled extensively in Central America. In 1913 he published the first comprehensive study of the Central American volcanoes (Sapper, 1913b). He later wrote two books, one describing the volcanoes (Sapper, 1925) and the other covering the regional geology of Central America (Sapper, 1937). Burri and Sonder (1934a; 1934b; 1936) described the petrography and chemistry of both the Cenozoic volcanic rocks and the Quaternary volcanoes.

More recently, McBirney and Williams (1965) produced a geological

map of Nicaragua with descriptions of all the major volcanic groups and volcanoes. In 1972 the Nicaraguan government, with the support of the United States Agency for International Development, completed an evaluation of the country's natural resources. It included report on the geology and water resources of western Nicaragua (Catastro, 1972).

1.5.1 Mina El Limon Area

The first report on the geology of the Mina El Limon area was compiled by Hulin (1950) after three weeks mapping in the vicinity of the Limon vein. He concluded that andesite flows and breccias are overlain by rhyolitic flows and pyroclastic deposits and identified a systematic decrease in ore grade in the Main Limon quartz vein with depth.

Subsequent geological mapping over a much larger area by Geyne (1952) identified three periods of faulting and four major map units - andesite porphyry (oldest), andesite vitrophyre, rhyolite vitrophyre (youngest) and rhyolite agglomerate (stratigraphic position undefined). Later company notes by Geyne (1953) describe the location and orientation of many of the quartz veins.

Hodgson (1972), as part of a regional study for the Catastro Project, divided the Limon area stratigraphy into andesitic flows and breccias overlain by andesitic to dacitic ignimbrites. These were considered to be part of the Tertiary Lower Coyo Group. Further sampling and core logging by Malone (1974) outlined a more detailed stratigraphy. Malone identified latite extrusions overlying andesite flows and breccias. The latites are overlain by ashflows and a rhyolite dome. The gold mineralization was related to faults associated with a

gradual caldera collapse which pre-dated the extrusion of the uppermost latite and rhyolite flows.

Systematic descriptions of the Panteon quartz vein system (Figure 2.11) are presented in two theses (Lamb, 1974; Gleason, 1977). Attempts by Lamb to correlate gold distribution with the strike and dip of the Hanging Wall and Footwall Veins were unsuccessful. Wall-rock alteration, groundwater and fluid inclusions from the Panteon vein system were studied by Gleason.

1.5.2 Telica Complex.

The Marrabios Range of volcanoes includes the Telica Complex. The Range has been described by many of the early geologists in Central America, most notably Sapper (1913b; 1925) and Burri and Sonder (1936). Recent descriptions of the petrology and geochemistry of these volcanoes have been made by McBirney and Williams (1965), Viramonte (1969) and Martinez and Viramonte (1973). The historical activity and physical characteristics of the active volcanoes have been described by Bullard (1956a; 1956b), Mooser et al. (1958), Stoiber and Rose (1974), Creusot (1976) and Simikin et al. (1981). All volcanoes were mapped at 1:50,000 scale as part of the Catastro project.

Although there are no studies specifically of the Telica Complex, Vargas (1971) and Hazlett (1977) mapped the San Cristobal Complex to the north. The 1968 eruption of Cerro Negro, another Marrabios Range volcano, and the resulting tephra deposits have been described by Viramonte and DiScala (1970), Taylor and Stoiber (1973) and Rose et al. (1973).

1.6 Regional Geology

Western Nicaragua consists of a complex sequence of volcanic, intrusive and sedimentary rocks that vary in age from Paleozoic to Recent (Weyl, 1980; Catastro, 1972a). During the last 20 million years, island arc volcanic activity on the western edge of the Caribbean Plate (above the subducting Cocos Plate) has controlled the eruption and deposition of both volcanic and sedimentary rocks. In general, marine sediments rocks were deposited to the west of the volcanic arc and lacustrine and fluvial sediments to the east. The following description of the geology of Western Nicaragua is taken principally from Catastro (1972a).

1.6.1 "Basement" Rocks

The oldest rocks in Central America form a basal metamorphic complex which extends from Guatemala southward to northern Nicaragua (Figure 1.4; Weyl, 1980). This Paleozoic sequence of schists, phyllites, marbles and quartzites, commonly called the Nueva Segovia Schist (Table 1.1), was intruded by Cretaceous plutonic rocks. Although the southern limit of the Nueva Segovia Schist is unknown, it is generally believed that the Paleozoic rocks do not extend much further south than shown by their surface exposures in northern Nicaragua, near the Honduran border (Dengo, 1968; Lloyd, 1963; Kesler, 1971).

In northwestern Costa Rica, an ophiolitic suite, the Nicoya Complex, of Late Cretaceous to Early Tertiary age is the oldest unit (Gallagher, 1979). It is composed of mafic to intermediate volcanic and plutonic rocks, volcanic breccia, hyaloclastite, radiolarian chert,

Figure 1.4 Geological map of Central America (from Weyl, 1980).

Figure 1.1 Stratigraphic Relations for the Catastro (Catastro, 1972)

limestone and their metamorphic equivalents (Dengo, 1962; Galli-Oldivier, 1979).

Weyl (1980) divides Central America into northern and southern parts on the basis of their crusts particularly their "basement" rocks (Figure 1.5). Northern Central America is underlain by a "basement" of continental crust while southern Central America consists of an oceanic crust overlain by later sediments and volcanics. Northwestern Nicaragua occurs near the boundary between these two parts of Central America.

1.6.2 Sedimentary Formations

The Rivas Formation, consisting of interbedded shale, siltstone, graywacke and conglomerate, is the oldest formation exposed in the study area. It is believed to have formed contemporaneously with the Nicoya Complex (Table 1.2).

Resting on the Rivas Formation, are late Cretaceous to early Tertiary clastic sedimentary rocks with minor limestone and volcanic flows that belong to the Brito Formation. On the southern Pacific Coastal Plain the Brito Formation consists of a basal conglomerate overlain by two persistent limestone units interbedded with graywacke sandstone, tuffaceous siltstone and shale. This 2.5 km thick sequence is cut by dikes, sills and stocks, and includes some volcanic breccias near its top that appear to have formed from eruptions through, and onto, water-saturated sand and coral reefs.

The Masachapa Formation, overlying the Brito Formation with slight angular unconformity, consists of interbedded tuffaceous and calcareous

Figure 1.5 Schematic crustal cross-sections through northern and southern Central America (from Weyl, 1980).

		SW Nicaragua	Guanacaste	Valle Central	SW Costa Rica	Limón Basin
QUATERNARY		Alluvium Volcan Las Sierras Group	Volcanics Liberia Form Bagaces Form	Volcanics Ujarrés Form Ureán Form	Alluvium Charco Azul Form Paso Real Form	Volc Limón Form Imeliv Creek Suratwa Form Rio Hic Bañano Form ▲ 500m
TERTIARY	Plioc.	Upper Lower	El Salto Formation 100m	400-800m Aguate Formation 900m	800m	
	Miocene	Upper	El Fraile Tamarindo Group 900m	Aguate Form 800m Pto Carballo Form 200m	Coris Form 400m San José Form 9-18m 70m max 50m	Gatún Formation 1700m
		Middle	2500m		Turrucates Form 150m	
		Lower	Masachapa Formation	Terraba Formation 1300m	Terraba Formation ~1300m	Uscari Formation 1200m
	Oligocene	Upper	1500m			Senosi Formation 850m
		Middle				
		Lower				
	Eocene	Upper	Brito Formation 2550m	Brito Form max 2700m	Brito Form 1100m	Brito Form 850m
		Middle				
		Lower				
	Paleocene	Upper		Las Palmas Form max 900m		Rio Lari Formation 2800m
		Lower				
CRETACEOUS		Rivas Formation 2800m	Nicoya Complex		Nicoya Complex	Changuinola Formation 1200m

Table 1.2 Stratigraphic correlation chart for the Cenozoic rocks of Southwestern Nicaragua and Costa Rica (from Eyles, 1980).

shale, siltstone and sandstone. This 1.5 km thick Oligocene to Miocene sequence probably formed under shallow water and outcrops on the Pacific Coastal plain. To the east, the marine detrital rocks become volumetrically less important and occur interbedded with andesitic lavas and ash flows. The name Matagalpa Series (McBirney and Williams, 1965) or Matagalpa Group (Catastro, 1972a) is given to the succession where volcanic rocks predominate. Red conglomerate, sandstone, siltstone and mudstone beds of the Totogalpa Formation intertongue with the Matagalpa Group in northern Nicaragua. The Totogalpa Formation is a fluvial and possibly lacustrine, red-bed sequence that overlies the Paleozoic Nueva Segovia Schist.

Miocene siltstones, pebbly conglomerates and limestones belong to the 2.2 km thick El Fraile Formation. The latter rests conformably on the Maschapa Formation and is stratigraphically equivalent to the Tamarindo Group (Table 1.1).

The Pliocene El Salto Formation overlies unconformably the El Fraile Formation and the Tamarindo Group (Table 1.1). It outcrops only on the Pacific Coastal plain and consists of less than 100 m of tuffaceous sandstones and siltstones and limestone. Intercalated with and overlying the El Salto Formation is the Las Sierras Group that consists of subaerial and subaqueous pyroclastics up to 680 m thick.

1.6.3 Volcanic Rocks

The Tertiary volcanic sequence in Nicaragua is divided into the Tamarindo and Lower and Upper Coyol Groups. Deposited in predominantly subaerial environments, they consist of accumulations of pyroclastic flows, lava flows, tuffs and epiclastic breccias with minor associated

... and grade laterally into sedimentary rocks.

The Miocene Lower Coyol Group consists of basal andesitic lavas and breccias overlain by andesitic to dacitic ash flows. It occurs mainly in the Nicaraguan Highlands. In many localities the ash flows overlain by a dacitic breccia. Sedimentation, contemporary with volcanicity, resulted in beds of shale, sandstone, chert lenses, tuffaceous sediments and massive, bioclastic limestone intercalated with the ash flows. Miocene andesite flows and breccias and dacite ash flows also outcrop in the northern portion of the Pacific Coastal plain. These rocks belong to the Tamarindo Group which has been correlated with the Lower Coyol Group (Catastro, 1972a).

The Mio-Pliocene to Middle Pliocene Upper Coyol Group rests unconformably on the Lower Coyol Group. Massive basalt flows and agglomerates at the base of the Upper Coyol Group are overlain by andesitic ash flows, commonly associated with dacitic or rhyolitic breccias. Small, andesitic to dacitic, intrusive plugs cut these conformable rocks. In some regions younger basaltic lavas and breccias cover the andesitic flows.

Post-Pliocene activity in western Nicaragua has been restricted to the eastern and western boundaries of the Nicaraguan Depression.

Effusive and explosive mafic volcanic activity has built numerous volcanic edifices.

The Plio-Pleistocene volcanoes consist of several dissected basaltic cones and a crater (El Ciguatope, San Jacinto Viejo and Las Lajas) with associated flows on the eastern margin of the Nicaraguan Depression. No specific volcanic centres of this age can be identified

along the western margin of the Depression, but pyroclastic rocks of the Las Sierras Group are correlated with the Plio-Pleistocene volcanics to the east. The Las Sierras Group intertongues with the El Salto sediments.

The Central American volcanic chain of 38 active centres consists of a series of 7 linear segments (Stoiber and Carr, 1973) along the western margin of Central America (Figure 1.6). In Nicaragua the Quaternary volcanoes form two linear segments situated along the western margin of the Nicaraguan Depression. Only the northernmost of the two segments is within the study area, where it encompasses the four active volcanoes, Telica, Santa Clara, San Cristobal (also called El Viejo) and Cerro Negro. The volcanoes are composite cones composed of basaltic andesites.

1.6.4 Structural Features of Nicaragua

McBirney and Williams (1965) recognized three types of structural features in western Nicaragua:

- 1) graben boundary faults;
- 2) faults and fracture zones transverse to the graben; and
- 3) broad folding and tilting.

The Nicaraguan Depression, a broad shallow graben trending northwest, is the dominant structural feature in Nicaragua. Several boundary faults have been identified on the northeastern side of the Nicaraguan Depression (Map 1, Figure 1.4). Faults on the southwest side of the graben are largely obscured by Quaternary volcanoes; they are only evident west of Managua (Catastro, 1972a). Stoiber and Carr (1973) identified normal faults in the Quaternary volcanic rocks that trend

Figure 1.6 Map of the Quaternary volcanoes of Central America (from Weyl, 1980).

parallel to the chain of volcanoes and the graben. These may reflect relatively recent movement on the southwestern side of the graben.

Faults and fracture zones oblique to the graben occur throughout the study area (Map 1). In the Quaternary volcanic rocks, there are north-trending and north-northeast-trending faults and alignments of cones and craters (Stoiber and Carr, 1973).

McBirney and Williams (1965) and Hodgson (1972) have documented broad folding of the Tertiary volcanic rocks with associated faulting.

1.7 Tectonic Setting of Central America

The Middle America island arc contains many of the features common to island arcs - a deep sea trench, large gravity anomalies, a linear chain of volcanoes, numerous shallow and intermediate-depth earthquakes, and high heat flow in localized areas (Molnar and Sykes, 1969; Brown, 1976). These features can be related to the underthrusting of the Cocos plate beneath the Caribbean plate (Figure 1.7).

Most of Central America lies within the Caribbean plate which is bounded by the Middle America Arc, the Motagua-Polochic-Cayman Trough fault zone, the West Indian Arc and a transform fault along the southern boundary (Molnar and Sykes, 1969, Figure 1.7). To the west, the adjacent Cocos Plate is bordered by the East Pacific Rise, the Galapagos Rift Zone, the north-trending Panama Fracture Zone and the Middle America Arc.

At the present time the Cocos Plate is moving away from both the Pacific and Nasca Plates and is being underthrust beneath Mexico and Guatemala (North American Plate) in a northeasterly direction and

Figure 1.7 plots the coupling of the $M_{10}^{(1)}$ modes in the two arcs.

beneath the rest of Central America (Caribbean Plate) in a more north-northeasterly direction. The Caribbean Plate is being overthrust onto the Cocos Plate (Brown, 1976).

The spreading rates (3 to 6.5 cm/yr half spreading rate) across the East Pacific Rise are among the fastest observed (Herron, 1972). Using records of historical seismic activity, Molnar and Sykes (1969) have determined similar half spreading rates of 3.2 cm/yr for Mexico and Guatemala and 2.0 cm/yr for the rest of Central America.

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2. Mina El Limon Area

2.1 Introduction

An inlier of Tertiary volcanic rocks surrounded by Quaternary sedimentary and volcanic rocks outcrops 80 km northwest of Managua (Map 1). Several mines, including the El Limon Mine, have produced gold and silver from quartz veins hosted by these volcanic rocks. During the present study a region of 85 square kilometres (Figure 1.1), covering the northwestern half of the inlier, was mapped. The map is centred on the town of Mina El Limon.

2.2 Stratigraphic Succession

The volcanic rocks of the Mina El Limon area were initially correlated with rocks of the Matagalpa Series by McBirney and Williams (1965). Hodgson (1972), however, correlated them with the Miocene Lower Coyol Group (Table 2.1) on the basis of stratigraphic similarities. For example, Lower Coyol Group volcanic rocks for the nearby El Sauce region (Figure 2.1). Both the El Sauce and Mina El Limon areas are underlain by mafic flows and volcanoclastics overlain by andesite and dacite flows. The El Sauce volcanic succession, however, includes ashflows which are not found in the Mina El Limon area.

The Tertiary volcanic sequence in the Mina El Limon area was mapped in detail (Map 2) and the stratigraphy established. The latter consists of basal basalt and andesite breccias and porphyry flows (units 1 and 2) overlain by dacite lavas and volcanoclastic rocks (unit 3). Intermediate to felsic flows (unit 4) are found at the top of the volcanic succession. Felsic and mafic intrusions (units 5 and 6) and

Table 2.1 Table of Formations in the Mina El Limon area

VOLCANIC AND SEDIMENTARY ROCKS

<u>Era</u>	<u>Period</u>	<u>Epoch</u>	<u>Lithology</u>	<u>Unit</u>
Cenozoic	Quaternary	Pleistocene and Recent	1-10 m alluvium, soil and tephra	
		unconformity		
	Tertiary	Miocene	>400 m Lower Coyol Group; mainly basalt, andesite and dacite flows; some volcaniclastic rocks of similar composition	1 to 4
		base not seen		

INTRUSIVE ROCKS

<u>Era</u>	<u>Period</u>	<u>Epoch</u>	<u>Lithology</u>	<u>Unit</u>
Cenozoic	Tertiary	Miocene	Dacite and basalt dikes and stocks	5 to 6

Legend

- OBSIDIAN
- TUFF BRECCIA
- ASH FLOW
- WELDED ASH FLOW
- BRECCIA
- TUFF
- AGGLOMERATE
- EVAPORITE
- ARGILLITE
- LUTITE
- FLOWS
- LAHARS

Figure 2.1 Stratigraphic column for the Tertiary volcanic rocks near El Sano, Nicaragua (derived from Higgins, 1977). El Sano lies 27 km northwest of Mina El Limon.

quartz veins cut the conformable rocks (units 1 to 4). The complete succession is more than 400 m thick (Figure 2.2).

2.3 Description of Map Units

Thirty centimetres to ten metres of alluvium, tephra and soil cover much of the Mina El Limon area (Malone, 1974). In this study only the underlying Tertiary rocks have been mapped.

Names are assigned to the igneous rocks using the terminology of Travis (1955) and Streckeisen (1979) that emphasizes their macroscopic features, in particular, the phenocryst types. The "non-genetic" terminology of Fisher (1961) is adopted to describe those rocks with predominantly volcanic clasts. Detailed petrographic descriptions of selected samples are presented in Appendix II. The map units identified in the Mina El Limon area, in order of decreasing age, are:

- 1) basalt and andesite volcanoclastic rocks and flows;
- 2) two-pyroxene andesite porphyry flows;
- 3) dacite domes, flows and volcanoclastic rocks;
- 4) andesite and dacite flows;
- 5) dacite dikes and stocks; and
- 6) andesite and basalt dikes.

Each of the units is described in turn. Their relationships to other units and distribution are noted and their general macroscopic and microscopic features discussed.

Units 1 and 2 generally form low, rounded hills while units 3 and 4 form steeper hills and mesas. Steep cliffs are formed only by unit 4 flows. Almost all volcanic sandstone in the Mina El Limon area are weakly consolidated and weather recessively. Dikes, stocks and quartz veins commonly form the spines of ridges and the peaks of hills.

Figure 2.2 • Idealized stratigraphic column for the Mina El Limón area.

3.2.1 Basalt and Andesite Volcaniclastic Rocks and Flows (unit 1)

Volcaniclastic rocks and flows of plagioclase clinopyroxene phyric basalt and andesite (unit 1) outcrop in the southeastern, central and northwestern regions of the map area (Map 2). Volcaniclastic rocks predominate in unit 1. The volcanic breccia and conglomerate beds vary in thickness from tens of centimetres to 20 metres, while individual flows are between 2 to 10 m thick. The volcaniclastic breccias, conglomerates and flows are well-exposed northwest of Mina El Limon (Map 2). Unit 1 volcanic sandstones and siltstones occur in underground workings at Atravesada and Mina El Limon and in diamond drill core from near the Panteon vein system. The best exposures of unit 1 are in the Limon and Panteon mines, where the unit is more than 250 m thick.

Contacts between individual flows and volcaniclastic beds are sharp. Unit 1 is overlain by two-pyroxene andesite porphyry flows (unit 2) in diamond drill hole #62, on the hill immediately south of Atravesada and near the gravel road east of Urden (Map 2). The contact between the two units is above the last appearance of volcanic conglomerate or breccia. In hole #62, the contact between units 1 and 2 is marked by 3.5 m of unconsolidated volcanic sandstones. At Cerro Blandon and the hill to the south, unit 4 andesites overlie unit 1 volcanic breccias with only a thin volcanic sandstone between them.

Volcaniclastic breccias and conglomerates of unit 1 are green or purple in colour, moderately magnetic, and contain clasts of basalt or andesite set in a fine-grained matrix. Fragment colour and texture

vary within individual beds. A small proportion of clasts are amygdaloidal and some contain plagioclase and pyroxene phenocrysts. The clasts rarely exceed 1 m in size and grade down to less than a 0.1 mm. No systematic variations are observed in grain-size or composition towards the margins of the clasts. Sub-angular to sub-rounded fragments are common. Rounded fragments outcrop in the northwest part of the map area around Cerro Blandon and Cerro Guadalupe (Plate 2.1). The clasts are commonly framework-supported. Malone (1974) noted moderate sorting and bedding in unit 1 "agglomerates" in diamond drill core. No bedding or graded bedding has been observed in unit 1 conglomerates and breccias in this study.

The matrix of the volcanic breccias and conglomerates consists of a chaotic mixture of small rock fragments (similar in composition to the the larger clasts), plagioclase and pyroxene crystals (some broken), and fine-grained secondary minerals such as chlorite, carbonate, hematite and sericite. No amygdules are found in the matrix.

Fine- to medium-grained volcaniclastic rocks occur in diamond drill core from the southeastern corner of the map area in the footwall of the Hanging Wall vein (DDH 1029, 1030). Thin beds of volcanic sandstone and siltstone are also found in the the footwall of the Main Limon and Atravesada veins (Hulin, 1950; mine records). These beds are between 2 cm to 2 m thick and most are less than 0.5 m thick. Beds are commonly gray or green and poorly consolidated. Graded bedding (tops up) can be seen underground in volcaniclastic sandstones in the

Plate 2.1. Weathered volcanic breccia of unit 1 near Cerro El Guadalupe contains rounded mafic volcanic fragments from 20 cm to less than 5 mm in size. Note pencil for scale.

Atravesada and Limon mines. Plagioclase laths are observed within individual beds. Although hydrothermal alteration masks much of the original texture of the drill hole samples, plagioclase crystals and mafic volcanic rock fragments were noted in several thin sections.

The flows are grey or purple on the fresh surface and light green when they have been hydrothermally altered. Most flows are moderately magnetic and contain amygdules (< 17 vol. %) filled with quartz, hematite, chlorite or carbonate. Autobrecciation is rare. White plagioclase phenocrysts are ubiquitous and dark green-black clinopyroxene phenocrysts are commonly present.

The euhedral, plagioclase phenocrysts are lath-like, up to 3 mm long and make up 12 to 27 vol. % of the rock. They exhibit continuous normal zoning from bytownite to labradorite (An_{80} to An_{65}), have few primary inclusions and exhibit well-developed Carlsbad and albite twins. Plagioclase has been replaced by carbonate, sericite, hematite, and/or chlorite (Plate 2.2). Subhedral augite ($2V=46^{\circ}$; $Z\angle c=49^{\circ}$) phenocrysts, <1.5 mm in size, make up to 4 vol. % of the rock and can exhibit simple twins. Augite is pseudomorphed by secondary minerals in several flows. Small, subhedral grains of magnetite and minor pyrite make up <2 vol. % of the rock and are commonly associated with clinopyroxene phenocrysts.

The phenocrysts are set in an intersertal groundmass of plagioclase (An_{55} to An_{50}) and pyroxene microlites, opaques, secondary chlorite and/or carbonate and cryptocrystalline minerals (Plate 2.3). Secondary minerals commonly occur in irregular patches.

Plate 2.2 Photomicrograph showing altered plagioclase basalt porphyry wall-rock from the Panteon Footwall vein. Quartz, carbonate and chlorite fill amygdúles and partially replace the matrix. Subhedral plagioclase phenocrysts are altered to sericite, chlorite and carbonate. Field of view is 1.2 mm.

Plate 2.3. Relatively fresh amygdaloidal augite plagioclase basalt porphyry flow (unit 1) with typical groundmass of plagioclase and pyroxene microlites, magnetite and secondary chlorite and carbonate. Field of view is 1.4 mm.

All the features observed in unit 1 volcanoclastic mudflow rocks could have formed in a predominantly subaerial environment. No criteria for subaqueous deposition, such as the presence of pillowed flows and hyaloclastite, have been identified.

The mafic clasts in the volcanic breccias and conglomerates vary in shape, size and composition. The matrix of these volcanoclastic rocks contains rock fragments, plagioclase and pyroxene crystals (some broken) and abundant secondary minerals. No scoriaceous fragments, chilled rims, or shards occur in unit 1 fragmental rocks. The texture and composition of the volcanic breccias and conglomerates are consistent with epiclastic deposits derived from unit 1 lavas. The unbedded, poorly-sorted nature of these deposits with the presence of large angular blocks and absence of pyroclastic fragments suggests that these units are lahars.

Unit 1 volcanic siltstones and sandstones are similar in mineralogy to the conglomerates and breccias and were undoubtedly derived from the same source as the lahars. The textural difference between these finer-grained rocks and the lahars is probably due to a higher water to solid ratio during their emplacement. The volcanic sandstones and siltstones probably formed from mudflows and during dewatering of lahars.

McBirney (1979) has defined volcanic facies on the basis of distance from the locus of volcanism, each recognized by lithological, structural and alteration features. Because unit 1 contains lahars with rounded fragments that rarely exceed 1 m, the unit is believed to have been deposited distal to the volcano. None of the features of proximal

facies volcanic rocks, such as dikes, sills, and ~~pyroclastic~~ rocks, occurs in unit 1.

The source for the unit 1 volcanic rocks was most likely a high volcano active during Miocene time, that shed epiclastic material and effused flows onto the adjacent plain, much like the active volcanoes in Nicaragua today. Both the limited number of flows and the predominance of rounded fragments in breccias in the northwest corner of the Mina El Limon map area suggest that this area was more distal from the volcano. The volcano was probably south or east of the present position of Mina El Limon. McBirney and Williams (1965) have suggested that there was a belt of basaltic cones near the present Central Highlands during the Tertiary.

2.3.2 Two-Pyroxene Andesite Porphyry Flows (unit 2)

Purplish-gray, gray or black, pyroxene phyric andesite flows (unit 2) outcrop over the southern two-thirds of the map area and near Cerro Guadalupe (Map 2). The flows are more abundant towards the southern part of the map area. The maximum thickness of unit 2 is approximately 75 m; the largest exposures of unit 2 occur near Cerro Aparejo. Four quarries for road building materials occur in flows of unit 2 at Lourdes, Spencer, west of Santa Rosa, and Santa Pancha.

In drill holes # 57 and # 62, on Lomas Las Mesas and Loma Cebadillos, and in the hanging wall of the Panteon vein system, unit 2 lavas are overlain by unit 3 volcanoclastic rocks. The contact between the two units is sharp.

Individual flows are between 1 m and 30 m thick. Most flows are massive, although some exhibit flow brecciation or flow layering.

Joints are found in some flows spaced 0.5 to 0.8 cm apart and oriented roughly parallel to the flow contacts (Plate 2.4). These joints probably reflect shear surfaces that developed as the flow advanced (MacDonald, 1972). Flow contacts are sharp and flows are rarely amygdaloidal. Matrix clasts in the flows were probably derived from the underlying unit flows.

Unit 2 flows are pitted and orange-brown on the weathered surface, while the fresh surface is aphanitic, massive and gray. Moderately to strongly magnetic, unit 2 flows contain small phenocrysts of altered pyroxene and plagioclase in an aphanitic groundmass. The translucent to white, euhedral plagioclase laths reach 3 mm in size. Dark green, euhedral pyroxene crystals are usually less than 1.5 mm long, but can reach up to 4 mm in length. Glomerophenocrysts of plagioclase, and/or plagioclase and pyroxene are common.

Equidimensional, pleochroic hypersthene phenocrysts are generally small (<1 mm), subhedral and rounded. Hypersthene is generally more abundant (0.5 to 5 vol. %) than augite (0 to 4 vol. %). Lath-like or angular augite phenocrysts (<1 mm) are generally less abundant than hypersthene. Pyroxenes are altered to chlorite and hematite. Serpentine (?) occurs along fractures in the hypersthene. Opaque inclusions occur in some augite phenocrysts.

Plagioclase phenocrysts are set in a groundmass made up of plagioclase and pyroxene microlites and a cryptocrystalline aggregate of alteration and primary minerals (Plate 2.5). Carlsbad-, and albite-twinned, euhedral laths of labradorite (0-28 vol. %) commonly have pronounced oscillatory zoning towards their margins. Many of many crystals are rounded. Glass and magnetite inclusions are common.

Plate 2.4. Platy joints in unit 2 andesite near Pitahaya.

Plate 2.5. White plagioclase phenocrysts with rounded to subhedral hypersthene (opx), sub-angular augite (cpx) and magnetite phenocrysts in a unit 2 two-pyroxene andesite. The groundmass consists of plagioclase and pyroxene microlites set in a cryptocrystalline aggregate of predominantly secondary minerals. Field of view is 2.2 mm.

Labradorite can be altered to sericite and chlorite. Some of the smaller plagioclase crystals are angular, possibly fragments of larger crystals.

Subhedral to anhedral magnetite phenocrysts (< 1.5 mm) form up to 3 vol. % of the rock, and many have hematitic borders. Pyrite was noted in several samples collected close to quartz veins. Carbonate, hematite and chlorite pseudomorphs occur in some flows.

Unit 2 andesites are a monotonous series of flows with no intercalated pyroclastic rocks or sediments. They do not exhibit any features characteristic of subaqueous deposition and were probably deposited subaerially. Because Unit 2 flows are found only in the southern two-thirds of the map area, the vent for these flows lay to the south, southwest or southeast of Mina El Limon. Possibly they came from the same volcano as the unit 1 flows and volcaniclastic rocks.

2.3.3 Dacite Domes, Flows and Volcaniclastic Rocks (unit 3)

Domes, flows, breccias and volcanic conglomerates of dacitic composition (unit 3) outcrop throughout the map area (Map 2). The largest surface exposures occur as broad irregular belts south of Mina El Limon. The greatest exposed thicknesses of unit 3 exist at Cerro Nato (100m) and Cerro El Tagua (80m). South of Cerro Tigra drill hole #57 cut approximately 35 m of unit 3 volcanic sandstones, conglomerates and breccias. In other parts of the map area, such as Cerro Guadalupe and Cerro Blandon, minor felsic breccias and volcaniclastic sandstones less than 5 m thick, belong to unit 3.

Unit 3 is overlain by unit 4 andesite flows on Lomas Babilonia,

Lomas Gabatillos and drill holes # 156 and 57. In almost all cases, andesite flows directly overlie unit 3 volcanoclastic rocks.

Domes at Tres Cerritos, Cerro Los Natos and north of Cerro Tigra (Figure 2.3) have been identified by vertical flow-banding, their associated volcanoclastic rocks, and the increased thickness of unit 3. There may also be domes at Cerro El Tagua where unit 3 is very thick and at Cerro Los Palmeras where dacite flows are cut by several dacitic dikes.

Cerro Los Natos is the most completely exposed dome. This oval, flow-banded dome is 500 m in diameter and within it steeply dipping flow banding is roughly concentric with the margins of this endogenous dome. On the dome's eastern side the dips of the flow banding form a fan-structure. The Cerro Los Natos dome is flanked by obsidian flows, felsic breccias and volcanic conglomerates which dip shallowly outward. The pumiceous, cherty and glassy clasts (< 2 m in diameter) in the volcanoclastic rocks are angular to sub-rounded and framework-supported. Massive flows occur only near the dome. A black obsidian flow occurs on the south flank of the Cerro Los Natos dome.

Poorly exposed, perlitic rhyolites with brecciated or flow-banded phases form the Tres Cerritos dome. The dome north of Cerro Tigra is composed of massive and flow banded dacite flanked by volcanic breccias and conglomerates.

The purple or gray flows, commonly flow banded, exhibit weakly conchoidal fractures. Spherulites are found in some of the flows and several flows are autobrecciated. Vesicles, when present, are small (< .5mm); in one glassy flow elongate cavities reach up to 1.5 cm in size.

The volcanoclastic rocks of unit 3 are extremely variable in

Figure 2.3 Distribution of unit 3 dacite domes, flow, and volcaniclastic rocks (stippled area).

colour (purple, red, gray, green, white) and degree of consolidation. Many of the volcanic sandstones are only weakly consolidated while the coarser fragmental rocks are much more coherent. Volcanic conglomerates and breccias are more abundant than volcanic sandstones. Pitted surfaces, common on the weathered surfaces of breccias, reflect the more weather-resistant nature of the matrix compared to the fragments. The fragments in the breccias are up to 2 m in maximum dimension and are commonly framework supported. Fragments form up to 70 vol. % of the rock and can occur in a variety of shapes. Weak sorting of fragments was noted in several volcanic breccias. In contrast, the volcanic conglomerates commonly exhibit well-developed bedding. The breccias contain a mixture of felsic fragments including vitrophyric, porphyritic and weakly vesicular clasts that have the same composition as unit 3 flows and domes. Two possible bombs with vesicular cores were identified in volcanic breccias near Santa Pancha and Cerro Los Natos. Siliceous fragments were found in volcanic breccias south of Cerro Los Natos, southwest of Santa Rosa and on Cerro El Tagua. In one outcrop the siliceous fragments are micro-vesicular, a feature common to many of the felsic rocks.

The matrix of the volcanoclastic rocks is commonly light coloured and relatively soft. In thin section small rock fragments, containing phenocrysts of plagioclase and quartz, grade in size from a cm to less than 0.5 mm. The fragments are set in a mixture of quartz, feldspar, opaque minerals and secondary minerals.

The domes, flows and fragments in the volcanoclastic rocks of unit 3

are virtually identical in composition. Plagioclase laths (0 to 12 vol. %) less than 1 mm are common; some can be up to 3 mm long. Sericite and chlorite commonly replace feldspar. Rounded to euhedral quartz phenocrysts, with embayments and curved fractures, are present in some flows. Quartz, biotite and opaques are usually present only in trace amounts (Plate 2.6). The matrix is glassy or an aphanitic holocrystalline mixture of quartz, feldspar, and opaques.

Some outcrops of pitted breccias, orange-red on the weathered surface, were mapped as part of unit 3 during this study. However, in thin section these breccias contain fragments of altered plagioclase andesite or basalt surrounded by a quartz-rich matrix (Plate 2.7). The fragments have a feldspar porphyritic texture similar to that observed in unit 1 and 2 flows. Although primary minerals are not preserved in these breccias, chemical analyses clearly demonstrate that these are silicified mafic volcanic rocks (section 4.2.2). Geyne (1952) also noted areas of silicification within breccias which he believed were originally felsic. These silicified breccias commonly occur near, or at the contact between units 2 and 3.

The dacitic rocks of unit 3 vary from a central facies consisting of steeply-dipping flow banding in domes, rhyolite flows and possible pyroclastic rocks to a proximal facies made up of volcanoclastic rocks that are variably sorted, conglomerates and breccias. Some of the bedded conglomerates that contain a variety of felsic clasts were probably formed by fluvial sedimentation.

6 9 9

Plate 2.6. This unit 3 quartz dacite porphyry flow, originally vitrophyric, is now completely recrystallized. Quartz-feldspar secondary minerals are white and commonly form spherulites (sph). The quartz (qtz) phenocryst in the centre of the photograph has a radiating overgrowth. The brownish patches exhibit a weak foliation and may originally have been welded glass shards. Field of view is 1.4 mm.

Plate 2.7. Silicified mafic breccia almost completely replaced by fine-grained quartz. The brownish colour is due to minor hematite. White are the remnants of plagioclase phenocrysts. Rock fragment outlines have been emphasized with dashed lines. Field of view is 1.4 mm.

Most of the volcanic breccias and some volcanic conglomerates contain felsic clasts set in a matrix of smaller rock fragments, plagioclase crystals and secondary minerals. The fragments are clearly derived from unit 3 flows and domes. The breccias may have formed as lahars or talus breccias.

The thickness of unit 3 is extremely variable and seems to correlate both with: (i) proximity to the domes and (ii) an increase in the ratio of flows to fragmental rocks. Three domes were identified during mapping (Figure 2.3).

The Mina El Limon domes formed on the flanks of the stratovolcano that erupted rocks belonging to units 1 and 2. They could represent late stage activity of a composite volcano or a totally independent eruption.

2.3.4 Andesite and Dacite Flows (unit 4)

Purple, red and white andesite and dacite flows (unit 4) crop out throughout the area as isolated, gently-dipping sheets on hill tops and mesas. Extensive exposures of unit 4 outcrop at Cerro Guadalupe, Cerro Santa Emilia, Cerro Rosa, Lomas Cebadillos, Buena Vista and Las Mesas (Map 2).

Unit 4 has a maximum thickness of 100 m. The upper contact of unit 4 is always an erosional unconformity which is overlain by Quaternary alluvium, tephra or soil. Individual flows vary from 5 to 30 m in thickness. Two flow types can be distinguished - purplish, glassy dacite flows and gray to black andesite porphyry flows.

The dacite flows exhibit contorted flow banding and were mapped by

Geyne (1952) as purple vitrophyre. Columnar jointing is developed in some of the vitrophyric dacite flows of unit 4 (Plate 2.8). Many are partially devitrified with well-developed spherulites; some spherulites are cored by plagioclase or other phenocrysts. Euhedral plagioclase phenocrysts (>2 mm) show a fluidal texture in thin section and form 2 to 16 vol. % of the flow. They show weak albite twinning and their cores are altered to sericite and chlorite. Quartz phenocrysts are rounded and embayed, but are present only in trace amounts. Euhedral opaques form up to 0.5 vol. % of unit 4. The matrix contains microlites of plagioclase, opaque needles, and glass; the latter is commonly devitrified.

The andesite porphyry flows (unit 4) are gray to black on the fresh surface with plagioclase and pyroxene phenocrysts up to 2 mm. The flows have a holocrystalline matrix and are moderately magnetic.

Lath-shaped, euhedral to subhedral labradorite phenocrysts (<4 mm) make up 20 to 30 vol. % of the andesite. Some phenocrysts appear broken, others are weakly embayed. Carlsbad and albite twins, as well as zoning (continuous and oscillatory) are common features of the labradorite crystals. The phenocrysts contain up to 15 vol. % glass and pyroxene inclusions. Some unit 4 andesite flows contain glomeroporphyritic clusters of plagioclase with minor associated pyroxene phenocrysts. Accessory augite phenocrysts (0-8 vol. %) are commonly euhedral and are normally smaller than the plagioclase phenocrysts. Square to lath-shaped crystals (<1 mm) of enstatite or hypersthene occur in some flows (up to 5 vol. %). Some orthopyroxene

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Plate 2.8. Well-developed columnar jointing in dacite flow of unit 4 at top of Cerro Guadalupe. Note the hammer handle for scale.

Plate 2.9. Photomicrograph of a andesite flow (Unit 4) from the Cerro Penasco area. Euhedral and angular (broken?) plagioclase phenocrysts with minor magnetite grains set in a groundmass of plagioclase and pyroxene microlites, altered glass and patches of secondary minerals. Field of view is 1.4 mm.

phenocrysts have augite rims. Magnetite phenocrysts form 2 to 3 vol. % of the flows. The hypocrystalline matrix is made up of labradorite microlites, pyroxene cristolites, opaques, glass and fine-grained secondary minerals (Plate 2.9). Skeletal textures and swallowtail terminations of plagioclase-microlites occur in some flows.

A small part of unit 4 consists of felsic and mafic breccias and volcanic conglomerates up to 5 m thick, intercalated with the flows. The mafic breccias are commonly flow breccias, while the dacitic breccias are probably of epiclastic origin. At Cerro Renasca steep flow layering and absence of internal contacts define a circular stock (Figure 2.4).

No hyaloclastite or subaqueous sediments occur within unit 4. The predominance of flows with some associated epiclastic rocks indicates a proximal to distal volcanic facies. Cerro Renasca is the only known vent for unit 4.

2.3.5 - Dacite Dikes and Stocks (unit 5)

Dacitic dikes and stocks (unit 5) occur at Cocao, Pozo Boho, Lomas Babilonia, east of Lourdes and several other localities (Map 2). Some of the dikes, for example those at Santa Pancha, Lourdes, Mina El Limon, and Larga, are associated with quartz veins. Dacite intrusions cut all map units except the mafic dikes of unit 6. In general, dacite dikes cut rocks of units 1 and 2; dacite stocks have been emplaced into rocks of units 3 and 4.

Figure 2.4 Distribution of unit 4 andesite and dacite flows (stippled area).

The average width of the dikes is of the order of several metres, but one dike at Cacao reaches 50 m across. Most stocks are roughly circular in plan and up to 400 m across. Rocks of unit 5 have steeply-dipping flow banding and contacts. Most are spherulitic.

The dacite intrusives are the hypabyssal equivalents of the unit 3 rocks. The orientation of the dacite dikes is similar to that of some of the quartz veins (section 2.5). At Larga and Urden felsic dikes are cut by quartz veins.

2.3.6 - Basalt and Andesite Dikes (unit 6)

A number of small andesite and basalt dikes (unit 6) cut units 1, 2 and 3. The best exposures of unit 6 are at Cerro Blandon, Guadalupe, Atravesada and east of Cerro Bonete (Map 2).

The massive mafic dikes are grey or black, up to 2 m wide, and typically aphanitic. Phenocrysts of plagioclase, pyroxene and olivine are present in small amounts. Andesites and basalts at the base of the Upper Coyol Group to the north and east of the area (Map 1) have the same mineralogy as unit dikes. Unit 6 dikes may thus be considerably younger than the Limon area extrusive rocks (units 1 through 4).

2.4 Metamorphism

Although no penetrative deformation is found in the Mina El Limon area rocks, the primary mineralogy of the volcanic rocks is only partially preserved. Virtually all volcanic glass is devitrified and a perlitic texture is generally developed. Both the matrix and phenocrysts are partially altered to chlorite, sericite, carbonate, clays and other minerals. The absence of zoisite or clinozoisite, the presence of pumpellyite, and the abundance of clays in the the hydrothermally altered zones is indicative of sub-greenschist metamorphic grade (Winkler, 1974) due to metamorphism at shallow depths.

Outside of the zones of hydrothermal alteration, metamorphic minerals such as chlorite, carbonate and sericite are most abundant in the groundmass (0-25 vol. %) and within pyroxene phenocrysts (0-30 vol. %). Less than 10 vol. % of the feldspar phenocrysts are replaced by metamorphic minerals.

2.5 Structural Geology

In the Mina El Limon area the conformable units (1,2,3 and 4) generally strike north, except in the southern portion of the map area where they trend in an easterly direction (Map 2). These units dip shallowly ($< 20^{\circ}$) in various directions.

Broad, open folds may occur in the region (Hodgson, 1972) but are difficult to establish because of the limited structural information available (contacts, flow layering, columnar and platy jointing, and bedding). Geyne (1952) states that a synclinal structure is apparent on

the north-trending Lomas Cebadillos hills that start "at Pozo Eono and end in the neighbourhood of Penasca". Geological mapping completed during this thesis study found no evidence for this syncline.

Faulting is far more important than folding in the area (Geyne, 1952; McBirney and Williams, 1965; Hodgson, 1972; Malone, 1974). The volcanic strata are divided by steeply-dipping faults into tilted, homoclinal sequences. The major faults in the general region trend east and northeast (Hodgson, 1972). Geyne (1952) subdivided the north and northeast-trending "earlier" faulting into two periods which corresponded to emplacement of intrusive "trachyte" and subsequent deposition of quartz veins. This distinction is not kept in the present study because the quartz veins and dacite (= trachyte) dikes follow the same fractures.

In the Mina El Limon area two sets of faults can be identified by their orientation. One set trends north and northeast and the other strikes roughly east (Map 2).

2.5.1 North- and Northeast-Trending Faults

Quartz veins and dacite dikes were emplaced along many of the north and northeast-trending faults. Mining of the quartz veins has provided considerable information about these faults (Table 2.2). North- and northeast-trending faults are commonly normal with tens to hundreds of metres of apparent vertical movement. These faults dip 45° to 80° to the east. Their strike-slip displacements are difficult to determine because these faults trend roughly parallel to map unit contacts. The north- and northeast-trending faults typically are filled with several

Table 2.2 Major faults in the Mina El Limon area

Name	Strike	Dip	Apparent Vertical Movement	Apparent Horizontal Movement	Comment	Associated Quartz Vein
North and Northeast-Trending Fault Set						
Main Limon	0	45E	> 150m		Normal	yes
Limon North	0	45E	> 150m		Normal	yes
Atraveasada	45	60N	> 50m		Normal	yes
Babilonia	25	60E	~ 200m		Normal	yes
Hanging Wall	355	80E	> 50m		Normal	yes
Footwall	330	72E	> 125m		Normal	yes
Santa Pancha	310	56NE	?		Reverse?	yes
San Luis	15	70E	?		Reverse?	yes
Bucarda	0	E?	>40	>50	LH, east side down	no
East-Trending Fault Set						
Geyne	90	S?	?	?	south side down	no
Kelly	85	N?	?	~200	RH, north side down	no
Porvenir	85	S?	?	~200	LH, south side down	no
Haigie	90	N	150?	~30?		no
Lourdes	90	S?	?	?	North side up	no
Guadalupe	90	N?	?	?	North side down	no
Malone	75	S?	?	?	South side down	no

LH - left-hand fault
RH - right-hand fault

generations of quartz.

The poles for thirty-one quartz veins, determined from this study and from Geyne's map (1952), are plotted on a stereonet (Figure 2.5). Although the interpretation of the stereonet is hampered by the small data base, the poles do cluster around three orientations:

- 1) 0° , dipping 65° to 80° E;
- 2) 47° , dipping 70° W; and
- 3) 25° , dipping 75° W to 70° E.

These three sets conform to a fracture indicatrix with a principal stress located in an approximately horizontal position; fault sets 1 and 2 being A-C conjugate shears and set 3 being tension fractures (see Figure 2.6). The conjugate shear pattern is obvious on the map (Map 2) with numerous veins, and some dikes, displaying Y-shaped patterns. Most auriferous quartz veins lie along conjugate shear faults, although some important veins are associated with tension fractures (Santa Pancha and Footwall).

Underground workings at the Panteon Mine show that the dip of the Hanging Wall and Footwall veins steepen with depth from 74° to 80° and 66° to 84° respectively (Lamb, 1974). At the Limon Mine the principal quartz vein has a weakly curvilinear surface, but the dip decreases with depth (Map 2). It is possible that a component of the dip of the conformable map units could result from rotation during movement on curvilinear fault planes.

Figure 2.6 Rose diagram of the strikes of 31 quartz veins from the Mina El Limon area.

Figure 2.5 Contoured equal area plot of poles to 31 quartz veins from the Mina El Limon area.

2.5.2 East-Trending Faults

Much less is known about the east-trending, post-mineralization faults identified by Geyne (1952). These faults are inferred from abrupt changes in lithology, offset quartz veins and photolinears defined by steep hillsides and linear drainage patterns. Only two unimportant quartz veins, Spencer and Morales (Map 2), strike in an easterly direction.

The dip and displacement on these faults are not generally known (Table 2.2), except for the Haigie fault which offsets the Limon vein system approximately 30 m laterally and 150 m vertically.

The east-trending Geyne fault is an important structural feature that was identified by previous workers (Malone, 1974; Hodgson, 1972). No quartz veins have been found in the Mina El Limon area south of this fault.

2.6 Hydrothermal Alteration

Hydrothermal minerals such as sericite, adularia, calcite, chlorite and pyrite have been identified in the wall rock adjacent to quartz veins in the Panteon vein system (Gleason, 1977). Geyne (1952) also identified silicified rhyolite agglomerates that are probably equivalent to the silicified andesites described in section 2.3.3.

Although hydrothermal alteration affects all rock types, it is strongest and most extensive in the basal mafic rocks (units 1 and 2). There are three alteration assemblages in the mafic wall rocks adjacent to the quartz veins that grade laterally into one another. Typically the quartz veins are surrounded by a sericite-adularia alteration

envelope that extends several metres from the quartz vein. A somewhat larger zone of argillic alteration lies outside the sericite-adularia zone and can extend up to tens of metres from the vein. A propylitic alteration zone is found outside the zone of argillic alteration.

In the sericite-adularia zone original textures are largely destroyed. The quartz-sericite assemblage is characterized by adularia, sericite, quartz, calcite, illite, pyrite, sphene, leucoxene and chlorite (Gleason, 1977). Also common in this zone are quartz veinlets with hematite and carbonate, pervasive silicification and quartz-filled amygdules.

Rocks from the argillic zone are altered to a light green or greenish-white colour, cut by rare veinlets of quartz, carbonate and hematite, and peppered with disseminated-pyrite. Original textures are preserved. Sericite, chlorite, carbonate, pyrite, nontronite and kaolin are the principal secondary minerals associated with the argillic alteration zone. The clinopyroxene phenocrysts are partially altered to chlorite, hematite, nontronite and carbonate. The groundmass is variably altered to chlorite, carbonate and clay minerals. Sericite, chlorite, montmorillonite, carbonate, nontronite, zeolites and possibly kaolinite partially replace the plagioclase phenocrysts. Associated volcaniclastic breccias are typically more strongly bleached and contain more disseminated pyrite than the lava flows, a feature that probably reflects their greater permeability.

In the propylitic zone the rocks are not noticeably bleached; the only macroscopically obvious alteration feature is the replacement of plagioclase phenocrysts by soft, secondary minerals. The principal propylitic alteration minerals are chlorite, sericite, carbonate and hematite that partially replace both phenocrysts and matrix. The alteration is less intense than in the argillic zone.

Mafic volcanic flows from units 1 and 2 were examined in thin section to determine the extent of hydrothermal alteration. The degree of alteration was plotted against the distance from the nearest quartz vein. No consistent relationship was observed between degree of alteration and distance from quartz veins for the pyroxene phenocrysts (Figure 2.7) or the groundmass. However, 90 % of the plagioclase phenocrysts that occur within 100 m of a quartz vein are substantially replaced (more than 40 vol. %) by secondary minerals (Figure 2.8). As the distance from the quartz veins increases the feldspar phenocrysts are less altered. Obviously, the extent of feldspar alteration could serve as a very useful exploration guide to quartz veins. Extensive alteration halos around auriferous quartz veins have been documented in other studies, including those at Red Lake, Ontario (McGeehan et al., 1982) and on Pachua-Real del Monte, Mexico (Geyne et al., 1963).

2.7 Economic Geology

The Mina El Limon area is underlain by a Tertiary volcanic sequence which is cut by numerous quartz veins, many of which contain gold and silver mineralization. The first ore was extracted by an English company from the Santa Pancha and San Luis veins between 1870

Figure 1. Extent of alteration of pyroxene as a function of distance from the contact. The data are from the same area as shown in Figure 2. The correlation coefficient between extent of alteration and distance is 0.54.

Figure 2. Extent of alteration of plagioclase as a function of distance from the contact. The data are from the same area as shown in Figure 1. The correlation coefficient between extent of alteration and distance is 0.54.

and 1913 (Gleason, 1977). These veins were only mined to depths of 30 m because of high groundwater levels (Gleason, 1977). The discovery at surface of the Limon North quartz vein in the 1930's by Minera Empresa de el Setentrion led to the start of their mining operations in the area. Setentrion's initial ore production came from the Limon North, Main Limon and Pozo Bono veins. Later mining operations also included the Santa Pancha and San Luis veins (at a greater depth than the English company's workings) and the Mercedes, Atravesada and Spencer veins. In the late 1960's Minera Empresa de el Setentrion opened up the Panteon vein system, west of Santa Pancha, which then became the main source of ore.

Annual production of gold and silver from the veins in the Mina El Limon area has been quite variable. For example, in 1945 Minera Empresa de el Setentrion produced 30,000 troy ounces of gold and 10,000 troy ounces of silver and twenty-five years later they extracted 66,570 troy ounces of gold and 64,901 troy ounces of silver (Hodgson, 1972). By the end of 1979, total production from all the veins in the Mina El Limon area stood at an estimated 750,000 troy ounces of gold from 1.5 million tons of ore (figures revised from Gleason, 1977, pg 12). Most of the gold has been extracted from the Santa Pancha, San Luis, Main Limon, Pozo Bono and Atravesada veins (Table 2.3). Since the revolution in 1980, the Nicaraguan government has operated the mine at a much reduced level of production.

2.7.1 Quartz Veins

Four auriferous quartz vein systems (Panteon, Santa Pancha, Limon and Atravesada) and numerous other quartz veins occur in the Mina El

Figure 2.9 Quartz veins in the Mina El Limon area, Widths of lines not to scale.

Table 2.3 Quartz veins in the Mina El Limon Area

Name	Strike degrees	Dip degrees	Grade oz/T	Production tons x 1,000
1. Panteon			0.62	1,000
Hanging Wall	355	80E	0.40	yes
Footwall	330	72E	0.60	yes
Southern Ext.	315	75E	-	yes
Intermediate	330	70E	-	yes
2. Santa Pancha				
San Luis	15	70E	-	yes
Santa Pancha	310	56N	-	yes
Mercedes	0	75E	-	100
Aparejo	25	60E	-	no
3. Limon			0.25	
Limon North	0	45E	0.89	yes
Main Limon	0	45E	0.35	yes
Pozo Bono (H.W.)	0	30E	0.4-0.7	yes
4. Attravesada				
Attravesada	45	60N	0.27	yes
Spruance	10	90	-	no
Portal	25	85W	0.14	no
Larga	50	75N	0.13	no
Santa Emilia	20	65W	-	no
5. Tecuapapa	70	70S	-	no
6. Babilonia				
Palanca	0	65E	-	no
Babilonia	25	60E	-	no
7. Lourdes				
Urden	15	85E	-	no
8. Spencer	80	70N	0.27	yes
9. Morales	285	55N	-	no

* troy ounces per ton

ore production in tons

+ Information from mine records, Hulin (1950); Geyne (1952, 1953); Lamb (1974); Gleason (1977).

Limon area (Figure 2.9, Map 2). Some auriferous quartz veins also contain economic concentrations of silver. The veins vary from tens of centimetres to a maximum of 20 metres in width and major veins can be followed along strike for hundreds of metres. The two largest vein systems, Limon and Panteón, have been mined to depths of >250 m and >325 m respectively.

2.7.2 Panteon Vein System

The Panteon vein system consists of the Hanging Wall, Footwall, and Southern Extension veins (Map 2). The Hanging Wall and Footwall veins are believed to join at depth (Lamb, 1974) and merge towards the south to form the Southern Extension vein. The following description by Gleason (1977) of the Panteon vein system is based on the Hanging Wall and Footwall veins:

"The most persistent feature in the veins is well-developed banding. This banding is seldom if ever colloform in nature. The veins are composed of a core of central massive white quartz becoming progressively more banded towards the wall rock. The bands are clear to white quartz, frequently displaying excellent comb structure, ranging in width between a millimeter and a few centimeters. Some bands are (considerably) greenish, assumably due to propylitic, fine grained impurities. Narrow dark bands, composed of silicified andesite are common and contain fine-millimeter-sized grains of pyrite."

The veins vary in width from 0.3 to 6 m with an average width of 1.3 m (Gleason, 1977). Vein contacts with the wall rock are sharp, and mafic volcanics are noticeably altered near the veins (section 2.6). Angular clasts of wall rock commonly occur in the quartz veins and vary from microscopic fragments to horses of rock several metres across (Gleason, 1977; Plate 2.10). The fragments are typically surrounded by fine-grained quartz. Gouge occurs throughout the quartz veins, and a major gouge zone occurs at the footwall contact of the Footwall vein.

Plate 2.10. Sample of the Panteon quartz vein from the 800 level that contains an altered volcanic clast cut by late quartz veins. Field of view is 4 cm.

Plate 2.11. A quartz breccia with reddish quartz matrix from Limon North vein.

Small veins and veinlets of quartz and calcite cut the wall rock adjacent to the main quartz veins (Figure 2.10) but decrease in abundance until they disappear at distances of metres to tens of metres.

The Panteon vein system is hosted by unit 1 mafic flows and volcanoclastics and unit 2 flows. A unit 3 felsic breccia is found at surface in the hanging wall of the Hanging Wall vein. The approximate combined vertical displacement on the Footwall and Hanging Wall faults is >175 m.

Gangue minerals in the Panteon vein system consist of quartz with minor carbonate and pyrite. The quartz occurs as:

- 1) fine-grained, anhedral, roughly equant aggregates;
- 2) comb-textured quartz with crystals up to 2 mm long; and
- 3) crystals in vugs.

The quartz is commonly brecciated and cemented by later generation of quartz, which may be accompanied by calcite. The quartz varies in colour from pure white to purple, pink and grey. The veins commonly contain small drusy vugs (< 0.5 cm). Gleason (1977) reports large vugs with scalenohedral calcite crystals, up to 1 metre in length, commonly coated with small quartz crystals. Calcite occurs as anhedral to euhedral grains (<1mm) in the fine-grained quartz, as dog-tooth spar in the vugs and in small veinlets. T. Kelly, a former mine foreman at the Panteon Mine, reports that the highest gold values were found in the greenish layers in the banded veins which are commonly formed of equigranular quartz containing altered fragments of wall rock (personal communication, 1977). Anhedral to euhedral grains of disseminated pyrite, less than 1 mm in size, are present in parts of the veins. The pyrite, particularly the euhedral variety, is commonly brecciated with

Figure 2.10. Schematic diagram of the Mina El Limon area quartz veins

gangue or chalcopyrite filling the fractures and forms clusters and trains of grains. Although disseminated in the wall rock (0.5 to 3 vol. %), pyrite is mainly confined to the fine-grained quartz and the wall rock fragments in the veins.

Chalcopyrite, sphalerite, electrum and minor covellite and chalcocite are the ore minerals (Lamb, 1974). Chalcopyrite, seen only in those samples that contain pyrite, occurs as sub-rounded to angular blebs, less than 0.1 mm in size, and as infillings in microfractures and incomplete rims on pyrite grains. The presence of microscopically visible chalcopyrite correlates with the macroscopic distribution of pyrite which is most abundant in equigranular quartz and in close proximity to wall rock fragments. Sphalerite occurs in trace amounts as carrot-shaped grains less than 0.05 mm long. It is not associated with other sulphides. Base metal contents are low (Table 2.4), although Malone (1974) found that the zinc content can reach up to 0.20 % (unless otherwise specified all % values are weight %) in the Panteon veins. The Panteon quartz veins have an average grade of 0.62 oz/ton gold with a silver to gold ratio of 2.5:1 (Gleason, 1977). Mineralization extends to depths of 330 m below the surface where it drops off sharply (Gleason, 1977).

Gleason (1977) reported visual identification of a speck of electrum from the Panteon vein system. Indeed, the Setentrion mill at Mina El Limon was designed to process free gold and electrum which were thought to occur interstitial to the quartz grains.

Numerous small grains (<0.001 mm) of a highly reflective metallic mineral occur in the Footwall and Hanging Wall quartz veins which could be electrum, gold or pyrite, all minerals with similar petrographic

Table 2.4 Analyses of grab samples from quartz veins

Sample	Location	Au ppm	Ag ppm	Cu ppm	Zn ppm
446	200 level, Footwall vein, Panteon	10.5	33.0	36	45
418	1st sublevel, Pozo Bono	1.75	2.0	25	15
383	70' above Hangingwall vein, Panteon	11.6	10.0	87	52
201	solitary quartz vein west of Mina El limon	2.75	.5	30	27
202	surface, Limon North	17.0	.5	40	19
391	25' below 400 level, Hanging Wall vein, Panteon	34.0	.75	80	144

* Lake Dufault laboratory, Noranda, Québec

characteristics. A limited number of electron probe analyses failed to reveal any gold-bearing minerals. Similar difficulties in identifying the gold-bearing mineral have been reported from other deposits such as the Vitu Levi deposit in Fiji where the electrum is approximately 0.00001 mm in size (Ramdohr, 1969).

2.7.3 Santa Pancha Vein System

The San Luis, Santa Pancha, Mercedes and Aparejo quartz veins are segments of the 6 km long Santa Pancha vein system (Figure 2.9, Map 2). The veins are hosted by mafic volcanics of units 1 and 2. Only the Aparejo vein has not produced any gold; free gold has been identified in the Mercedes vein (Anderson, 1963).

The Santa Pancha quartz vein consists primarily of massive white to purple quartz cut by later veinlets of white quartz. At surface the quartz vein is associated with an altered, purple felsic dike which is not found at depth (Geyne, 1952). Fragments of the dike occur within the quartz vein. A similar dike occurs in the footwall of the Aparejo vein (Geyne, 1953).

2.7.4 Limon Vein System

The Limon North, Main Limon and Pozo Bono veins make up the Limon vein system (Figure 2.09, Map 2). The Limon North and Main Limon veins are sections of the same vein offset by the east-trending Haigie fault. The Pozo Bono vein occurs above the Main Limon vein in the hanging wall along the basal contact of a latite dike. Mafic volcanics of units 1

and 2 occur in the footwall and hanging wall of all these veins. Unit 3 volcanoclastic rocks and unit 4 flows are found only in the hanging wall (Figure 2.11).

The North Limon vein is up to 20 m wide and forms the spine of a north-trending ridge. Gangue minerals are quartz and trace pyrite. Quartz, typically anhedral, varies both in colour (white, pink, purple) and grain size. Small, cross-cutting veinlets of comb quartz cut the vein which is commonly banded or brecciated. The brecciated samples consist of quartz fragments, with or without altered greenish rock fragments, cemented by reddish quartz (Plate 2.11). Intensely brecciated quartz ore from the open pit on the Limon North vein, south of El Tigra, had the highest gold grades found at surface (Haigie, former mine manager, personal communication, 1977).

The Main Limon vein which is compositionally and texturally similar to the Limon North vein, also forms a north-trending ridge. Commonly white quartz fragments are cemented by a red silica matrix. Small vugs with quartz crystals are associated with the Main vein. Gouge is present in the hanging wall and sometimes in the vein (Hulin, 1950).

Overlying the southern part of the Main Limon vein is the Pozo Bono quartz vein (cross-section, Map 2) that follows the basal contact of an easterly-dipping felsic dike and joins the Main Limon vein near surface. The principal gangue minerals in the Pozo Bono quartz vein are quartz, pyrite and carbonate. Fragments of quartz and country rock are set in a matrix of quartz with minor chlorite. The rock fragments are intensely altered, cut by quartz veinlets and, in some cases, rimmed by

Figure 2.11 Schematic cross-section of Mina El Limon area quartz vein. The approximate level of erosion of the principal quartz veins is shown on the right.

fine-grained, and comb quartz (Plate 2.12). Pyrite is particularly abundant in the Pozo Bono vein.

The ore minerals in the Limon veins are chalcopyrite, sphalerite and presumably gold or electrum. The chalcopyrite occurs either as isolated grains up to 0.1 mm across, or as rims surrounding pyrite grains. Sphalerite is present only in trace amounts. Gold was not positively identified, although a yellow, highly-reflective mineral was noted healing fractures in a pyrite grain.

Gold grades for the northern part of the Main Limon vein systematically decrease with increasing depth from 0.56 oz/ton Au above the 100 level to 0.15 oz/ton Au at the 534 level (Hulin, 1950). The ratio of Au:Ag for the Limon vein system is greater than 1 (Malone, 1974).

2.7.5 Atravesada

The Atravesada quartz vein is a short, solitary vein. Mafic volcanics of units 1 and 2 form the footwall and intermediate flows of unit 4 the hanging wall. Colloform quartz forms bands of pink, pale blue and white quartz. The banded quartz is cut by comb quartz veinlets, which in turn are cut by quartz veinlets (Plate 2.13). The comb veinlets also contain small "rosettes" of quartz. Brecciated quartz healed with quartz was noted in several localities. Pyrite, the only other gangue mineral, forms small euhedral to subhedral grains.

The ore minerals chalcopyrite, sphalerite and possibly electrum are present in trace amounts. The chalcopyrite occurs as rims on pyrite and as small anhedral grains.

Plate 2.12 Photomicrograph from the Pozo Bono quartz vein showing cockscomb quartz rimming a rock fragment. Field of view is 2.2 mm. Crossed nicols.

Plate 2.13. Several generations of quartz can be seen in this sample from the Atravesada mine including cockscomb quartz. Field of view is 3mm. Crossed nicols.

2.7.6 Other Quartz Veins

The remaining quartz veins are less well-known. Several, such as Larga and Lourdes, occur along dike contacts and form ladder textures (Figure 2.10). Only the Spencer vein has produced ore.

2.7.7 Paragenesis

The Mina El Limon area auriferous quartz veins are characterized by a very simple paragenetic sequence.

Quartz was deposited in several stages, commonly with intervening periods of movement and brecciation along the host fault. Generally the earliest quartz is barren, white and massive. Equigranular, banded, grey or green, "dirty" quartz was deposited during intermediate stages of quartz deposition. Veinlets of comb quartz cut the white and "dirty" quartz. Calcite, present in only a few veins such as Pozo Bono and the Panteon vein system, formed towards the end of the paragenetic sequence, primarily filling vugs and occurring as late-stage veinlets.

Chalcopyrite, pyrite and sphalerite were deposited almost exclusively with equigranular quartz. The correlation of gold grades with the volume of sulphides, particularly the amount of pyrite, suggests that it was most likely deposited contemporaneously with the sulphides.

2.7.8 Wall-Rock Lithologies

The mineralized quartz veins in the Mina El Limon area typically have only unit 1 mafic rocks in the foot wall and all of the conformable map units in the hanging wall (Figure 2.11). This relationship between certain wall-rock lithologies and quartz veins was first noted by Hulin in 1950:

"In more detail, the known orebodies are closely related in vertical distribution to the portion of the felsite-andesite contact, the upper limits of known orebodies, erosional in most cases, being at or closely below the elevation of the felsite-andesite as represented in the hanging wall of the vein system."

The correlation between wall-rock lithologies and quartz veins is not coincidental but rather a feature of the mode of genesis of these veins (section 9.2).

2.7.9 Timing of Mineralization

Quartz veins cut all the conformable rocks in the Mina El Limon area. In addition, quartz veins cross-cut unit 5 dacite dikes (Larga and Lourdes) and the Santa Pancha vein contains dacite xenoliths. No quartz veins are in contact with unit 6 dikes. Therefore, the quartz veins are younger than almost all, or all, of the Tertiary volcanic rocks exposed in the Mina El Limon area. Deposition of auriferous quartz veins subsequent to magmatic events, other than minor late post-ore dikes, is common in most Tertiary gold deposits (Boyle, 1979).

The close relationship between dikes and veins could reflect the existence of a dacitic magma chamber at depth which provided not only the dike material, but also the heat needed to drive the hydrothermal solutions that produced the quartz veins.

Malone (1974) proposed that the quartz veins formed after the mafic volcanic activity and prior to the extrusion of the intermediate to felsic flows. This conclusion was based on possible fragments of quartz vein within a rhyolite breccia near Santa Rosa. Although siliceous clasts do occur in unit 3 dacite breccias, but these are fragments of felsic volcanics.

2.7.10 Genesis of Mineralization

Traditionally geologists believed that auriferous epithermal quartz veins formed from hydrothermal fluids derived from a body of magma near the site of deposition of the vein (Lindgren, 1933). More recent work has shown that gold is more likely to be derived from the country rock (Boyle, 1979) and that the source of any hydrothermal fluids associated with the gold mineralization is normally meteoric water (Taylor, 1974).

Both of these features could be tied into a model for gold mineralization in the Mina El Limon area. Meteoric groundwater could have descended along faults to the more permeable mafic volcanoclastic rocks near the base of the volcanic succession and then migrated, laterally because of the relatively impermeable overlying andesite and dacite lavas (caprock). Heat from a shallow dacitic magma chamber and associated dikes and stocks could have supplied the heat which produced hydrothermal fluids that exchanged hydrogen for silicon, gold and copper with nearby rocks. Eventually the fluid could have escaped along faults to the surface. As the fluid migrated along the faults it interacted with the wall rock, leaching Na, Ca, Mg, Fe and Mn and depositing Si, K

Figure 2.12 Schematic model of the formation of quartz veins in the Mina El Limon area. Arrows represent groundwater and fluid circulation paths.

and volatiles. Changes in pressure and temperature in the fluid near the hanging wall caprock layer led to the deposition of quartz veins with associated gold and silver.

3. The Telica Complex

3.1 Introduction

Telica, an active volcano in northwestern Nicaragua ($12^{\circ}36'N$, $86^{\circ}52'E$), is part of the chain of Quaternary volcanoes along the western margin of Central America. Several adjacent volcanic edifices, including Santa Clara, Cerro de Agueró and San Jacinto coalesce with Telica to form one of the groups of hills in the Marrabios Range (Figure 3.1) on the southwestern margin of the Nicaraguan Depression. The volcanic deposits from Telica and the contiguous volcanic centres frequently overlap or interfinger and form a distinct geomorphological section of the Marrabios Range called the Telica Complex (Martínez and Viramonte, 1971; Creusot, 1976). The Telica Complex covers approximately 80 square kilometres and extends from the town of Telica in the south to Las Marias in the north, and from near San Jacinto in the east to near Colonia Agrícola Cristo Rey in the west (Figure 3.2).

McBirney and Williams (1965) used the name San Jacinto for the Santa Clara volcano and El Liston for the hills surrounding the San Jacinto crater. In this study the volcanoes are identified by names used by Martínez and Viramonte (1971) and Catastro (1972a).

3.2 Historical Volcanic Activity

There are two active volcanoes in the Telica Complex: Santa Clara and Telica. Historical volcanic activity at Santa Clara has been restricted to solfateric activity during the sixteenth century (Mooser et al., 1958). During the last 500 years Telica has had extended periods of solfateric activity and numerous small explosive eruptions. A list

Figure 3.1 Volcanoes of the Maricao Range. Volcanoes El Viejo and San Jacinto are now called San Cristobal and Santa Clara respectively (from McBirney and Williams, 1965).

Figure 3.2 Principal volcanic landforms of the Telica complex.

Table 3.1 Historical volcanic activity of Telica and Santa Clara*

1527-1529	Continuous solfataric activity
1577	Santa Clara? (#8)
1684-1685	Continuous solfataric activity
1740-1743	Continuous activity, ejection of ash and earthquakes
1850	No details (#8)
1907 (Nov.)	Continuous activity, ejection of ash
1918 (Jan.)	Solfataric activity and earthquakes
1927 (Aug. - Nov.)	Explosive eruption, ejection of ash and earthquakes
1929 (Jan.)	Weak eruption, ejection of ash
1932 (Dec.)	Continuous solfataric activity
1934 (Jan.)	Continuous activity, ejection of ash
1935 (Jan. - Mar.)	Continuous solfataric activity
1936 (May - July)	Crater plugged up, solfataric activity and earthquakes
1937 (Nov.)	Eruption with ejection of ash, earthquakes and damage to fields
1940 (May - June - Oct.)	Crater plugged up, earthquakes Eruption of ash
1941 (Jan. - Aug.)	Continuous solfataric activity, earthquakes
1943 (Dec.)	Eruption with ejection of ash, earthquakes and damage to fields
1944 (Feb. - Apr.)	Continuous activity, ejection of ash and damage to fields
1946 (Apr. - Aug. - Dec.)	Continuous activity, ejection of ash and damage to fields Earthquakes
1948 (Jan. - Dec.)	Continuous activity, ejection of ash, earthquakes and damage to fields
1949 (Nov.)	Continuous activity, ejection of ash
1950 (July)	Continuous solfataric activity
1951 (July)	Explosive eruption (#8)
1954 (Mar.)	Crater plugged up
1962 (Jan.)	Weak eruption of ash
1965 (Jan. - May)	Continuous activity, ejection of ash
1966 (June)	Continuous activity, ejection of ash
1969 (Feb. - Aug.)	Continuous activity, ejection of ash

Table 3.1 cont.

- 1970(Aug. Continuous activity, ash deposited as far away as
Sept.) Chichigalpa (#4)
- 1971(Jan. Continuous activity, ejection of ash
- May)
(Dec.) Active lava lake (#1)
- 1972 Volcano extinguished
- 1973(Mar.) Continuous activity, weak ejection of ash
- 1975(May Continuous solfataric activity, lava lake
- Dec.)
- 1976(Jan. Continuous solfataric activity, lava lake
- Mar.)
(July Continuous solfataric activity (#2)
- Aug.)
- 1977(July Continuous solfataric activity, lava lake (#2)
- Aug.)
(Nov. Ejection of ash (#3), initial explosions every hour,
- Dec.) with ash being deposited as far away as Pacific
Ocean (#5)
- 1980(Feb.) Minor white plume (#7)
- 1981(Dec.) Small gas and ash eruptions with earthquakes (#6)
- 1982(Jan. Continuing seismic activity, with largest eruptions since
- Feb.) 1976, 50 people evacuated, ash deposited as far away as
Pacific, damage to fields (#6)

* Material from A. Creusot (1976) unless otherwise indicated

- #1 - Taylor (1973)
- #2 - Lefebure (Field observations, 1976, 1977)
- #3 - Chapman (personal communication, 1978)
- #4 - Viramonte (1973)
- #5 - Arbuto (1977)
- #6 - Geotimes (May & April, 1982)
- #7 - Stoiber et al. (1980)
- #8 - Simikin et al. (1981)

of the known historical eruptions (Table 3.1), although incomplete, shows increased activity in the 20th century. Since the year 1900, Telica has ejected ash during at least 22 different eruptive periods and exhibited almost continuous solfateric activity (Plates 3.1 and 3.2). Remnants of a nineteenth century forest can be seen on the northern flanks of Telica (Plate 3.3). These trees were killed by gases from Telica (Creusot, personal communication, 1977) in a similar manner to the defoliation of the pine forest at the summit of San Cristobal in the 1970's (Hazlett, 1977).

In 1977 the escaping gases gave an audible "roar" near the edge of the crater, possibly similar to the sound heard in San Cristobal's crater in the early 1970's (Hazlett, 1977). A lava lake, first noted in 1971 (Taylor, 1973), was still present in 1977 at the bottom of Telica's 400 m deep circular crater.

3.2.1 Description of Recent Eruptions

In February and on May 14, 15 and 17, 1969, intermittent large columns of gas and fine ash reached heights up to 1500 m above sea level, but ash falls were not reported beyond the limits of Telica's cone (Viramonte, 1973). One of the largest eruptions in recent years in 1970 (August 17th to 25th), consisted of ejections of large columns of gas and ash approximately every 10 minutes. The eruption column reached a maximum elevation of 2,000 m and the ash cloud was blown towards the northwest. Ash falls were reported in the towns of Chichigalpa and Corinto (Map 1).

Telica erupted again in November and December, 1977. Starting on

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Plate 3.1 Telica exhibiting weak solfateric activity. Telica Este crater is visible on the left of the photograph. The shoulder north of the Telica crater can be seen at the base of the dark brown upper portion of the Telica's cone immediately above some small gullies. Photograph taken by F.M. Bullard on June 29, 1957 looking south.

Plate 3.2 A view of the Telica crater from the southeast on June 27, 1957 showing extent of solfateric activity. The wedge-shaped plateau described in section 3.5.8 is clearly visible on the left side of the photograph (photograph by F.M. Bullard).

Plate 3.3 Tree trunk, on the upper western slopes of Telica, is a remnant of a forest that covered the volcano in the nineteenth century. The indurated lapilli-tuff and tuff-breccia form an "armour plate" on the flanks of Telica which resists erosion by wind and water.

Plate 3.4 A typical recent eruption of Telica showing a light coloured ash cloud being blown to the southwest of the volcano. Photograph taken from south of Telica by A. Burack, November, 1977.

Plate 3.5 An ash eruption from Telica, November, 1977. Photograph taken from the same location as Plate 3.4 later the same morning by A. Burack. The ash cloud visible in Plate 3.4 has been blown farther from the vent.

November 11, sizeable explosions began to occur at the rate of one per hour (Arbuto, 1977). The ash from some of the stronger eruptions travelled 35 km, as far as the Pacific Ocean. By early January, Arbuto reports that the "explosion frequency had declined to 1-2 per day and ashfall was no longer reaching the ocean". Some of the eruptions from Telica during the November 25th to 27th period were observed (Plates 3.4 and 3.5) by Dartmouth College geologists (1977) who prepared the following report:

"During the early morning of 25 November, our group observed a series of ultravulcanian ash eruptions from Telica. An explosion was observed at 0605 from Leon, 19 km from Telica, producing a light brown ash cloud which rose 0.91 km above the summit. A dispersed cloud of ash from an earlier explosion was noted SW of the volcano. Four more explosions were observed, at 0617, 0622, 0626 and 0644. For the rest of the day, only intermittent observations were possible, but explosions were noted at 0740, 0835, and 1530. Ash fell in a zone extending about 5 km SSW of the volcano. Four km from the source, ash formed a discontinuous coating <1 mm thick. Samples were collected for analysis at Dartmouth. A similar explosion, sending ash 1.6 km above the cone, was seen at 0605 on 26 November. At 0920 on 27 November, a dust cloud, presumably produced by another explosion, was seen from the air."

Further eruptions occurred in late December, 1981 to early January, 1982 with small gas and ash eruptions. Ash falls were confined to the area near the crater and seismicity remained higher than normal in late January (Geotimes, April, 1982). This activity culminated during the February 12th to 20th period producing the largest eruptions since 1976 (Geotimes, May, 1982). An eruption cloud reached 3.7 to 4.3 km altitude on the first day. During this 9 day period blocks and scoria up to 13 m in diameter fell as far as 200 m from the crater rim and ash fell on the Pacific coast. At least 50 people were evacuated from the south flank of the volcano from February 12th to 14th. The vigorous

activity for the first few days killed some farm birds and coated cotton fields with ash. A large eruption on February 19th threw ash to more than 3.5 km altitude and fell up to 35 km away. These eruptions doubled the size of the active vent to 75 m by 50 m.

Telica's historic eruptions have resulted in vertical ejections of basaltic ash and gases over periods of days or weeks with associated seismic activity. During the stronger eruptions, lapilli, bombs and blocks were ejected onto the crater rim and flanks of Telica and ash has fallen as far away as the Pacific Ocean. Telica has sometimes erupted with a periodicity of minutes to hours. There has been almost continuous solfateric activity between historic eruptions.

Many of the features of Strombolian volcanoes (MacDonald, 1972; Greeley, 1974; Bullard, 1979), including a white eruption cloud, short repose cycle, extended periods of activity, solely pyroclastic eruptions and minor energy release, are common features of Telica's eruptions. Telica's historical volcanic activity is similar to most of the other volcanoes in the Marrabios Range (McBirney and Williams, 1965; Hazlett, 1977) and some other Central American volcanoes such as Izalco (Stoiber, 1975).

3.3 Springs and Fumaroles

Hot and cold springs and fumarole fields occur at 8 localities in the central, eastern and northern parts of the Telica Complex (Table 3.2, Map 3). The springs and fumaroles occur along faults, permeable flow horizons and crater walls. The activity of the hot springs and fumaroles reflects the high heat flow in certain parts of the Telica Complex and the availability of groundwater. Their maximum activity

Table 3.2 List of Telica Complex fumarole fields and springs

Name	Location		Elevation	Activity*
	N	W		
1. Hervideros de San Jacinto	12° 35'	86° 47'	~190m	Fumarole field, thermal springs
2. Tisate	12° 36'	86° 47'	~150m	inactive fumarole field, thermal springs
3. El Najo	12° 38'	86° 48'	~300m	fumarole field, thermal springs
4. Santa Clara	12° 38'	86° 47'	~250m	warm water well
5. El Caroi	12° 37'	86° 50'	~500m	spring, fumarole fields
6. Cerro de Aguero	12° 38'	86° 51'	700m	inactive fumarole field?
7. Telica	12° 36'	86° 52'	<880m	solfateric activity
8. La Ceiba	12° 36'	86° 50'	~750m	inactive thermal springs

* based on field observations made in 1976 and 1977

Plate 3.6 Fumarole field at San Jacinto with dry run-off channel in foreground.

Plate 3.7 El Najo fumarole field during a quiescent period. Note intense alteration of outcrop. Packsack in foreground for scale.

occurs during and immediately following the rainy season. Many are inactive towards the end of the dry season.

Mud pots, hot springs and fumaroles cover 0.25 square km in the San Jacinto area (Plate 3.6). The hot springs and fumarole fields of San Jacinto and Tisate are located along the traces of northerly-trending faults (del Gluidice, 1959). Both the El Najo (Plate 3.7) and El Carol fumarole fields and springs are believed to lie in those areas where permeable lava flows reach surface. The solfateric activity of Telica and La Ceiba fumarole fields are associated with volcanic craters. The three areas of solfateric activity in the walls of Telica's crater are thought to mark the walls of three different vents (Creusot, personal communication, 1977).

The San Jacinto fumarole field and hot springs have been assessed by the Nicaraguan government for their potential to produce geothermal power. To date, the government has chosen to concentrate on the larger geothermal field near Momotombo. However, the high temperature of the water at surface (99°C), the relatively large area with surface manifestations of geothermal activity (0.25 sq km), and the persistence of surface activity throughout the year indicate that the San Jacinto area has potential to produce geothermal power. Other favourable localities within the Telica Complex for geothermal exploration are Tisate, El Najo and El Carol.

3.4 Geomorphology

Rising to a maximum elevation of 1060 m above the low-lying plains (~ 100 m), the Telica Complex can be subdivided geomorphologically into hilly areas (Cerro Las Portillos, San Jacinto), a lava "apron" spreading out

Name		Elevation		Coordinates		Description	
Name		Elevation		Coordinates		Description	
1. Tellica Este Crater		2000'	20° 15' N	86° 55' W		filled by Tellica lava, eruption, western rim, covered by debris, covered by Tellica, and NW side	
2. La Leiza Crater		2000'	20° 15' N	86° 55' W		breached to the north preserved on its north eastern and southern flanks, covered to the west by Tellica Este; extremely steep walls; seasonal hot spring activity on crater floor	
3. El Estero		2000'	20° 15' N	86° 55' W		the Rio in the western rim would be due to erosion of the later development of La Leiza Crater	
4. Santa Clara		2000'	20° 15' N	86° 55' W		symmetrical cone; small central crater breached on southwest and northwest sides; cinder cone vent for 17th century solfiter; active; crater is an east-west of circular summit ridge	
5. Cerro de Azuero		2000'	20° 15' N	86° 55' W		summit crater, two minor semi-circular somma ridges on east and south side	
6. El Azuero		2000'	20° 15' N	86° 55' W		original diameter 1.9 km, steep to moderately steep walls, north wall hidden or solfitered by Cerro de Azuero, south wall breached by erosion, and covered by lava flow from Tellica	
7. Martinez		2000'	20° 15' N	86° 55' W		flow originated from Volcan Tellica, partially filled crater, of Tellica Este before flowing to south	
8. El Pajon		2000'	20° 15' N	86° 55' W		margins of flows obscured by alluvium in some locations; originated from Tellica	
9. El Pajon		2000'	20° 15' N	86° 55' W		originated from Tellica	
10. Los Ranchos		2000'	20° 15' N	86° 55' W		originated from	
11. Los Ranchos		2000'	20° 15' N	86° 55' W		originated from	

from Telica and the three volcanic cones of Cerro de Aguero, Santa Clara and Telica (Figure 3.2 and Table 3.3).

3.5 Stratigraphy of The Telica Complex

The Telica Complex is underlain by lavas, tephra, alluvium, lahars and intrusive rocks (Table 3.4). Flows and tephra of basaltic and andesitic composition are the most abundant rock types. The epiclastic rocks occur in linear valleys on the flanks of the volcanoes and as more widely spread deposits on the surrounding plains. Hypabyssal intrusive rocks outcrop on the older volcanic centres, but are restricted in surficial extent.

The Telica Complex contains four easily recognizable volcanic edifices - San Jacinto, Aguero, Santa Clara and Telica. Two older centres, Cerro de La Ceiba, are identified in this study (Map 3). Several other volcanic centres (Telica Este crater, bridge), but these are now eroded and buried by late

Telica, an active volcano, is the youngest centre and rests on the other four volcanic centres. Telica's four compound flows have definite flow margins, little or no soil cover and immature forest cover similar to "Category-A Flows" on San Cristobal (Hazlett, 1977). Hazlett believes that the San Cristobal "Category-A" flows are approximately 450 years old, based on comparison with the weathering and re-vegetation of Hawaiian flows.

McBirney and Williams (1965) believed that the volcanoes of the Marrabios Range, including the Telica Complex, are of Quaternary age. More recent work by Catastro (1972a) and La Martinez and Viramonte

Table 3.4 Table of Formations for the Telica Complex

<u>Period</u>	<u>Epoch</u>	<u>Formation</u>	<u>Lithology</u>	<u>Unit</u>
Quaternary	Recent		alluvium and colluvium	9
		Telica	basalt lava and tephra	8
	Recent or Pleistocene		andesite lava	7
		San Jacinto	altered basalt lapillistone and tuff	6
		Santa Clara	basalt lava and tephra	5
		Cerro de Agüero	basalt lava and tephra	4
		El Najo	basalt lava	3
		La Ceiba	andesite lava	2
Tertiary or Quaternary	Pliocene or Pleistocene	Cerros Los Portillos	basalt lava	1

(1973) suggests that volcanoes such as Cerro Los Portillos which are strongly dissected and eroded, are Plio-Pleistocene in age. Volcanoes with some recognizable volcanic features such as San Jacinto are thought to be of Pleistocene age. All other volcanoes with nearly intact edifices are currently (Santa Clara, Telica) or were recently active (Cerro de Aguero).

The following section discusses the formations of the Telica Complex in order of stratigraphic position, starting with the oldest unit (Table 3.5.1). The stratigraphic nomenclature is based on the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983). Each unit is described in an identical fashion to the descriptions given for the Mina El Limon area rocks. Modal analyses and petrographic descriptions of samples are listed in Appendix II.

3.5.1 Cerro Los Portillos Formation (unit 1)

Cerro Los Portillos and Cerro Montosa, located immediately northwest of Telica, rise approximately 300 m above the plains to the north and northwest (Map 3). These two hills are the erosional remnants of an old volcano in the Telica Complex and are dissected by deep, radial gullies separated by narrow ridges. Alluvial fans occur at the lower end of these gullies, particularly on the western edge of Cerro Los Portillos. The Cerro Los Portillos Formation, named after the hill of the same name, outcrops as four exposures of gray, olivine basalt porphyry along the ridges.

A trough-like depression west of Cerro de Aguero (Map 3) is the only recognizable geomorphological volcanic feature. It is approximately 20 m deep and extends over 1500 m in a northerly direction.

Table 3.5 Description of volcanic units of the Telica Complex

Formation	Unit	Name	Phenocrysts	Groundmass
Telica	8c	Black pyroxene basalt porphyry tephra deposits	plag (An ₇₀₋₆₅) augite olivine (Fo ₇₅)	labradorite and clino- pyroxene microlites, opaques and sideromelane
Telica	8b	Gray pyroxene basalt porphyry flows	plag (An ₈₀₋₆₅) augite olivine (Fo ₈₅₋₈₀) orthopyroxene opaques	labradorite, clinopyroxene and olivine microlites, opaques, +/- sideromelane
Telica	8a	Gray pyroxene basalt porphyry lapilli and ash	plag (An ₈₀₋₇₀) augite opaques	labradorite microlites and sideromelane or tachylite glass
	7	Gray andesite porphyry flows	plag (An ₈₅₋₆₀) +/- augite opaques	andesine and clinopyroxene microlites, opaques and and intersertal glass
San Jacinto	6*	Brown or orange- brown altered basalt lapilli- stone and tuff	plag augite olivine	reddish-brown to black glass
Santa Clara	5	Gray olivine basalt porphyry flows and tephra	plag (An ₇₅₋₇₀) opaques olivine (Fo ₈₀)	labradorite and augite microlites, opaques and minor glass
Cerro de Aguero	4	Gray olivine andesite porphyry flows and tephra	plag (An ₈₀₋₇₀) opaques olivine (Fo ₇₅)	labradorite and augite microlites, olivine, opaques and glass
El Najo	3	Gray olivine pyroxene basalt porphyry flows	plag (An ₈₀₋₇₅) augite olivine	labradorite and clino- pyroxene microlites, opaques and intersertal glass
La Ceiba	2	Grey and red pyroxene andesite flows	plag (An ₈₅₋₆₅) bronzite opaques +/- olivine	plagioclase and clino- pyroxene microlites in glass
Cerro Los Portillos	1	Gray olivine basalt porphyry flows	plag (An ₈₅₋₆₀) olivine (Fo ₉₅₋₈₅) +/- augite	labradorite and clino- pyroxene microlites, opaques, minor glass

* Mineralogy only for the essential fragments.

It is the remnant of a leveed lava flow.

Tephra of the San Jacinto and Telica Formations outcrops on the summit and flank of Cerro Los Portillos and Cerro Montosa respectively and are presumed to overlie basalts of the Cerro Los Portillos Formation. The base of the Cerro Los Portillos Formation is not exposed.

Cerro Los Portillos Formation basalts have a smooth, whitish- to brownish-gray weathered surface and a light-gray, fresh surface. Colourless to white plagioclase phenocrysts (<3 mm) form about 40 vol. % of the rock and are set in a sparsely vesicular, aphanitic groundmass. Petrographic study reveals abundant phenocrysts and glomerophenocrysts of essential plagioclase and microphenocrysts of accessory olivine and opaques. The phenocrysts are set in an intergranular groundmass of labradorite and clinopyroxene microlites (Plate 3.8). Opaque grains are abundant in the groundmass; glass is sparse.

Euhedral plagioclase (<3 mm) phenocrysts (An_{85} to An_{60}) show both albite and Carlsbad twins. Concentric zones of glass inclusions occur in some plagioclase phenocrysts, and both normal and oscillatory zoning is present in a small number of phenocrysts.

Rounded to subhedral olivine phenocrysts (Fe_{95} to Fe_{85}) range up to 1 mm in diameter; olivine is not common in the groundmass. In some specimens olivine is mantled by a thin layer of clinopyroxene. Most of the olivine is partially altered to iddingsite, probably of deuteric origin. Olivine is associated with, and has inclusions of, subhedral magnetite crystals less than 1 mm in size.

Clinopyroxene occurs in small amounts (<1.7 vol. %) in a number of samples. The euhedral augite ($2V=40^{\circ}-60^{\circ}$) phenocrysts have weak

Plate 3.8 Photomicrograph of Cerro Los Portillos Formation basalt with labradorite and minor, rounded olivine phenocrysts. Field of view is 5 mm. Crossed nicols.

Plate 3.9 Contorted and fragmented layering with feldspar laths in La Ceiba Formation andesite near El Arenal.

pleochroism (alpha-pale brown, beta-pale brown, gamma-pale brown) and some show simple twinning.

These basalts were effused from a volcano, now largely eroded, of which the Cerro Los Portillos and Cerro Montosa hills are probably remnants.

3.5.2 La Ceiba Formation (unit 2)

Andesite flows form the La Ceiba Formation and these outcrop on the semi-circular La Ceiba somma ridge. The latter, a 2.5 km long semi-circular ridge, has steep interior walls up to 0.2 km high and is breached to the northeast. The arc described by the ridge has a radius of 0.6 km. The Telica Este crater may cover the western portion of the ridge assuming it was once a circular feature. The pyroxene andesite flows form one of the more extensive units in the Telica Complex and outcrop south of Telica and north of San Jacinto (Map 2).

La Ceiba Formation lavas vary from 3 to 15 m in thickness and exhibit steep, eroded flow margins that can be traced for distances of up to a kilometre. The outcrop pattern suggests a small number of simple flows. An exposure of a La Ceiba lava, west of Santa Clara, reveals a gradation from a flow-top breccia into a flow-layered core. Massive andesites on the walls of the La Ceiba somma ridge may be thick flows or hypabyssal intrusions.

South of Telica the La Ceiba Formation lavas are overlain by Santa Clara Formation and Porvenir Formation lavas and San Jacinto Formation tephra. The close proximity between outcrops of the El Najo and La Ceiba Formations north of San Jacinto suggests that the two units are stratigraphically close to one another.

The flows weather to a gray or reddish-gray colour and, commonly, exhibit discontinuous layering reflected by gray, purplish-brown, pinkish-gray and red colours on the fresh surface (Plate 3.9). Red flow breccias are found in some outcrops. Vesicles, less than 0.5 mm long, make up between 0.7 to 8 vol. % of the rock. The vesicles are locally filled with chlorite(?) or with amorphous secondary minerals. White plagioclase phenocrysts (<2 mm) are ubiquitous and commonly exhibit a fluidal texture. Small phenocrysts of pyroxene or olivine were observed in some samples and larger pyroxene phenocrysts (<2 mm) occur in outcrop near La Ceiba.

Plagioclase and pyroxene phenocrysts are set in a hyalopilitic groundmass of plagioclase and pyroxene microlites and a dark glass (Plate 3.10). The labradorite to andesine microlites exhibit swallowtail terminations and commonly form a felty or fluidal texture. The groundmass is charged with hematite indicating extensive oxidation. Dark-coloured flow layers contain more glass, orthopyroxene crystals and vesicles than the light-coloured layers. The plagioclase and opaque phenocrysts are equally abundant in both dark and light flow layers.

Lath-like, anhedral to subhedral, bytownite to labradorite phenocrysts (An_{85} to An_{65}) generally show continuous normal zoning. The plagioclase phenocrysts (10 to 34 vol. %) reach a maximum length of 4 mm. They commonly have rounded terminations, probably the result of resorption. Some crystals have concentric zones of glass or glass-pyroxene-opaque inclusions. Plagioclase, pyroxene or combinations of the two minerals form glomerophenocrysts.

Anhedral bronzite or enstatite phenocrysts, less than 2 mm across, make up 0.5 to 5 vol. % of the flows. Orthopyroxene does not occur

Plate 3.10 Photomicrograph of La Ceiba Formation andesite showing large labradorite phenocrysts and oval hypersthene grains set in a groundmass of glass, plagioclase microlites, opaques and minor pyroxene cristolites. Field of view 2.2 mm.

Plate 3.11 Platy joints in El Najo Formation basalt in a stream valley east of Cerro de Aguero.

in the matrix. The pyroxene crystals are typically pleochroic (alpha - light pink, beta - pale brown, gamma - pale green) with $2V_a = 80^\circ$ to 95° . Inclined extinction is common despite the fact that these are orthopyroxenes. These orthopyroxene crystals are probably similar to the "monoclinic hypersthene" described by Verhoogen (1937) from several Cascade volcanoes. However, Deer et al. (1963) point out that monoclinic (Mg,Fe)-pyroxenes have never been substantiated.

Subhedral magnetite grains, which make up 0.3 to 1.3 vol. % of the rock, are commonly found associated with the orthopyroxene phenocrysts. Anhedral olivine crystals (<1 vol. %) are partially altered to iddingsite. One sample (#467) contains trace amounts of small, hornblende phenocrysts rimmed by opaques.

La Ceiba Formation lavas outcrop on the La Ceiba somma ridge and the southwestern rim of the San Jacinto crater. These are the only two geomorphological features associated with the La Ceiba Formation that could be volcanic vents. The predominance of andesite on the La Ceiba ridge indicate that the La Ceiba Formation erupted from a vent inside the La Ceiba somma ridge.

Felsic volcanic rocks reported in the El Chorro region near San Jacinto (Map 3) by Dartmouth College students (Stoiber, personal communication, 1978) may belong to the La Ceiba Formation.

3.5.3 El Najo Formation (unit 3)

Some of the best exposures of the El Najo Formation basalts are along stream valleys, scarps and roads in the northeastern part of the map area centred on the El Najo farm (Map 3).

Although not directly overlain by any other unit in outcrop, both the San Jacinto Formation and Telica Formation tephra flank exposures of the El Najo Formation and are inferred to cover it elsewhere. The outcrop distribution of the El Najo and La Ceiba Formations indicates they are in contact with each other. Near El Desmonte the El Najo Formation basalt outcrops are located upslope from a La Ceiba Formation lava scarp and are believed to overlie the andesite. The base of the El Najo Formation is not exposed.

The olivine pyroxene phyric basalts are gray on fresh surfaces and typically weather to a reddish-orange colour. Vesicles (2 to 15 vol. %) have irregular boundaries, simple forms and are up to 5 mm long. In some flows the vesicles are partially to completely filled with carbonate. Several flows exhibit platy joints spaced at 2 to 4 cm intervals (Plate 3.11).

Phenocrysts of clinopyroxene, plagioclase, opaques and olivine are contained in an aphanitic, hypocrystalline, intersertal to hyalopilitic groundmass of labradorite microlites, glass, opaques and clinopyroxene (pigeonite?) cristolites. Plagioclase microlites define a fluidal texture.

Bytownite phenocrysts are normally zoned (An_{85} to An_{75}) and some contain concentric bands of pyroxene, opaques and glass inclusions. Plagioclase occurs as euhedral laths, up to 3mm in length, and forms between 15 and 25 % of the sample by volume. Both Carlsbad and albite twins are common. Plagioclase, clinopyroxene and minor opaque crystals form glomerophenocrysts.

Subhedral augite phenocrysts ($<2mm$) exhibit simple twins, and some

contain glass, opaque or olivine inclusions. They are weakly pleochroic (alpha - pale green, beta-pale green-brown, gamma - very pale green) with positive sign, and moderate $2V$ (40° - 60°). One flow south of Telica is characterized by pyroxene phenocrysts up to 8 mm in length.

Olivine, up to 2 vol. %, occurs as small ($< .5$ mm), anhedral, rounded phenocrysts commonly altered to iddingsite at their borders. Hematite is associated with the ferromagnesian phenocrysts.

Exposures of the El Najo Formation are roughly centred on the San Jacinto crater and also outcrop on the crater rim. The San Jacinto crater may therefore have been the eruptive centre for these lavas.

3.5.4 Cerro de Aguero Formation (unit 4)

Cerro de Aguero is a composite volcano due north of Telica that reaches a maximum elevation of 720 m (Plate 3.12). Gray, olivine basalt porphyry flows and tephra (Cerro de Aguero Formation) outcrop on the upper flanks and summit of Cerro de Aguero.

At the summit of Cerro de Aguero a shallow U-shaped trough trends in a northeasterly direction. East of the summit are two small depressions which occur at elevations of 700m. The flanks on Cerro de Aguero are cut by gullies more than 5 m deep. A lava flow on the northern side of the cone forms a ridge.

Cerro de Aguero is located near the western end of the El Azucenal somma ridge (Table 3.3). The ridge, breached to the north and south, is partially buried by later volcanic materials. The ridge consists of two

Plate 3.12 The symmetrical Cerro de Agüero cone as seen from Telica's crater rim. Immediately to the left of Cerro de Agüero is the El Azucenal somma ridge.

Plate 3.13 Lapilli deposits on the upper western flank of Cerro de Agüero:

segments, 2.5 and 1.6 km in length, and has maximum relief of 0.4 km.

Cerro de Aguero Formation lavas and tephra are overlain by San Jacinto Formation tephra. Although the basal contact of the Cerro de Aguero Formation was not seen, the distribution and relative elevations of the various formations suggest that the Cerro de Aguero Formation rests on lavas from the Cerro Los Portillos, La Ceiba and El Najo Formations (Map 3).

Accumulations of red-weathering scoria at least 7 m thick occur on the southern and western flanks (Plate 3.13). The ash and lapilli deposits are commonly bedded and at one locality dip at 25 degrees away from the top of the cone. The largest fragments, 10 cm long, occur in a partially-welded, lapilli layer exposed on the southern flanks. The flows are variably vesicular and commonly exhibit flow-top brecciation. Vesicles, up to 6 mm in size, are partially filled by an amorphous white mineral, possibly cristobalite. Plagioclase phenocrysts, up to 4 mm in length, are abundant (>20 vol. %) in all extrusive products of Cerro de Aguero. Minor amounts of olivine phenocrysts with associated iddingsite are present.

Petrographic study reveals plagioclase and olivine phenocrysts set in a hypocrystalline groundmass of labradorite and augite microlites, olivine, opaque minerals and variable amounts of glass. The groundmass is hyalophitic, intersertal or hyalopilitic. In one sample the glass contains abundant, fine-grained hematite.

The subhedral bytownite phenocrysts (An_{70} to An_{80}), with ragged terminations, form glomerophenocrysts rimmed by late-stage feldspar.

Strong oscillatory zoning is common and sericite and hematite partially replace plagioclase.

Euhedral olivine phenocrysts (some embayed) are less than 2 mm long, and can occur, along with plagioclase, as glomerophenocrysts. Iddingsite alteration along fractures is common and some phenocrysts are completely replaced. Small, anhedral magnetite grains are commonly clustered with, or included in, olivine phenocrysts.

Although historically inactive, Cerro de Aguero has a very well preserved volcanic cone indicating recent volcanic activity. The limited distribution of the rocks of the Cerro de Aguero Formation reflects the small volume of effused and ejected material and suggests the explosive eruptions were not particularly strong.

3.5.5 Santa Clara Formation (unit 5)

The symmetrical composite cone of Santa Clara (San Jacinto) reaches a maximum elevation of 865 m (Map 3). A few major radial gullies are developed on the southwestern flanks and a major arcuate gully on the northern side breaches the basin-shaped depression at the cone's summit (Plate 3.14). A small circular crater occurs on the eastern rim of the summit depression. The eastern flank of Santa Clara is covered by spatter and lavas.

The Santa Clara Formation, named after the volcano of the same name, is composed of basaltic lavas and tephra. Rocks of this Formation outcrop on Santa Clara's cone and form scarps up to 15m high to the south and east of the base of the volcano. The lavas extend up to 3 km from the volcano. The flows are commonly massive and some exhibit

Plate 3.14 The southern half of the Marrabios Range as seen from an airplane above Telica. Santa Clara is in the foreground.

Plate 3.15 Santa Clara Formation basaltic agglutinate on the upper flanks of Santa Clara.

flow brecciation. Agglutinate deposits crop out on the northeast slope of Santa Clara near the summit (Plate 3.15), while red scoria deposits occur on the southern flank and southwest of Santa Clara.

Santa Clara Formation basalts are believed to rest on La Ceiba and El Najo Formation flows. Near the base of the cone San Jacinto Formation tephra overlies Santa Clara flows. If the absence of any outcrops of the San Jacinto Formation tephra on the Santa Clara cone is due to burial by younger Santa Clara rocks, then the Santa Clara Formation could be in part older, and in part younger, than the San Jacinto Formation.

Scoria, agglutinate and lavas of the Santa Clara Formation, although markedly different in physical appearance, are very similar in mineralogical composition. Gray on the fresh surface, the basalts commonly contain plagioclase phenocrysts (>25 vol. %) and irregularly-shaped vesicles up to 5 mm in length. Some vesicles are partially filled with a white, botryoidal mineral. Large plagioclase (5 to 9 mm, with pinkish cores), olivine and sparse clinopyroxene phenocrysts are visible in hand specimen. Phenocrysts are set in a hypocrySTALLINE, intergranular matrix of labrad~~orite~~ and augite microlites, opaques and minor glass (Plate 3.16). In the vitrophyric tephra the groundmass is sideromelane.

Bytownite phenocrysts (An_{75} to An_{70}) form euhedral to subhedral laths (< 5mm); some crystal faces are irregular, perhaps due to partial resorption. Albite, Carlsbad and Pericline twins are common, and infrequent opaque and glass inclusions are irregularly distributed throughout the feldspar laths. The laths exhibit weak normal or oscillatory zoning. Most samples are characterized by the presence of

• Plate 3.16 Euhedral laths of plagioclase, subhedral olivine crystals and vesicles set in a groundmass of plagioclase microlites, magnetite and glass. Santa Clara Formation basalt. Field of view is 2.2 mm.

Plate 3.17 San Jacinto as seen from Santa Clara.

plagioclase glomerophenocrysts.

Accessory, anhedral to subhedral, olivine phenocrysts (Fo_{80}) are commonly altered to iddingsite along fractures; some olivine crystals are embayed. In one sample the olivine is embayed and rimmed by small augite microlites. Magnetite inclusions occur in a few olivine phenocrysts.

Accessory, subhedral augite phenocrysts occur in several samples, closely associated with olivine and opaque phenocrysts. The augite has been partially altered to hematite. The anhedral to subhedral magnetite phenocrysts ($<0.75\text{mm}$) constitute less than 1 vol. % of the flows.

Small gas cavities (3 vol. %) in a holocrystalline basalt in Santa Clara's summit crater, are partially filled with euhedral crystals of clinopyroxene. These cavities are probably segregation vesicles filled by high temperature minerals during the final stages of crystallization. The same basalt exhibits small micropegmatitic patches. Less than a hundred metres from the summit crater there is an agglutinate outcrop of the same unit (Plate 3.15). The agglutinate is solidified spatter possibly derived from a lava lake in Santa Clara's crater. Holocrystalline basalt at the top of Santa Clara may be remnant of the lava lake. Lava lakes are common in Nicaraguan volcanic craters such as the Masaya crater south of Managua.

The effusive products of Santa Clara outcrop within 4 km of the vent. Lava flows form the majority of outcrops but several tephra deposits are found on the flanks of the volcano. There is no evidence of violent explosive activity associated with Santa Clara. The only

lapillistone deposits in the Telica Complex belong to the Santa Clara Formation.

3.5.b San Jacinto Formation (unit 6)

The oval-shaped San Jacinto crater is approximately 1.4 by 0.7 km in size and contains a flat-bottomed, kidney-shaped crater whose eastern and southern rim coincides with the San Jacinto crater walls (Map 3). The San Jacinto crater has an uneven floor and has been partially breached to the west and south. The highest point, at over 900 m, is the northwestern rim of the crater. The surrounding hills are rounded and dissected by gullies up to 25m deep (Plate 3.17).

The San Jacinto Formation is a bedded tephra deposit of distinctive brown or orange-brown colour which outcrops over much of the Telica Complex. It is named from the San Jacinto crater where it is best exposed. The interlayered lapillistones and tuffs contain framework-supported gray and orange scoria fragments (Plate 3.18). The tephra varies in thickness from 4 cm to more than 4 m. Orange, white and gray vesicular plagioclase phyric lapilli occur as layers or as scattered clasts in a friable tuff matrix. On the southern rim of the San Jacinto crater the tephra beds grade repeatedly upwards from coarse lapilli into tuff (Plate 3.18).

San Jacinto Formation tephra overlies rocks of the La Ceiba and El Najo Formations. A small outcrop of San Jacinto Formation lapillistone rests on Cerro de Aguero Formation rocks at the western summit of Cerro de Aguero. Lavas of the Santa Clara Formation at the base of Santa Clara are mantled by tephra of the San Jacinto Formation. Both white pumice, lapilli tuffs in road-cuts east of Telica and a terra blanca described by Steen (1978) may correlate with the San Jacinto tephra.

Plate 3.18 Tuff and lapillistone beds of the San Jacinto Formation grade upward. The grading is repeated twice. Outcrop on rim of San Jacinto crater.

Plate 3.19 Photomicrograph of San Jacinto Formation tuff shows vesicular glassy fragments in a groundmass of smaller fragments, shards and secondary minerals. Field of view 1.4mm.

The San Jacinto tephra consists of mafic volcanic fragments, crystal fragments, glass shards, and an altered groundmass as well as vesicles and cavities (Plate 3.19). One tuff sample consists of approximately 50 vol. % rock fragments, 35 vol. % vesicles and cavities, 10 vol. % groundmass and 5 vol. % crystal fragments. The fragments consist of sideromelane and tachylite shards and scoria, with fragments of porphyritic basalt and andesite. Plagioclase, augite, olivine and opaque crystals and crystal fragments, commonly with glass adhering to their edges, occur in a matrix of glassy ash, rock fragments and alteration minerals. Secondary minerals are pervasive and rocks of the San Jacinto are the only ones that are strongly altered outside the areas of geothermal activity.

The essential, vitrophyric fragments contain phenocrysts of plagioclase, augite and sparse olivine set in a black to reddish-brown glass. Euhedral plagioclase laths exhibit Carlsbad and albite twins and normal, continuous zoning (An_{70} to An_{90} for one lath). Tachylite shards are blocky and have concave embayments (partial vesicle walls) along their margins. Only a few stubby Y-shaped shards were noted. The vitrophyric fragments and vitric shards probably represent juvenile ejecta of the vesiculating magma. The petrographic characteristics of the vitrophyric fragments are similar to those of the olivine basalt porphyry in the walls of the San Jacinto crater.

The andesite and basalt rock fragments are subrounded, perhaps the result of milling during explosive ejection. Some show similar textures and mineralogy to the essential vitrophyric fragments, and may represent accessory fragments of lava or hypabyssal intrusions. Other rock fragments exhibit hyalopilitic to intersertal textures with plagioclase

phenocrysts and pyroxene and olivine microphenocrysts set in a groundmass of plagioclase microlites and glass. Aphanitic to holocrystalline fragments, mafic to intermediate in composition, are common.

The San Jacinto Formation is believed to have erupted from the kidney-shaped crater at the eastern end of the San Jacinto crater, where it attains its maximum thickness (Figure 3.3). The wide distribution of tephra is best explained by explosive vertical eruption of ash and lapilli followed by dispersal by wind. The accessory lithic fragments were probably derived from the walls of the San Jacinto crater and possibly from a pre-existing volcanic cone destroyed by the eruption. The majority of fragments are juvenile glassy lapilli and ash. The San Jacinto eruption was probably similar to, but smaller than, the explosive 1835 Plinian eruption of Cossequina which formed a large crater and deposited ash more than hundreds of kilometres from the volcano (Williams, 1952).

3.5.7 Corral Falso Andesite (unit 7)

Corral Falso andesite lavas outcrop in the northern parts of the map area. No Corral Falso lavas were found in contact with rocks of other formations. However, their location near the El Najo Formation flows and their state of preservation suggest that they are younger and overlie rocks of the El Najo Formation.

The gray lavas are mainly aphanitic, but can contain phenocrysts of plagioclase, olivine and pyroxene (<2.5 mm in length). Phenocrysts are set in an intergranular to intersertal groundmass of felty labradorite, andesine and clinopyroxene microlites, opaques and glass.

Figure 3.3. Isopach map of San Jacinto Formation lapillistone and tuff.

Abundant euhedral to subhedral laths of bytownite to labradorite phenocrysts (<2.5 mm) exhibit normal and oscillatory zoning as well as Carlsbad and albite twins. Some of the larger plagioclase phenocrysts contain inclusions of pyroxene and glass.

Subhedral augite phenocrysts (<2 mm) form up to 4 vol. % of the rock. Pale-green twinned augite can occur in glomerophenocrysts with plagioclase or opaques. In one sample bronzite phenocrysts are rimmed by clinopyroxene. Microphenocrysts (<0.3 mm) of rounded olivine (Fo₇₅) are present in minor amounts in one sample (1 vol. %). Trace to accessory amounts of magnetite phenocrysts occur in all samples.

The Corral Falso lavas are similar petrographically to an "olivine-augite basalt from a volcanic cone near the eastern base of El Liston volcano" (McBirney and Williams, 1965, p. 58). This is probably Cerro El Bosque, a small eroded Quaternary cone east of Telica (Map 1). No volcanic vent for the Corral Falso andesite was identified during the mapping.

3.5.8 Telica Formation (unit 8)

Telica is a reddish-hued, composite volcano with a central crater. The cone reaches a maximum elevation of 1060 m and is devoid of vegetation on its upper flanks (Plate 3.20). Telica's central crater is roughly elliptical in plan (700 m by 425 m) with a maximum depth of 400 m below the eastern rim (Creusot, 1977) and a high western rim (1060m). Within the crater there is a circular vent (approximately 325 m in diameter) at the east end, a U-shaped sloping depression to the west,

Plate 3.20 Black and red scoria outcrops on the western flanks of Telica in the gullies. Note the gentler slope on the southwestern flanks of the volcano to right of photograph.

and a wedge-shaped plateau to the south (Figure 3.4). The sides of the circular vent slope inwards to form a cylindrical pipe 75 m by 50 m in size (Geotimes, May, 1980). Poorly-consolidated volcanic materials from the crater rim have slumped into the vent producing a U-shaped sloping depression and an enlargement of the vent. Fluvial erosion has produced gullies (up to 20m deep) in the unconsolidated tephra on the steep western and southern slopes. On the south-southwest side a series of fractures on the upper flanks of the volcano probably reflect tensional extension due to mass movement downslope of the tephra deposits.

Basaltic flows and tephra from Telica are the youngest igneous rocks of the Telica Complex. The Telica Formation is named after the Telica volcano and is subdivided into the following members (Map 3):

- i) Basal Tephra Member;
- ii) El Porvenir Lava Member;
- iii) El Pegon Lava Member;
- iv) La Martinez Lava Member;
- v) Los Ranchos Lava Member;
- vi) Terminal Lava Member; and
- vii) Upper Tephra Member;

For the sake of convenience the El Porvenir, El Pegon, La Martinez and Los Ranchos Lava Members are sometimes referred to collectively as the flank lavas.

3.5.8.1 Basal Tephra Member (unit 8a)

The Basal Tephra Member consists of gray, pyroxene basalt porphyry tephra deposits which outcrop on the southern and western flanks of Telica in the deeper gullies, near El Desmonte, and on Cerro Montosa

Figure 3.4 Sketches of the Telica Complex and Telica.

(Map 3). On the western flanks of Telica the tephra is more than 2 m thick (Plate 3.21), but it is difficult to trace this unit away from Telica because the land is cultivated and the ash has been mixed with soil.

The Basal Tephra Member deposits overlie basalts of the Cerro Los Portillos Formation. The El Porvenir, El Pegon and Terminal lava members and Upper Tephra Member rocks rest on rocks of the Basal Tephra Member. Intercalated with rocks of the Upper Tephra Member are fluvial conglomerates, sandstones and epiclastic breccias of unit 9.

The tephra consists of interbedded ash and lapilli with minor agglomerate. The ash beds are black, and the lapilli beds commonly red. Individual beds, from 2 cm to more than one metre thick, are found in gulleys on the western and southern flanks of Telica. In some gullies there are exposures up to 3 or 4 metres thick that exhibit no bedding.

Fragments in the tephra contain up to 42 vol. % oval vesicles (< 2 mm long) with smooth walls. The fragments are gray on a fresh surface and contain plagioclase (1-2 vol. %, < 3 mm long) and pyroxene (1.5-7 vol. %, < 1.5 mm long) phenocrysts set in an hyalopilitic groundmass of sideromelane or tachylite glass and labradorite (An_{55}) microlites (Plate 3.22). Olivine and opaque phenocrysts are also found in some beds. The glass in the groundmass is typically charged with hematite. Anhedral opaque grains and/or pyroxene microlites occur in the glassy groundmass in some samples. Some vesicles are partially filled with glassy shards and crystal fragments of clinopyroxene, plagioclase and olivine.

The bytownite phenocrysts (An_{90} to An_{70}) are predominantly

Plate 3.21 Bedded ash and lapilli of the Basal Tephra Member in a gulley on the western flanks of Telica. Rocks of Upper Tephra Member form a thin veneer on top.

Plate 3.22 Photomicrograph of highly vesicular Telica Basal Tephra Member. Phenocrysts of augite and plagioclase are set in a matrix of glass. Field of view is 2.2 mm. Crossed nicols.

ehedral laths that show both Carlsbad and albite twins and normal oscillatory zoning. Rings or irregular patches of glass inclusions are found in the plagioclase; one phenocryst has five concentric zones of glass inclusions. Clinopyroxene is the only other phase that occurs as inclusions in plagioclase.

Euhedral augite phenocrysts (0.25 to 2 mm in size) are colourless to pale green in thin section. In two samples the phenocrysts are embayed. The augite is biaxial positive with a large extinction angle ($2Ac=46^\circ$) with simple twins. Opaque inclusions are common. In one sample olivine is rimmed by augite.

Trace amounts of subhedral olivine ($Fe_{0.95}$) phenocrysts occur in one sample. The olivine microphenocrysts are <1 mm in size, embayed and altered to hematite.

The ash and lapilli are well-bedded and consist exclusively of juvenile scoria, both characteristic features of airfall pyroclastic rocks. The tephra was probably ejected by Strombolian eruptions similar to those documented during historic Telica eruptions. The greater volume and wider distribution of the Upper Tephra Member compared to the historic eruptions of ash suggests more powerful and sustained explosive eruptions of Telica in the past than have been seen. Thick deposits of the Upper Tephra Member blanket the western and southern slopes of Telica indicating that the prevailing wind direction during the eruption was to the southwest.

3.5.8.2 El Porvenir Lava Member (unit 8bpv)

The El Porvenir Lava Member is named after the small village of El Porvenir at the foot of the lava flows and consists of the San Rafael,

Los Canales and El Guanabo flows. It can be traced over a distance of 7.9 km (Map 3).

The El Porvenir Lava Member overlies the La Ceiba and San Jacinto Formations and near Telica underlies the Upper Tephra Member.

The lavas are gray on the fresh surface with abundant glassy or white plagioclase (<4mm), glassy, brown olivine (<2mm) and dark green pyroxene phenocrysts (<2.5mm). Glomerophenocrysts of plagioclase with either olivine or pyroxene phenocrysts can reach up to 14 mm in size. The groundmass is massive and granular in the cores of flows; at the margins the flows become glassy and vesicular. The vesicularity varies from less than 6 vol. % in the centre of the flow to greater than 24 vol. % in the surface scoria. The vesicles (<15 mm in length) have simple shapes and a smooth black coating on their walls. Gas cavities, up to 4 cm in maximum dimension, can occur in the surface scoria.

Phenocrysts are set in an intersertal to intergranular groundmass of labradorite and olivine microlites, clinopyroxene cristolites, fine opaque grains and brown glass. Samples from the cores of the flows contain little glass and exhibit an intergranular texture. The bytownite to labradorite phenocrysts are typically euhedral laths with abundant Carlsbad and albite twins and minor pericline twins. The phenocrysts contain inclusions of glass and clinopyroxene, usually found as concentric bands. Normal oscillatory and continuous zoning are seen in up to 20 vol. % of the feldspar phenocrysts. Weakly pleochroic (alpha = pale green, gamma = pale green and beta = very pale pink), subhedral to euhedral augite phenocrysts can show corroded margins. Inclusions of magnetite are common in the

matrix; plagioclase, olivine, and orthopyroxene (cores) inclusions in the augite are less common. Magnetite phenocrysts reach a maximum length of 0.5 mm.

Subhedral olivine phenocrysts (Fe_{80} to Fe_{85}), rimmed by opaque minerals, are strongly embayed in some samples. Hematite and/or iddingsite alteration can occur along fractures in the olivine. Olivine can occur in the cores of clinopyroxene phenocrysts.

The El Porvenir Lava Member flows probably erupted from a vent on the southwest flank of Telica which is now covered by tephra.

All lava flows of the Telica Formation exhibit the same mineralogy and textures as the El Porvenir Lava Member. However, there are changes in abundance and composition of the phenocryst phases among flows. For this reason, only the abundances and compositions of the phenocryst phases, as well as the thickness and distribution of the individual flows will be discussed in subsequent sections.

San Rafael Flow

The San Rafael Flow is an aa lava which has an average thickness of 3.7 m. This flow has a relatively flat top and extends 4 km from El Pozo to north of a power line where it is covered by the Los Canales Flow (Map 3). A cross-section of the flow can be seen in a road-cut near San Rafael.

The flow contains plagioclase (An_{65} to An_{80} ; 20-40 vol. %), augite (2-2.5 vol. %), olivine (Fe_{85} ; 3.7-4.8 vol. %) and magnetite phenocrysts. Plagioclase microlites in the matrix have the composition An_{50} to An_{55} .

Los Canales Flow

A simple aa lava, the Los Canales Flow averages 5.3 m thick. The surface of the flow has up to 4 m of relief and extends 5.7 km from El Porvenir to El Guanabo, where it is overlain by the El Guanabo Flow.

The flow-top scoria at the foot of the Los Canales Flow is used as a source of road-building material because of its proximity to Highway 24. At the edge of the quarry, a large accretionary lava ball lies directly on the flow (Plate 3.23). Approximately 3 m in diameter, it consists of a lava rind surrounding a semi-consolidated core of basaltic fragments set in a red, fine-grained matrix (Plate 3.24). The basaltic fragments are identical in composition to the underlying flow.

The basalt contains 32 vol. % plagioclase (An_{65}), 9.6 vol. % augite, 1.9 vol. % bronzite, 0.8 vol. % olivine and sparse magnetite phenocrysts.

El Guanabo Flow

The El Guanabo Flow surface is a complex series of leveed channels, solidified lava rivers and pressure ridges (Map 3). At the margins the thickness varies between 1 m and 5.5 m, while the flow's surface relief can reach 5 m. The flow extends from the base of Telica's cone to El Guanabo.

The flow contains 26 to 29 vol. % plagioclase (An_{75} to An_{65}), 6.7 to 11.6 vol. % augite, 2.6 to 3.7 vol. % olivine (Fe_{80} to Fe_{85}) and less than 2.3 vol. % magnetite phenocrysts.

Plate 1.23 A large accretionary lava ball at the edge of a quarry at the toe of Los Canales Flow. The reddish scoria overlying the massive core of the flow is clearly visible. The red basal scoria can be seen immediately above the hood of the jeep.

Plate 3.24 Close-up of lava ball on the Los Canales Flow showing clasts of lava in a reddish matrix surrounded by a rind of lava. The centre of the underlying flow can be seen at the bottom of the photograph.

3.5.8.3 El Pegon Lava Member (unit 8bm)

The El Pegon Lava Member extends over 6.2 km from Telica and is named after the El Pegon farm near the toe of the flow. The La Guatuzá and Los Cedros flows make up the El Pegon Lava Member. The upper part of the Los Cedros Flow is partially covered by the La Guatuzá Flow. Both flows erupted laterally from the same vent on the southern flanks of Telica. The vent is covered by tephra deposits.

Los Cedros Flow

The Los Cedros Flow is an aa lava (Plate 3.25) which extends from the base of Telica's cone to El Pegon. A lobe of the flow almost reaches Highway # 26 where the flow-top breccia has been quarried for construction materials.

The Los Cedros Flow contains 17.9 to 36.1 vol. % plagioclase (An_{70}), 2 to 5.9 vol. % augite, 2.7 to 4.2 vol. % olivine (For_{90}), less than 0.8 vol. % magnetite and trace orthopyroxene phenocrysts.

La Guatuzá Flow

The Guatuzá Flow extends 2.5 km from the base of Telica's cone to the Guatuzá farm. The toe of the flow is marked by a steep scarp approximately 8 m high. The basalt contains 27.6 vol. % plagioclase, 5.4 vol. % augite, 3.2 vol. % olivine and 0.4 vol. % magnetite phenocrysts.

3.5.8.4 La Martinez Lava Member (unit 8bm)

Composed of the El Arenal and Cura flows, the La Martinez Lava Member has length of 3.9 km. The Cura Flow fills and partially overflows the rim of the Telica Este crater. The upper portion of the

Plate 3.25 A cross-section of Los Cedros Flow showing the massive core of the flow sandwiched between flow breccias. The top and bottom contacts of the basal flow breccia are marked by the hat and hammer head respectively. The subjacent alluvium is baked red.

El Arenal Flow is overlain by the Cura Flow on the flanks of the Telica Este Crater. The El Arenal Flow extends as far as the El Arenal farm.

El Arenal Flow

The El Arenal aa flow averages 10 m in thickness. Although the head of the flow is covered by the Cura Flow, the source of the El Arenal Flow is probably an eruption from the east flank of Telica, immediately adjacent to the Telica Este crater. The flow contains 33.4 vol. % plagioclase, 5.5 vol. % augite, 2.8 vol. % olivine (Fe_{85}) and 0.5 vol. % magnetite phenocrysts.

Cura Flow

The semi-circular ridge of the Telica Este crater encloses a shallow depression that has been partially filled by the Cura Flow, and possibly the El Arenal Flow. The Cura Flow spills over the southern lip of the Telica Este crater and extends part way down the flank of the crater. Within the crater there are numerous pressure ridges on the surface of the flow and substantial levees along the flow margins. The Cura Flow erupted laterally from the east flank of Telica.

The Cura Flow phenocrysts are made up of 33.4 vol. % plagioclase (An_{65}), 5.5 vol. % augite, 2.8 vol. % olivine and 0.5 vol. % magnetite.

3.5.8.5 Los Ranchos Lava Member (unit 8br)

On the north side of Telica, the Los Ranchos Lava Member consists of the El Azucenal and underlying Santa Elena flows (Map 3). There is possibly a portion of a third older flow exposed southwest of El Carol and on the eastern border of Santa Elena. The lava member extends from

Telica's cone to the El Arenal and Los Ranchos farms. These aa flows are relatively thin (<5m). The El Azucenal Flow contains 32.7 vol. % plagioclase (An_{80} to An_{75}), 7.4 vol. % augite, 3.7 vol. % olivine (Fe_{80}), 0.4 vol. % magnetite and trace amounts of bronzite phenocrysts.

3.5.8.6 Terminal Lava Member (unit 8t)

Elongate flows less than a metre thick and several metres wide are found in gullies on Telica's flanks. These lavas belong to the Terminal Lava Member and are usually gray or black on the weathered surface.

Some flows are covered with a scoriaceous aa breccia while others have a smooth, ropy pahoehoe surface.

The Terminal Lava Formation is interbedded with epiclastic deposits of unit 9 (Plate 3.26) and directly overlies the Basal Tephra and El Pegon Lava Members. The Upper Tephra Member overlies some Terminal Lava Member flows.

The lavas are compositionally similar to the other lava members in the Telica Formation, in spite of the fact that they are the only flows to exhibit pahoehoe flow morphology. Plagioclase (An_{85} to An_{80}), augite (1.8-13.0 vol. %), olivine (1.6-4.5 vol. %) and magnetite (0.6-3.5 vol. %) phenocrysts are set in a groundmass of plagioclase microlites (An_{50}), pyroxene microlites, glass and vesicles. Trace amounts of orthopyroxene phenocrysts occur in several flows.

3.5.8.7 Upper Tephra Member (unit 8a)

A thin veneer of black, olivine pyroxene basalt porphyry ash, lapilli, agglomerate and breccia covers Telica's cone, Telica Este crater and the older rocks immediately to the west and southwest of

Plate 3.26 Terminal Lava Member basalt flow resting on a fluvial conglomerate which in turn overlies a lahar. The hat marks the contact between the conglomerate and the flow. The hammer head rests on a large fragment in the lahar.

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Telica. The Upper Tephra Member varies in thickness from several metres on the western flanks of Telica to less than several centimetres at a distance of 2 kilometres southwest of the volcano. It is deposited mainly in areas west of Telica.

The Upper Tephra Member overlies the Basal Tephra Member and the El Porvenir, El Pegon, La Martinez and Los Ranchos lava members near Telica's cone. Map unit 9 overlies the Upper Tephra Member in some gullies.

The coarser tephra deposits found on the upper flanks of Telica's cone weather to a distinctive reddish-brown hue (Plate 3.20). These tuff-breccia or lapilli tuff deposits have a mud matrix formed from ash, although much of the ash from the surficial tephra deposits has been removed by running water leaving lag deposits with correspondingly higher proportions of lapilli- and breccia-size fragments (Plate 3.3). The indurated lapilli tuff and tuff-breccia form a surface veneer that is relatively resistant to erosion until it has been breached. A similar "armour plate" has been described on Crater Elegante in Mexico (Gutmann, 1976, p. 1726).

Fusiform, ribbon, accretionary (Heiken, 1978) and scoria bombs and angular blocks of basalt form the breccia component of the Upper Tephra Member (Plate 3.27). Blocks (up to 4 m in size) are just as abundant as bombs (up to 8 m in size) in the tuff-breccia deposits. The largest block (4 by 3 m) is located on the southern rim of the crater approximately 150 m from the vent. The blocks have smooth,

Plate 3.27 Telica Tephra Member with a particularly large ribbon bomb surrounded by angular blocks and other bombs on the north rim of Telica.

pinkish-white, weathered surfaces and are weakly vesicular. Similar mineralogically to the bombs, they are believed to be fragments of sills, dikes and flows ripped from the crater walls. Some fragments are gabbroic.

The tephra deposits are gray or black in colour on the fresh surface and strongly vesicular. Plagioclase forms ubiquitous phenocrysts, less than 3.5 mm long. Small olivine phenocrysts are visible to the naked eye. Some of the pyroclasts are coated with sulphur from the solfateric activity in the vent.

Phenocrysts of plagioclase, clinopyroxene, olivine and opaques rest in an aphanitic groundmass. The essential ejecta contains labradorite and clinopyroxene microlites, variable amounts of magnetite, and intersertal sideromelane glass. The accessory blocks and lapilli typically have labradorite microlites, abundant magnetite grains, minor pyroxene cristolites and little or no glass.

Plagioclase phenocrysts (An_{65} to An_{70}) with abundant glass inclusions are found in the essential ejecta. Euhedral plagioclase laths (< 5 mm) are commonly twinned (Carlsbad, albite and pericline) and show both continuous and oscillatory zoning. Glomerophenocrysts of plagioclase, and occasionally plagioclase and clinopyroxene, are common. Clinopyroxene can be poikilitically enclosed by plagioclase.

The augite phenocrysts are euhedral (< 3 mm) and light green in colour. Olivine phenocrysts (Fe_{75}) are small (< 1 mm), subhedral to rounded, commonly rimmed by clinopyroxene and altered to iddingsite. Opaque phenocrysts, subhedral and less than 0.75 mm in maximum

dimension, are closely associated with the olivine and clinopyroxene phenocrysts. Opaque inclusions are common in these two minerals.

The accessory pyroclasts are generally similar in composition to the essential or juvenile ejecta, although they are less vesicular.

The Upper Tephra Member was produced by sporadic Strombolian eruptions over at least the last 245 years (section 3.2) and the limited distribution of the tephra suggests that these eruptions were relatively weak. The tephra is probably thickest and most extensive west of Telica because the predominant wind direction during eruptions was westerly.

The present shape of Telica's edifice reflects the construction and subsequent partial destruction of at least three successive edifices. The oldest cone, lower than Telica's present edifice, is buried except for the "shoulder" area on the northern flank of the cone at an elevation of 850 m (Plate 3.1). Near the northwest edge of Telica's crater there is a 0.4 km long somma ridge (Figure 3.4, Plate 3.2). This is the only distinguishable feature of an intermediary cone. The present cone rests upon, and almost completely covers, the two older edifices.

3.5.8.8 Modal Mineralogy of Rocks of the Telica Formation

Twenty-nine samples of the Telica Formation were examined and their modal abundances and vesicle contents determined. The principal objective was to identify any changes in mineralogy and vesicle content with stratigraphic position. The latter was determined using simple field criteria such as superposition and distance from source within a given flow. Three samples from the Upper Tephra Member are blocks of

Figure 3.7 The volume of open spaces in the Telica Formation rocks against eruptive sequence.

unknown stratigraphic position and they are not plotted on Figures 3.5 and 3.6.

All Telica Formation rocks are vesicular and contain from 2 to 43 vol. % open spaces (Appendix II). Vesicles in the tephra make up more than 25% of the rock, while the lavas typically contain less than 20 % (Figure 3.5). Modal abundances of Telica Formation rocks have been recalculated to 100% without vesicles (Table II-3) because the vesicle content of a mafic volcanic rock depends principally on the mode of formation, not its original composition. Rose et al. (1978) used the same approach for samples of the Fuego volcano.

Using this approach, the phenocryst abundances exhibit considerable variation when plotted against stratigraphic position (Figure 3.6). Two important conclusions can be drawn from Figure 3.6:

- 1) plagioclase and olivine phenocrysts are more abundant in the Upper Tephra Member than in the Basal Tephra Member; and
- 2) the plagioclase and clinopyroxene abundances are lowest in the initial flows of the El Porvenir and El Pegon Lava Members.

On the basis of plagioclase and clinopyroxene phenocryst abundances rocks of the Telica Formation can be divided into phenocryst-poor (< 25 vol. % plagioclase and < 5.9 vol. % clinopyroxene) and phenocryst-rich groups. The Basal Tephra Member, San Rafael Flow, lobe of Los Cedros Flow near Highway # 26 and a Terminal Lava Flow on the northwest flank of Telica belong to the phenocryst-poor group. All other lavas and tephra of the Telica Formation belong to the phenocryst-rich group.

Figure 3.6 Modal mineral abundances of the Telica Formation plotted against stratigraphic position. The samples lying within the diagonal lines contain higher abundances of plagioclase and clinopyroxene phenocrysts.

3.5.9 Alluvium and Lahars (unit 9)

Alluvium and colluvium of unit 9 occur throughout the Telica Complex; fluvial sediments and epiclastic breccias have been deposited in gullies, valleys and on the adjacent plains (map 3).

The fluvial sediments consist of sands, gravels and conglomerates. Some of the fluvial deposits form during flash floods which are relatively common during the rainy seasons. Epiclastic breccias outcrop near Cerro de Aguero, west of Santa Clara, on the northern flanks of San Jacinto and in the stream beds on the flanks of Telica. They are all narrow elongate deposits characterized by a chaotic mixture of rock fragments of various shapes, sizes and compositions. The fragments are set in a weakly-consolidated, siltstone matrix. These epiclastic breccias probably formed as lahars which flowed down stream valleys.

Anorthositic gabbro blocks which are found in the streambeds on Telica were first described by McBirney and Williams (1965). The gabbro consists of equigranular plagioclase, clinopyroxene, olivine and magnetite, with small amounts of brown glass interstitial to the crystals. These could be fragments of a cumulate phase which formed in the Telica magma chamber. Similar gabbroic inclusions have been found in co-genetic Quaternary lava flows in El Salvador (Carr et al., 1981).

3.5.10 Soil

Soil horizons are developed virtually everywhere in the Telica Complex except on the Telica Formation and eroded outcrops. Map 3 shows only the rock units.

3.6 Alteration

Secondary minerals in the volcanic rocks are hematite, iddingsite and rarely chlorite. Alteration is mainly limited to areas of geothermal activity such as El Najo and unit 6 tephra (Plate 3.7). Outside the geothermal areas, alteration is restricted to oxidation of the glass with the introduction of hematite and partial replacement of olivine by hematite and/or iddingsite.

3.7 Structural Geology

There has been little deformation in the Telica Complex. Three northerly-trending faults have been identified by previous workers at El Tisate, Finca Santa Clara and the fumarole field of San Jacinto (Mooser et al, 1958; Catastro, 1972a). Hot springs and fumaroles occur along the traces of these faults. Arcuate or linear scarps, up to 40 m high and 2 km long, on the northeastern flanks of the San Jacinto hills that strike in a northerly direction and face towards the west (Map 3) and probably represent fault traces.

The volcanic centres in the Telica Complex form two alignments: an east-trending alignment of Cerro Los Portillos, Telica, La Ceiba and San Jacinto and a northwest-southeast alignment of Santa Clara, La Ceiba and Cerro de Aguero (Figure 3.2). La Ceiba lies on both trends near the centre of the Telica Complex. Similar alignments of volcanic features have been noted elsewhere in the Marrabios Range (Hazlett, 1977; McBirney, 1965) and along the Central American chain of volcanoes (Carr and Stoiber, 1974). The three orientations of volcanic edifices or depressions in

The principal ranges are north-south, east-west, and northwest-southeast. A structural study of Central American volcanoes by Carr (1976) shows that the north-trending faults are tensional and the two other orientations are shear planes caused by north-south compression.

3.8 Size of Cones and Craters

The Telica Complex, one of the smaller, active volcanic centres in Central America, has been estimated to contain 30 km^3 of volcanic material (Stoiber and Carr, 1973). Telica, Cerro de Aguero and Santa Clara have well-preserved composite volcanic cones. The approximate volumes estimated for the cones of these edifices (Table 3.6) make up only 5% of the volume of the Telica Complex estimated by Stoiber and Carr (1973). Santa Clara is the largest (1 km^3), while Cerro de Aguero's cone (0.07 km^3) is the smallest. These edifices are two orders of magnitude smaller than the largest composite continental volcanoes, such as Fujiyama and Etna (Williams and McBirney, 1979). Even the total volume of the Telica Complex is an order of magnitude smaller than these volcanoes.

The volumes of the basaltic flank lavas (El Porvenir, El Pegon, La Martinez and Los Ranchos Lava Members) from Telica and the older La Ceiba Formation andesite lava are presented in Table 3.7. The area and volume determinations for these lavas are minimum estimates because the flows are not completely exposed.

The andesite lava of the La Ceiba Formation, the thickest and largest flow in the Telica Complex, has an average thickness of 15 m and a volume of 0.2 km^3 . The flank lavas are compound flows that vary in

Table 3.6 Size of volcanic cones and craters in the Telica Complex

Feature	Area (km ²)	Volume (km ³)
Cones		
Santa Clara	6.9	1.0
Telica	2.9	0.52
Cerro de Agüero	0.26	0.07
Craters		
Telica crater	0.38	0.15
San Jacinto crater	0.79	0.16
kidney-shaped crater within San Jacinto crater	0.27	0.005

The area of the cone is calculated from the dimensions of the base of the edifice. The volumes of the cones were determined assuming simple right cones and corrected for the erosion of the peak and Telica's summit crater.

Table 3.7 Size of lava flows in the Telica Complex.

Name	Length (km)	Area (km ²)	Thick. (m)	A.R.*	Vol. (km ³)
La Ceiba Formation	6	14	15	280	0.2
San Rafael Flow	7.9	7.0	5.3	560	0.04
Los Canales Flow	7.3	3.3	3.7	550	0.01
El Guanabo Flow	3.5	6.2	5.5	510	0.03
El Porvenir Lava Member	7.9	16.5	-	-	0.08
Los Cedros Flow	6.2	6.7	1.6	1332	0.011
La Guatuzá Flow	2.5	2.5	8	220	0.02
El Pegon Lava Member	6.2	9.2	-	-	0.03
El Arenal Flow	3.9	0.83	10	<160	0.008
Cura Flow	2.5	1.3	>8	100	0.01
La Martínez Lava Member	3.9	2.1	-	-	0.018
Santa Elena	4.7	0.94	1.5	400	0.001
El Azucenal	1.6	0.42	-	-	-
Los Ranchos Lava Member	4.7	1.8	-	-	-

* Aspect ratio (A.R.) is the ratio of the horizontal extent to the thickness, where the horizontal extent is the diameter of a circle covering the same area as the lava (Walker, 1973).

length between 3.9 and 7.9 km. The largest basaltic flow is Los Canales Flow with a volume of 0.04 km^3 ; the largest compound flow is the Porvenir Flow with a volume of 0.08 km^3 . The volume of all flank lavas is 0.16 km^3 . This calculation was made by assuming that the Los Ranchos Lava Member has a thickness of 1.5 m, and therefore, a volume of 0.027 km^3 . Total volume of the lava flows is remarkably close in magnitude to the estimated volume of the Telica crater (0.15 km^3) which suggests the flows may have largely formed by draining the magma-filled crater.

Similar in size to most historic basaltic flows, Telica lavas are an order of magnitude smaller than the largest historic flank eruptions from Mauna Loa, a large Hawaiian shield volcano (Williams and McBirney, 1979). The aspect ratios of the Telica flows (Walker, 1973) are typical of smaller basaltic effusions (Figure 3.7). A comparison of the lengths of lava flows from several other volcanoes (Walker, 1973) suggests that the Telica flows erupted at moderate rates ($\sim 1\text{-}50 \text{ m}^3/\text{sec}$), rates that are more typical of composite volcanoes than shield or fissure eruptions (Figure 3.8).

The four Lava Members, El Porvenir, El Pegon, La Martinez and Los Ranchos, are composed of multiple flows, that have erupted laterally from Telica. Within each member the stratigraphically lower flow or flows extend further from Telica, are thinner, and typically cover more surface area than the overlying flows. The overlying flows have more irregular surfaces with pressure ridges and solidified lava rivers. The characteristics of the stratigraphically lower flows could reflect a higher initial rate of effusion than the rate for the overlying flows. Modern eruptions at Mount Etna display the same change in effusion rate

Figure 3.7 The dimensions of lava flows from Volcan Telica. The dotted lines give the volumes of circular disc-like bodies of the dimensions shown. The dashed lines give the aspect ratio, H/V (after Walker, 1973).

Figure 3.8. Plot of lava length against average effusion rate for basaltic lava eruptions. C, Cerro Negro, 1965; M, Mauna Loa, 1852, 1868, 1907, 1914, 1926, 1947 and L, Taki (1783) (after Walker, 1973).

which led Walker (1972) to propose that initial mafic flows from composite cones are the largest.

3.8 Potential Volcanic Hazards

Any future volcanic activity in the Telica Complex poses a threat to the lives and property of the several thousand people living and working in the immediate area. The types of volcanic activity in the Telica Complex that pose hazards are:

- i) explosive eruptions,
- ii) plumes of volcanic gases,
- iii) lahars, mudflows and floods,
- iv) shallow earthquakes, and
- v) lava flows.

Explosive eruptions of Telica Complex volcanoes with ejection of tephra pose the greatest threat to people's lives and properties. Large quantities of ash represent a health hazard to people with respiratory problems and will kill some livestock and wildlife. Large accumulations of ash destroy crops, temporarily contaminate water supplies and cause buildings to collapse. The possible extent of an explosive eruption of Telica can be gauged by superimposing the isopach map from the moderately-sized 1968 Cerro Negro eruption on Telica. The village of Cristo Rey and a number of farms would receive 20 cm of ash or more from an eruption of this strength (Figure 3.9). A similar eruption from Santa Clara would deposit 20 cm of ash on the town of Telica and numerous farms along Highway 26. The areas judged to be most likely to receive 20 cm or more of ash from future eruptions of Telica or Santa Clara are shown as areas of high risk on Map 4.

Figure 3.2 Isopach map of 1968 Cerro Negro eruption superimposed on the Telica Complex as if tephra erupted from the Telica volcano (data from Rose et al., 1973).

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The hazards associated with volcanic gases occur almost exclusively down wind from a volcano. Should Telica develop a strong gas plume, the people living on the small farms on its western and northwestern flanks might experience respiratory difficulties. Crop damage would probably be restricted to the fields in this area, although farms near Cristo Rey might also be affected. A gas plume from Santa Clara could result in local crop damage but would probably dissipate or rise into the sky before affecting any inhabited areas.

Lahars in the Telica Complex are restricted to gullies and stream beds and vary between 2 and 4 km in length. They represent a hazard to people and property located along creeks and gulleys (Map 4).

Shallow micro-earthquakes are common before, during and after volcanic activity of Telica due to magma movement and structural readjustments within and beneath the volcano. These micro-earthquakes are very weak and do not constitute significant geological hazard in the Telica Complex.

Large lava flows from any of the volcanoes could destroy valuable farm land but represent little threat to human life. The areas most likely to be affected by lavas are on the slopes of Telica and Santa Clara, particularly gulleys and depressions.

4. Lithogeochemistry of the Mina El Limon Area

4.1 Introduction

Thirty-three rock samples, representative of the Mina El Limon area, were analysed for major and minor elements and norms were calculated (Appendix I). Sample localities are shown in Figure III-1. The lithogeochemical results are used to quantify the extent of hydrothermal alteration, to fingerprint the individual map units and to determine magma type. The hydrothermal alteration is discussed first. Only by identifying and discarding strongly altered samples can the chemical analyses be used to characterize the Mina El Limon map units.

4.2 Alteration

Alteration is found in rocks up to 100 m from the quartz veins, along faults and in devitrified dacites. Because of the presence of quartz veins throughout most of the map area, the assumption is made that most of the volcanic rocks have been altered. Examination of the chemical analyses (Table I-5) reveals that many samples typically have $\text{FeO}/\text{Fe}_2\text{O}_3$ ratios less than 0.5 and contain more than 1% volatiles (Figure 4.1), both common features of altered volcanic rocks (Coombs, 1963). More than half of the samples contain normative corundum, a mineral commonly found in altered volcanic rocks (Franklin, personal communication, 1979). With such widespread alteration, the analyses of Mina El Limon area rocks must be used cautiously when discussing primary compositions.

There are three types of alteration in the Mina El Limon area: wall-rock alteration associated with quartz veins, silicification and potassium metasomatism.

Figure 4.1 H_2O total contents of the Mini El Limon area mafic volcanic rocks plotted against the distance to the nearest quartz vein. The straight line is the best fit line for all the data except the silicified breccia samples.

4.2.1 Wall-Rock Alteration

Three zones of alteration are found in the wall rock adjacent to quartz veins in the Mina El Limon area. These are (i) sericite-adularia alteration zone, (ii) argillic alteration zone and (iii) propylitic alteration zone.

At Mina El Limon wall-rock alteration had been noted previously but only Gleason (1977) discussed it in detail. Gleason implied that hydrothermal alteration did not affect the wall rock more than several metres from the auriferous quartz veins, perhaps because almost all his samples were from underground in close proximity to quartz veins. Gleason's analyses of "unaltered" samples collected 23 m from the quartz veins show these rocks are not pristine. These samples have H_2O^+ (31%) and S (>0.14%) contents which are 10 to 100 times greater than those found in unaltered volcanic rocks. Therefore, Gleason may never have sampled outside the wall-rock alteration enveloping the quartz veins. This conclusion is supported by the more abundant plagioclase alteration in wall rock within 100 m of quartz veins (section 2.6).

Although variations in weight per cent or parts per million are useful in studying wall-rock alteration, they only show the absolute change of any component if the total mass of the rock has not changed during alteration. Since mass is rarely conserved during alteration it is necessary to compare intensive properties, such as molar ratios or specific gravity, and to have one extensive property, such as the mass of an immobile component or the volume of the rock, remain constant to determine the quantitative chemical changes caused by metasomatism.

Meyer and Hemley (1967) concluded that chemical gains and losses could best be evaluated assuming constant volume. In studies of altered Archean volcanic rocks both Rye (1976) and Gibson (1979) found that minimal volume changes were indicated by the preservation of primary textures even in intensely altered rocks. Altered volcanic rocks from the Mina El Limon area typically have intact primary textures, even those adjacent to quartz veins (Gleason, 1977). Quantitative comparisons can be made between wall-rock samples of the same original composition by assuming constant volume during alteration. Specific gravity was measured for all samples (Appendix I) and used to convert weight % or ppm analyses into units of gm/cc or 100 gm/cc to enable quantitative comparisons.

A suite of unit 1 and 2 mafic rocks (13 samples) was collected at various distances from known quartz veins. The least-altered samples, from outcrops more than 1 km from a quartz vein, show little evidence of significant hydrothermal alteration such as high volatile contents, low alkali values or normative corundum. Primary textures of these samples are similar to the more altered samples in the footwall of the Footwall Vein. The absolute abundances of the relatively immobile elements TiO_2 and Zr (Floyd and Winchester, 1978; Finlow-Bates and Stumpfl, 1981) are similar for all samples regardless of the extent of alteration. Other oxides which are reasonably constant for all samples are MnO , Na_2O and P_2O_5 . Because of the similarity of these elements it was assumed that most samples had similar original compositions and that variations in composition can be attributed solely to alteration. The chemical changes associated with quartz vein wall-rock alteration are discussed below.

4.2.1.1 Sericite-Adularia Alteration Zone

The alteration in the sericite-adularia zone has produced a decrease in specific gravity, and CaO and Al_2O_3 values and an increase in K_2O and SiO_2 contents in the wall rock to the quartz veins (Gleason, 1977). In addition, Gleason noted that the H_2O^+ content is greater and Al_2O_3 , CaO, FeO_{total} , MgO, MnO, Na_2O and TiO_2 values smaller in the sericite-adularia zone than in his "pristine" rocks.

4.2.1.2 Argillic Alteration Zone

Two samples (#119, 120) from the argillic alteration zone have higher SiO_2 , Zn and volatile contents and lower Ba, CaO, Cr, K_2O , and R values than the least-altered mafic volcanic rocks from units 1 and 2 (Table 4.1). Low CaO values are the most distinctive chemical signature of this alteration zone.

If constant volume is assumed, CaO and K_2O show the the only significant absolute variations between the sericite-adularia and argillic alteration zones. The high K_2O content of the quartz-sericite alteration zone is reflected in the formation of adularia (Gleason, 1977). An increasing abundance of calcite close to the quartz veins may explain the higher CaO values in the wall rock.

Compared to the propylitic and least altered mafic rocks, the argillic alteration zone contains smaller absolute amounts of CaO and higher abundances of SiO_2 and Zn (Figure 4.2). Average absolute gains and losses for argillic, propylitic and least-altered samples relative to a little altered sample (#284) are plotted in Figure 4.3. Although the data base is small, the figure shows the pronounced decrease in CaO and increase in SiO_2 of the argillic alteration zone relative to the

Table 4.1 Representative analyses of altered Mina El Limon area rocks

	A	B	C	D	E	F
Sample #	76-12c	119	129	284 wt %	average	400
SiO ₂	59.67	58.5	49.9	56.7	69.1	78.2
TiO ₂	0.5	0.82	0.79	0.59	0.60	0.20
Al ₂ O ₃	16.1	16.4	15.7	17.4	18.13	11.4
Fe ₂ O ₃	2.0	2.6	ND	3.2	1.39	1.1
FeO	5.9	6.2		4.2	0.07	0.39
FeOT+	7.7	-	9.1	-	-	-
MnO	0.38	0.26	0.22	0.15	0.02	0.02
MgO	3.7	3.5	7.0	4.0	0.01	0.25
CaO	3.6	1.4	8.6	8.5	0.07	0.00
Na ₂ O	1.20	4.9	3.1	3.0	0.04	0.76
K ₂ O	2.00	0.18	0.62	0.79	0.20	6.6
P ₂ O ₅	0.08	0.15	0.12	0.09	0.18	0.02
H ₂ OT	3.6	2.9	2.9	1.3	8.50	0.90
CO ₂	1.4	1.5	1.9	0.60	0.31	0.54

ppm

Ba	-	130	860	550	895	1890
Cr	-	19	35	13	8	13
Cu	-	26	28	87	50	28
Ga	-	18	ND	20	20	13
Nb	-	3	2	2	2	6
Ni	-	7	7	1	0	4
Pb	-	1	ND	-	5	4
Rb	-	0	10	8	4	165
S	-	ND	500	ND	-	-
Sr	-	395	470	390	608	53
V	-	285	ND	235	158	22
Y	-	28	19	22	14	26
Zn	-	135	83	69	13	28
Zr	-	88	56	76	153	105

A - sericite-adularia zone (from Gleason, 1977)

B - argillic zone

C - propylitic zone

D - relatively unaltered

E - silicification (average of three analyses)

F - potassium metasomatism

ND - not determined

+ - T represents total

Figure 4.2 Oxide and trace element content of Mina El Limon area mafic volcanic rocks plotted versus distance in metres from nearest quartz vein. Oxides are in units of g/cc and trace elements are in units of 100 gm/cc. Samples from sericite-adularia alteration zone (inverted triangles), argillic alteration zone (squares), propylitic alteration zone (circles) and least altered alteration zone (triangles).

Figure 4.3 Absolute changes in average oxide content of the argillite (squares) and propylite (triangles) alteration zones and least altered mafic volcanics (circles). Volume assumed constant and sample #284 used as base composition.

propylitic and least-altered rocks. CaO depletion undoubtedly correlates with the breakdown of the plagioclase phenocrysts, while scattered quartz veinlets and weak pervasive silicification of the groundmass probably explain the high SiO_2 contents in the argillic alteration zone.

4.2.1.3 Propylitic Alteration Zone

Rocks from the propylitic alteration zone contain more MgO and H_2O^+ than the least-altered mafic volcanic rocks (Figures 4.2 and 4.3). Enrichment in MgO and H_2O^+ corresponds to chlorite development and other secondary minerals in both groundmass and phenocrysts.

The outer limits of the propylitic alteration zone are not easily ascertained because at distances of more than tens of metres from the quartz veins it becomes difficult to distinguish wall-rock alteration from low-grade metamorphism. Until a more comprehensive study is made of propylitic alteration, the best criteria for establishing its outer limit is the extent of plagioclase alteration (section 2.6).

4.2.2 Silicification

In the Mina El Limon area silicification can be so intense that quartz replaces almost all primary minerals, although original plagioclase phenocrysts are still discernible in some samples (section 2.3.3). Two of the three analysed silicified breccias (Table 1-5) contain as much SiO_2 as the dacites even though unaltered unit 1 and 2 lavas have less than 60% SiO_2 . In the field the silicified rocks were mapped as part of unit 3 because of their resemblance to dacite flows. It is not uncommon for silicified mafic volcanic rocks to be mapped as

dacites or rhyolites. For example, silicified andesite in Noranda, Quebec has been mapped for many years as rhyolite. Gibson (1979) has shown how a hot, silica-saturated solution could add SiO_2 to and deplete Al_2O_3 , Cu, FeO, MgO, TiO_2 , and Zn from an andesite. Outcrops of silicified volcanic rock are identified on Map 2.

Most other oxides present in the silicified rocks display anomalously low values. These rocks contain less than 0.65 % total alkalis and plot well away from other Mina El Limon area rocks and outside the normal igneous spectrum (Figure 4.4). They also have much smaller amounts of MgO and CaO than most volcanic rocks (Table 4.1). The $\text{FeO}_{\text{total}}$ content of these samples is more variable than MgO and CaO and is roughly equivalent to values in the dacites. Excessive amounts of H_2O ($> 6\% \text{H}_2\text{O}_{\text{total}}$) are present in the silicified rocks in comparison to unaltered volcanic lavas ($< 1\%$) and other rocks from the Mina El Limon area (Figure 4.10). Their TiO_2 contents are similar to values from basalts and andesites of units 1 and 2 (Figure 4.6).

Trace elements in the silicified rocks exhibit a chemical signature with characteristics of both felsic and mafic rocks. Cr, Rb and Zr are present in similar amounts to the unit 5 dacitic rocks while V and Y contents are equivalent to levels found in basalts. The base metals, Cu and Zn, are depleted relative to all other Mina El Limon rocks. Sr values are extremely high.

Petrographic textures and chemical analyses suggest that the silicified rocks are highly altered mafic lavas of unit 1 and 2. Any similarities to dacites reflect extensive alteration with introduction of Cr, H, Rb, Si, Sr and Zr and leaching of Ca, Cu, Mg and Zn.

Figure 4.4 The Mina El Limon area rocks lie predominantly in the igneous spectrum on the Hughes alkali diagram. Most of the felsic rocks and several of the mafic samples plot within the potash keratophyre field. The alkali-depleted, silicified breccias lie along the abscissa.

Figure 4.5 Al_2O_3 Barker diagram of the Minneriya area volcanic rocks. Al_2O_3 value decreases with increasing SiO_2 content.

Figure 4.6 TiO_2 Barker diagram of the Minneriya area volcanic rocks. TiO_2 contents can be used to differentiate mafic and felsic rocks.

4.2.3 Potassium Metasomatism

Three devitrified dacitic rocks of unit 3 have K_2O values over 6 wt % (Figure 4.8), close to the stoichiometric K_2O contents for pure potassium feldspar. Despite this, there are no potassium-rich phenocrysts such as potassium feldspar, nepheline, leucite or phlogopite in the dacites. The dacites consist of quartz phenocrysts set in a groundmass of quartz, feldspar and opaques. The low sodium contents (Figure 4.3) and high K_2O/Na_2O ratios (3.7 to 10.3) of these rocks are unusual for unaltered volcanic rocks. Shoshonitic rocks and some high-K calc-alkaline rocks found in island arc settings do have K_2O contents >2% but their K_2O/Na_2O ratios are typically about 1 (Taylor, 1969; Jaques, 1976; Jakes and White, 1972). The high K_2O contents of the devitrified felsic rocks are probably the result of potassium metasomatism.

These altered dacites also have low CaO , FeO_{total} and MgO values (Table I-5) for unaltered volcanic rocks. These abundances are similar to those found in the silicified rocks. The Al_2O_3 , SiO_2 , and TiO_2 contents of the altered dacites are similar to island arc rhyolites and unit 5 dacites and H_2O_{total} contents vary from 0.90 % to 2.6% compared to more than 6 % for the silicified rocks.

Stewart (1979) in attempting to explain the origin of similar "potassic siliceous rocks" examined the role of liquid immiscibility, gaseous transport of alkalis, partial melting, perfect fractional crystallization and peritectic melting. He concluded that secondary hydration of glassy felsic flows by meteoric groundwater produced

Figure 6.7 Na_2O Barker diagram of Mineral Point area volcanic rocks. Silicified breccias and flows are depleted in Na_2O .

Figure 6.8 K_2O Barker diagram of Mineral Point area volcanic rocks. K_2O increases with silica; flows (containing more than 6% K_2O) round off between fields (after Irvine and Taylor (1966)).

enrichment of H_2O and K^+ and depletion in Na_2O . Previous work by Lipman (1965) had documented an increase in H_2O and Al_2O_3 contents with associated depletion of Na_2O , SiO_2 and Fe_2O_3 values in the hydrated, glassy portions of felsic igneous bodies relative to their crystalline parts. A similar hydration process producing enrichment in H_2O_{total} and depletion of CaO , FeO_{total} and MgO could have caused the potassium metasomatism which has affected the devitrified dacitic rocks of the Mina El Limon area.

4.3 Lithogeochemistry of Units

Despite the pervasive nature of the alteration in the Mina El Limon area, some of the chemical analyses are still little changed from their primary compositions. For example, the alkali contents of most samples lie within the igneous spectrum (Hughes, 1973; Figure 4.4). Only the silicified and potassium metasomatized rocks plot consistently outside of the igneous spectrum. In the following sections the chemistry of each unit is compared both to representative island arc samples and to the other Mina El Limon units.

4.3.1 Basalt and Andesite Lavas (unit 1)

Nine lavas from unit 1 were analysed; all but one of these came from the hydrothermally altered footwall of the Panteon Vein System. Discussion is limited to the six, least-altered samples from the propylitic alteration zone. None shows corundum in the norm.

The average chemical composition of unit 1 lavas, given in Table 4.2, is similar to the composition of a high-alumina basalt (Taylor, 1969; Table 4.3). The average analysis shows low SiO_2 (< 53.2) and K_2O (< 0.7 %) and moderate TiO_2 , Al_2O_3 , MgO , CaO and Na_2O contents. The Cr,

Table 4.2 Average analyses of units from the Mina El Limon area

Unit	1	2	3	4	5	6
n	6	4	3	8	15	2
	wt %					
SiO ₂	51.20	56.65	76.33	63.11	72.50	52.35
TiO ₂	0.80	0.68	0.20	0.74	0.30	0.81
Al ₂ O ₃	16.80	17.25	11.87	15.16	13.20	18.35
Fe ₂ O ₃ *		3.73	1.26	4.35	1.9	4.75
FeO		3.58	0.24	1.95	0.32	3.80
FeOT+	9.41	-	-	-	-	-
MnO	0.29	0.15	0.02	0.12	0.05	0.18
MgO	5.99	3.38	0.21	1.47	0.35	4.20
CaO	6.83	7.85	0.27	4.52	1.30	9.09
Na ₂ O	2.60	3.28	1.05	3.30	3.50	2.87
K ₂ O	0.66	1.02	6.50	2.58	4.00	1.17
P ₂ O ₅	0.13	0.11	0.01	0.18	0.01	0.13
H ₂ OT	3.53	1.65	1.53	2.40	1.30	1.00
CO ₂	0.91	0.37	0.34	0.28	0.13	0.23

	ppm					
Ba	540	693	1770	1225	1890	595
Cr	33	10	6	29	13	10
Cu	88	102	18	74	28	120
Ga	21	21	13	18	13	19
Nb	4	4	5	5	8	2
Ni	14	2	4	7	1	3
Pb	1	3	6	4	6	1
Rb	16	18	147	64	97	11
S	2500	-	-	-	-	-
Sr	392	434	80	318	165	298
V	-	204	15	130	12	220
Y	23	27	36	40	43	21
Zn	110	71	34	71	46	73
Zr	77	73	160	219	280	83

n = number of analyses

S = sample #439

Table 4.3 Representative analyses of island arc volcanic rocks

	A	B	C	D	E	F
	-----	-----	-----	-----	-----	-----
	wt %					
	-----	-----	-----	-----	-----	-----
SiO ₂	51.9	51.7	55.5	55.0	65.1	75.3
TiO ₂	0.8	-	0.81	1.9	0.51	0.27
Al ₂ O ₃	16.0	16.9	17.7	17.4	16.5	13.5
Fe ₂ O ₃	-	-	4.4	-	-	-
FeO	-	-	4.0	-	-	-
FeOT+	9.56	10.4	-	7.56	3.86	1.68
MnO	0.17	-	0.18	-	0.08	0.05
MgO	6.77	6.5	3.4	4.2	1.48	0.25
CaO	11.8	11.0	8.0	7.5	4.75	1.49
Na ₂ O	2.42	3.1	4.0	2.8	4.60	4.12
K ₂ O	0.44	0.4	1.6	1.1	2.05	3.39
P ₂ O ₅	0.11	-	0.35	-	-	-
H ₂ OT	-	-	-	-	-	-
CO ₂	-	-	-	-	-	-
	ppm					
	-----	-----	-----	-----	-----	-----
Ba	75	115	250	226	520	870
Cr	50	40	9	196	13	1.7
Cu	-	35	46	41	22	6
Ga	-	13	-	-	-	16
Nb	-	4	4	-	6	5.6
Ni	30	25	6	20	5	-
Pb	-	1.7	5	-	5.2	18
Rb	5	9.6	25	25	44	108
S	-	-	-	-	-	-
Sr	200	328	810	501	460	125
V	270	255	178	-	688	8.5
Y	-	20	17	19	20	25
Zn	-	-	74	104	-	-
Zr	70	100	81	-	100	170

A - average island arc tholeiite (Basaltic Volcanism Study Project, 1981; p. 206)

B - high-alumina basalt from Taupo, New Zealand (Taylor, 1969)

C - tholeiitic medium-K basic andesite (Gill, 1981, p.100)

D - calc-alkaline medium-K basic andesite (Gill, 1981, p.100)

E - dacite, Solomon Islands (Taylor, 1969)

F - average New Zealand rhyolite (Taylor, 1969)

3

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Nb, Ni, Pb, Rb, Sr, V, Y, and Zr values of unit 1 rocks (Table 4.1) are generally similar to those reported for high-alumina basalts. The moderately high Cr and Ni contents for the unit 1 rocks suggest that these rocks are only weakly differentiated.

For rocks with less than 1% K_2O , Ba is present in relatively large amounts (360 to 875 ppm). Such high Ba values are typically found in more potassium-rich andesites (Table 5.2 in Gill, 1981) or felsic volcanic rocks (Table 4.3). High Ba values (for given K_2O and SiO_2 contents) compared to other island arc rocks are characteristic of the Mina El Limon area volcanic succession (see below).

The variation in Cu and Zn by a factor of three is undoubtedly caused by propylitic alteration. The unusually high S concentrations (average of 2500 ppm) compared to normal basalts (average content < 900 ppm, Basaltic Volcanism Study Project, 1981) also support this conclusion.

4.3.2 Two-Pyroxene Andesite Porphyry Lavas (unit 2)

Because of the weak alteration of Unit 2 lavas, all four samples have been considered as primary, chemical compositions. The average analysis is given in Table 4.2.

SiO_2 (53-60 %) and TiO_2 (0.57-0.80 %) contents of unit 2 rocks are typical of island arc andesites (Taylor, 1969). The K_2O and some trace element data place these rocks among medium-K andesites (Gill, 1981; Table 4.3) although two-pyroxene andesite porphyry lavas contain more Ba and less Cr, Ni, Y and Zr. The low abundances of Y and Zr in unit 2 lavas may reflect a less differentiated composition than a typical island arc andesite.

4.3.3 Dacite Flows (unit 3)

All three analyses of dacites from unit 3 plot well outside Hughes' igneous spectrum because of potassium metasomatism (Figure 4.4).

Potassium, SiO_2 and $\text{H}_2\text{O}_{\text{total}}$ have been added and CaO , MgO and $\text{FeO}_{\text{total}}$ depleted (section 4.2.3). Any discussion of the original chemistry of unit 3 must be restricted to the less mobile elements, such as Ti and Al.

Both TiO_2 and Al_2O_3 abundances are characteristic of rhyolites (Taylor, 1969). The TiO_2 values can be used to discriminate between felsic and intermediate and mafic rocks in the Mina El Limon area. All dacites and rhyolites contain less than 0.3 % TiO_2 and all other rocks in the area have more than 0.3 % TiO_2 (Figure 4.6). A similar TiO_2 threshold serves to identify rhyolites in Noranda, Quebec (Gibson and Watkinson, 1979). All trace elements, except Ba, Rb and Sr, in rocks of unit 3 are similar in abundance to a typical analysis of a New Zealand rhyolite (Table 4.3).

4.3.4 Andesite and Dacite Flows (unit 4)

Unit 4 samples are little altered. All but one of the unit 4 flows lie within the igneous spectrum shown in Figure 4.4. These lavas span a wide range of SiO_2 (56-70 %), Rb (13-100 ppm), Sr (140-525 ppm) and Y (25-57) contents. Unit 4 samples have TiO_2 , Cr and V contents higher than those found in dacites and closer to values reported for basalts and andesites (Table 4.3).

Because of the wide compositional range shown by unit 4 lavas it is difficult to compare them as a unit to analyses of typical island arc rocks. Individual samples are similar to tholeiitic andesites or calc-alkaline andesites and dacites.

4.3.5 Dacite Dikes and Stocks (unit 5)

Three of four samples of unit 5 dacite dikes plot outside the igneous spectrum in the potash-keratophyre field (Figure 4.4). In addition, all three contain more than 3% H_2O_{total} , a feature characteristic of altered rocks. Possibly weak potassium metasomatism has affected these three samples. The least altered sample (#439), plots in the igneous spectrum, and contains 1.3% H_2O_{total} . It has higher CaO, Na_2O and FeO and lower K_2O and H_2O_{total} values than an average analysis of the other unit 5 samples.

The oxide and trace element abundances of this single sample are similar to a typical calc-alkaline rhyolite from New Zealand (Table 4.3), except for its higher Ba and Zr abundances. A virtually identical average analysis for six rhyolites from the Recent Obrajuelo Complex in Guatemala is reported by McBirney and Weill (1966).

4.3.6 Basalt and Andesite Dikes (unit 6)

The two unit 6 dike samples are virtually unaltered. They are geochemically similar to high-alumina basalts (p. 206, Basaltic Volcanism Study Project, 1981) although they contain more K_2O and less Al_2O_3 than the typical sample given in Table 4.3.

4.3.7 Identification of Units

The litho-geochemistry of the map units can be used to distinguish one from another. Unit 1 lavas are chemically similar to unit 6 dikes, however, unit 1 rocks usually contain more Ni and less CaO and K_2O . It is possible to distinguish rocks of unit 1 from rocks of units 2, 3, 4 and 5 by the lower SiO_2 and K_2O and higher MgO contents of the former.

The two-pyroxene andesite lavas contain higher SiO_2 and K_2O and lower TiO_2 and MgO values than unit 1 lavas. The chemical differences between the two units can be explained by magmatic differentiation from a basaltic to andesitic composition. Units 3, 4 and 5 are more felsic in composition than unit 2 with higher SiO_2 , K_2O , Y, Zr and lower CaO , Sr and V contents.

Unit 3 flows and domes have higher SiO_2 , K_2O and Rb and lower Al_2O_3 , Sr and Zr contents than unit 5 dacite intrusions. Both the extrusive and intrusive dacites can be distinguished from rocks of the other units (1, 2, 4, 6) by their higher K_2O and Rb and lower Al_2O_3 and TiO_2 contents.

For most oxides and trace elements unit 4 rocks have compositions intermediate to those of andesites of unit 2 and dacites of unit 5 (Figures 4.5 to 4.10). The Cr, Rb, Sr, Ti and V contents of unit 4 samples are similar to the abundances found in units 1, 2 and 6.

The lower SiO_2 content of the unit 6 dikes can be used to distinguish these rocks from those of units 2, 3, 4 and 5.

4.4 Magma Type

The Mina El Limon area rocks range in composition from basalt to rhyolite. On Harker diagrams they form coherent, simple trends (Figures 4.5 to 4.10) that suggest they belong to a single, cogenetic suite of volcanic rocks. Much of the scatter associated with these trends is probably the result of alteration.

The most probable magma types in Nicaragua are island arc tholeiites, calc-alkali volcanics and shoshonites. Generally island arc tholeiites are erupted onto oceanic crust, close to deep-ocean trenches,

Figure 4.9 MgO Barker diagram of Mima Hill area and units 1 to 6. MgO versus SiO_2 with SiO_2 .

Figure 4.10 CaO Barker diagram of Mima Hill area and units 1 to 6. Both units have CaO content that is intermediate to other rocks.

calc-alkali volcanics are extruded onto continental crust and oceanic crust farther back from the trenches, and shoshonites are erupted far behind the trenches onto continental crust (Pearce, 1976).

None of the unaltered Mina El Limon area rocks contain sufficient K_2O to be shoshonites (commonly over 2 wt % at 50% SiO_2). Therefore, the Nicaraguan volcanic rocks are either island arc tholeiites or calc-alkali volcanics. On the basis of their chemical compositions most samples are classified as calc-alkaline (section 4.3). In general, they exhibit the high, nearly constant, Al_2O_3 and low TiO_2 , K_2O , Ni and Cr contents which are all features of calc-alkali rocks (Taylor, 1969; Table 4.1).

All analysed Mina El Limon samples have been classified according to their norms (Irvine and Baragar, 1975). These results are presented in Table I-7 and summarized below:

- 1) unit 1 - tholeiitic andesite and calc-alkaline high-alumina basalt,
- 2) unit 2 - calc-alkaline high-alumina basalt and tholeiitic andesite,
- 3) unit 3 - too strongly altered for classification,
- 4) unit 4 - tholeiitic and calc-alkaline basalt, andesite and dacite,
- 5) unit 5 - calc-alkaline dacite and rhyolite, and
- 6) unit 6 - calc-alkaline basalt.

On an AFM plot the majority of the Mina El Limon area volcanic rocks plot within the calc-alkaline field (Figure 4.11). Only unit 1 samples plot within the tholeiitic field. Most samples lie close to the trend defined by Kuno's (1966) hypersthene-rich volcanic rocks from Japan. Kuno also proposed a classification scheme for island arc volcanics based on their Na_2O , K_2O and SiO_2 contents (Figure 4.12). Most of the Mina El Limon volcanic rocks lie within Kuno's high-alumina field. On a MgO versus FeO_{total} diagram the Mina El Limon area rocks

Fig. 4. AFM diagram of the Hina F. Line area volcanic rocks. Their change in composition (unit 1) shows the trend of Kuno's (1968) hypersthene-rich series of volcanic rocks. For Hina, inverted triangles are subdivided breccia samples and squares are unit 1 rocks.

Figure 4.12 The Mina El Limon area volcanic rocks lie principally within the high-alumina field of Kuno (1960) on a $\text{Na}_2\text{O} + \text{K}_2\text{O}$ versus SiO_2 variation diagram. Symbols are defined on Figure 4.9.

plot between the Cascade island arc suite in the western USA and an island arc tholeiite suite (Figure 4.13). A SiO_2 versus $\text{FeO}_{\text{total}}/\text{MgO}$ plot shows that Mina El Limón area rocks fall within both tholeiitic and calc-alkaline fields (Figure 4.14).

The ambiguity in precisely defining the magma type of the Mina El Limón area rocks reflects both the variable criteria used by different authors and the gradational nature of the boundaries between the two types. Gill (1981), for example, has discussed the criteria used to separate tholeiitic and calc-alkalic andesites. He points out that the various criteria to separate these magma types provide conflicting answers. The conflicting answers could reflect in some cases a gradational boundary between these two magma types. Sakuyama (1983), for example, has documented tholeiitic and calc-alkaline rocks in a single composite volcano.

All the data suggests the Mina El Limón area volcanic rocks belong to one cogenetic igneous suite with predominantly calc-alkaline characteristics. Only unit 1 rocks are considered as having tholeiitic affinities.

Figure 9a: MgO versus FeO variation diagrams of $Mn+11$ (iron-ore) volcanic rocks. $Mn+11$ (iron-ore) lies between the dashed trend and the field for the iron-ore rocks.

Figure 9b: FeO/MgO versus SiO_2 variation diagrams of $Mn+11$ (iron-ore) volcanic rocks. $Mn+11$ (iron-ore) lies between the dashed trend and the field for the iron-ore rocks.

5. Lithogeochemistry of the Telica Complex

5.1 Introduction

A total of 50 whole-rock analyses of volcanic rocks from the Telica Complex are given in Appendix I. Over half (29) of these are from the youngest volcano, Telica, and are supplemented by electron microprobe analyses of the phenocrysts (Appendix V). The majority of the samples collected from the Telica Complex are fresh. Areas with obvious hydrothermal alteration were not sampled. Pervasive alteration was noted in only one map unit, the San Jacinto Formation lapillistone and tuff.

5.2 Rock Types

The Telica Complex volcanic rocks can be broadly divided into basalts and andesites on the basis of their normative mineralogy. Normative quartz is virtually absent from the basalts, while the andesites contain significant quartz and no olivine. Only La Ceiba flows approach the levels of 10% normative quartz found in many andesites.

Basalts and andesites from the Telica Complex can be separated on the basis of their whole-rock analyses (Table I-5). Basaltic rocks of the Telica Complex typically have lower SiO_2 and higher CaO and MgO contents (Figures 5.1 and 5.2) than the andesites. Taylor (1969) has classified similar island arc rocks as high-alumina basalts and low- SiO_2 andesites (basic andesites of Gill, 1981). Barium is a useful discriminant of rock type in the Telica Complex. Most basalts (92 %) contain less than 900 ppm Ba and virtually all andesites contain greater than 900 ppm Ba.

Figure 1. Scatter plot of SiO_2 vs. Al_2O_3 for the samples shown in Figure 2. The dashed line separates the 'Altered Tephra' from the 'Low-SiO₂ Andesite'.

Figure 2. Scatter plot of SiO_2 vs. Al_2O_3 for the samples shown in Figure 1. The dashed line separates the 'Altered Tephra' from the 'Low-SiO₂ Andesite'.

5.3 General Geochemical Characteristics

Analyses of Telica Complex rocks cover a fairly restricted range of volcanic compositions (Table 5.1) compared to most volcanic rocks. High Al_2O_3 , $\text{FeO}_{\text{total}}$, Ba and Cu values relative to most other basalts and andesites are typical of rocks of the Telica Complex. Other Quaternary basalts from Central America contain comparable amounts of Al_2O_3 , $\text{FeO}_{\text{total}}$ and Ba (Carr et al., 1981; Carr, 1984). The Cu values of the Telica Complex rocks are at least twice the values found in typical mafic rocks (Table 4.3).

A Pearson linear correlation coefficient was used to determine correlation coefficients between various oxides and elements for all the analyses from the Telica Complex (Table 5.2). The highest correlations for the major elements are SiO_2 with Na_2O , SiO_2 with K_2O , Na_2O with MgO and K_2O with both Ba and Rb. MgO demonstrates moderate correlations with SiO_2 , Na_2O , K_2O , P_2O_5 , Ba, and Y. The trace elements Ti, Cr and Ni have particularly high correlation coefficients with one another. Such correlations are not expected between unrelated rocks. Both Pearson linear correlations and the common trends on variation diagrams (Figures 5.1 and 5.2) are consistent with formation of these rocks by magmatic differentiation of a common suite of rocks.

5.4 Geochemistry of Individual Volcanoes

The geochemistry of each volcanic centre is discussed below in order from the oldest (Cerro Los Portillos) to youngest (Telica).

5.4.1 Cerro Los Portillos

The three Cerro Los Portillos Formation rocks are remarkably uniform in composition and are similar to other volcanic rocks of the

Table 5.1 Average analyses of rocks from the Telica Complex

Unit	Cerro Los Portillos	La Ceiba	El Najon	Cerro de Aguero	Santa Gloria	San Jacinto	Telica	
	1	2	3	4	5	6	7	8
	3	5	2	3	3	2	2	29
	wt %							
SiO ₂	50.80	55.36	50.95	53.67	47.33	42.60	54.15	50.86
TiO ₂	0.98	0.73	0.72	0.80	0.86	0.93	0.87	1.11
Al ₂ O ₃	19.80	17.82	17.05	18.10	20.00	20.15	17.60	17.22
Fe ₂ O ₃ ⁺	4.2	3.2	4.0	3.6	6.4	8.4	3.8	2.27
FeO ⁺	6.9	4.3	6.2	6.8	4.9	4.5	4.2	6.41
FeOT	9.42	7.16	9.80	8.82	10.14	12.06	8.91	9.48
MnO	0.29	0.17	0.19	0.23	0.21	0.23	0.21	0.18
MgO	3.27	2.52	5.05	2.77	3.77	4.90	2.75	4.98
CaO	10.37	7.24	10.50	8.53	11.27	6.10	8.60	10.51
Na ₂ O	3.12	3.32	2.40	3.40	2.47	1.40	3.45	2.71
K ₂ O	0.61	2.06	1.15	1.01	0.48	0.62	1.76	1.06
P ₂ O ₅	0.14	0.15	0.12	0.18	0.14	0.10	0.17	0.14
H ₂ OT	0.49	1.06	0.44	1.42	1.57	8.55	0.83	0.47
CO ₂	0.17	0.18	0.30	0.33	0.57	1.30	0.05	0.17

	ppm							
Ba	578	1299	667	870	648	638	1045	615
Cr	9	6	11	4	9	8	15	59
Cu	233	184	153	207	262	153	188	163
Ga ⁺	18	21	21	23	24	23	21	21
Nb	3	5	5	4	3	4	3	7
Ni ⁺	5	3	8	-	6	5	3	37
Pb ⁺	1	5	8	-	9	5	-	1
Rb	9	36	21	16	9	16	21	23
S	-	-	-	-	-	-	-	600
Sr	753	470	455	515	582	405	560	452
V ⁺	200	152	235	230	330	278	-	241
Y	23	30	24	29	19	25	28	23
Zn	70	81	82	92	85	87	86	83
Zr	66	131	98	86	72	88	90	101

n - number of analyses used to calculate average values

+ - number of samples used to calculate average is less than n

Table 5.2 Pearson correlation matrix for selected oxides and elements from rocks of Telica Complex.

	SiO ₂	TiO ₂	MgO	Na ₂ O	K ₂ O	P ₂ O ₅	Ba	Rb	Y	Zr
SiO ₂	1.00	-0.17	-0.62	0.81	0.76	0.52	0.68	0.67	0.66	0.41
TiO ₂		1.00	0.30	0.08	-0.25	0.13	-0.44	-0.15	-0.03	0.22
MgO			1.00	-0.75	-0.53	-0.59	-0.68	-0.37	-0.64	-0.17
Na ₂ O				1.00	0.52	0.79	0.51	0.37	0.64	0.31
K ₂ O					1.00	0.34	0.77	0.78	0.71	0.66
P ₂ O ₅						1.00	0.35	0.20	0.52	0.16
Ba							1.00	0.67	0.72	0.49
Rb								1.00	0.55	0.66
Y									1.00	0.64
Zr										1.00

	TiO ₂	Cr	Ni	Nb	V
TiO ₂	1.00	0.71	0.81	0.83	0.34
Cr		1.00	0.95	0.72	0.02
Ni			1.00	0.79	0.09
Nb				1.00	0.14
V					1.00

A Pearson correlation coefficient expresses the degree of correlation between two mathematical variables, in this case element or oxide compositions of a rock. Because of the small size of the data set, a high correlation coefficient (> 0.75) is necessary to ensure that the correlation is significant for more than 999 cases out of a 1000 (Lavin et al., 1981).

high-alumina basalt (Tables 4.3 and 5.2), except for their higher Ba, Cu and Sr values and lower Cr, Ni and Zr contents. The Al_2O_3 contents of these rocks show considerable variation (Figure 5.3). Rocks of this Formation have the highest Sr values in the Telica Complex and lower Ba, Rb and Zr contents than most of the other units. The high Sr values may reflect the strongly feldspar porphyritic nature of the basalts (> 40 vol. %).

5.4.2 La Ceiba

The average major and minor element geochemistry of the La Ceiba Formation rocks is comparable to a typical tholeiitic, medium-K basic andesite (Tables 4.3 and 5.2). However, La Ceiba andesites have high Ba, Cu, Rb, Y and Zr contents and low Sr and V values compared to this typical andesite. The Ba contents (820-2240 ppm) are very high, and are at least three times the normal value for a tholeiitic medium-K basic andesite (Gill, 1981). La Ceiba andesites are easily separated from the other less differentiated rocks in the Telica Complex by their higher SiO_2 (up to 60.0 %), K_2O (> 1.5 %), Rb and Zr and lower TiO_2 contents (Figures 5.4 and 5.5).

5.4.3 El Najo

The El Najo Formation rocks have similar major and minor element abundances to a typical high-alumina basalt, except for their K_2O values which are almost twice as great. As with the other formations, trace element abundances do not correlate as well with the typical analysis. Ba, Cu, Pb, Rb and Sr are more abundant and Cr and Ni less abundant than in a typical high-alumina basalt. These differences could reflect

Figure 10. Al_2O_3 versus SiO_2 for Tellica complex gabbros.

Figure 11. Al_2O_3 versus SiO_2 for Tellica complex gabbros. The Al_2O_3 -rich Tellica gabbros are outlined.

Figure 2 is a K-O Harker diagram of the horn complex plotted as $\text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Mg})$ versus $\text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Fe}^{3+})$ and with Fe^{3+} calculated by the method of Banno *et al.* (1968). The hornblende from the hornblende gneiss is plotted at 100% Fe^{2+} .

derivation from a more differentiated parent magma. Basalts of the El Najo Formation contain more MgO than rocks from all other volcanoes except Telica and generally less Al_2O_3 , TiO_2 and Na_2O than the other unaltered rocks of the Telica Complex.

5.4.4 Cerro de Aguero

Tephra and lavas from the Cerro de Aguero Formation are similar to tholeiitic basic andesites and high-alumina basalts. Their K_2O values are characteristic of Gill's low-K basic andesites (1981), although their Ba, Cu, V and Y values are high and their Cr and Sr contents low for a medium-K andesite (Tables 4.3 and 5.2). Rocks of the Cerro de Aguero Formation commonly contain less Na_2O and Cr and more Y than other rocks in the Complex.

5.4.5 Santa Clara

Although Santa Clara Formation basalts are most similar to high alumina basalts (Study of Basaltic Volcanism, 1981; p. 206), their Cr, Ni, and Zr contents are low and Ba, Cu, Pb, Sr and V values high when compared to values from high-alumina basalts. These rocks have the lowest SiO_2 (<49.5 %), K_2O (< 0.65 %) and highest V (> 295 ppm) contents of any of the unaltered rocks in the Telica Complex. Santa Clara Formation basalts also have high Al_2O_3 and CaO and low Ba and Rb contents relative to rocks of the other formations.

5.4.6 San Jacinto

Rocks of the San Jacinto Formation contain higher levels of volatiles (> 8 % $\text{H}_2\text{O}_{\text{total}}$ and > 1 % CO_2) and smaller amounts of most other oxides (<43 % SiO_2 , <7 % CaO and <1.2 % Na_2O) than are found in

unaltered mafic volcanic rocks. If the analyses of Unit 6 are recalculated to 100% without volatiles, the SiO_2 composition (47.4 %) corresponds to that of rocks from Santa Clara. Two relatively immobile elements, Al_2O_3 and TiO_2 , and trace elements are present in the same amounts in both San Jacinto Formation tephra and Santa Clara Formation rocks. Therefore, the original composition of rocks of the San Jacinto Formation probably corresponded to a high-alumina basalt similar to rocks from Santa Clara.

5.4.7 Unit 7 Andesite

Unit 7 lavas have identical major and minor oxide compositions to a tholeiitic medium-K basic andesite (Table 4.3), although they do contain higher contents of Ba, Cu and Y and lower Sr values. The andesites of unit 7 have higher SiO_2 , K_2O , Na_2O (Figure 5.6), Ba and lower Al_2O_3 than most other rocks of the Telica Complex.

5.4.8 Telica

Telica rocks are similar to high-alumina basalts except for their higher contents of Ba, Cr, Cu, Nb, Ni, Rb and Sr. The lavas have higher average abundances of TiO_2 (1.11 %), Cr (59 ppm), Nb (7 ppm) and Ni (37 ppm) than lavas from any of the other volcanoes in the Telica Complex.

The contrast in compatible element contents between rocks of the Telica Formation and those from other formations shows up clearly on Ni versus TiO_2 variation diagram (Figure 5.7). Rocks of the Telica Formation are clearly more enriched in Ni than those from other volcanoes. Telica appears to be a relatively unusual Quaternary volcano in Central America because of its high concentrations of compatible elements.

Figure 5.7 Ni versus TiO₂ variation diagram. The Tellica Formation has higher Ni contents than the other Tellica Complex rocks. Ni and TiO₂ contents correlate for the Tellica Formation rocks.

(Carr et al., 1982; Carr et al., 1981; McBirney and Williams, 1965; Catastro, 1972a; Weyl and Pichler, 1976). Walker (1984) has found higher compatible element contents in cinder cones at Granada and Nejapa.

5.4.9 Summary

Despite general similarities in composition, the Cerro Los Portillos, La Ceiba, Santa Clara and Telica volcanoes have chemical compositions that are sufficiently different to enable distinguishing them from one another and the other volcanoes in the Telica Complex. Unfortunately the few samples analysed from the San Jacinto volcano are too altered to determine any geochemical signature. Systematic variations in composition from one volcano to another do not seem to exist.

5.5 Changes in Composition of Telica

The high correlation coefficients between certain elements in Table 5.2 is strongly influenced by changes in composition of the Telica Formation because it makes up 60 % of the data set. Therefore, a Pearson correlation matrix was determined for the Telica samples which included a series of numbers representing stratigraphic position of each sample (section 3.5.8.8). The resulting correlations are given in Table 5.3 in the right hand column. Both the compatible elements Cr, Mg, Ni and Ti and the incompatible element Ba exhibit weak correlations with stratigraphic position. Manganese exhibits the strongest correlation with stratigraphic position.

Table 5.3 Average Analyses of Telica Formation Rocks

Subunit	Basal Tephra 8a	Flank Lavias 8b	Terminal Lavias 8b	Upper Tephra 8c	Correlation with eruptive sequence
n	3	12	6	5	
	wt %				
SiO ₂	50.23	50.08	50.40	52.20	0.325
TiO ₂	1.53	1.14	1.22	0.88	-0.584
Al ₂ O ₃	16.96	17.34	16.98	17.28	0.112
Fe ₂ O ₃ ⁺	8.6	3.21	3.37	3.5	-
FeO ⁺	2.8	6.79	6.70	6.00	-
FeO _{total} ⁺	10.4	10.12	10.40	10.10	-
MnO	0.16	0.17	0.17	0.19	0.642
MgO	5.76	5.36	5.28	4.05	-0.613
CaO	10.31	10.65	10.38	10.42	0.036
Na ₂ O	2.87	2.65	2.70	2.70	-0.264
K ₂ O	0.88	1.00	1.04	1.20	0.431
P ₂ O ₅	0.16	0.14	0.14	0.13	-0.298
H ₂ O _{total}	0.44	0.44	0.56	0.46	0.192
CO ₂	0.04	0.15	0.51	0.39	0.479
	ppm				
Ba	472	557	579	757	0.601
Cr	134	57	75	29	-0.516
Cu	126	162	150	178	0.406
Ga ⁺	-	21	21	-	0.057
Nb	10	7	8	5	-0.452
Ni	83	38	44	15	-0.610
Pb ⁺	-	-	-	-	-
Rb	19	21	21	28	0.489
Sr	-	125	150	250	0.554
Sr	413	456	434	465	0.368
V ⁺	-	235	240	-	0.512
Y	25	23	23	24	-0.066
Zn	95	82	85	82	-0.261
Zr	107	105	108	92	-0.344

n - number of analyses used to calculate average values
+ - not all samples have been analysed for this element

Similar changes in composition with respect to stratigraphic position can be seen for average analyses of rocks from the Telica Formation (Table 5.3). K_2O , Ba, Cu, and Rb show a general increase while Ti, Cr, and Ni generally decrease with higher stratigraphic position (Figure 5.8). The Al_2O_3 and FeO_{total} values are constant.

Telica rocks can be separated petrographically into two groups based on their phenocryst abundances (section 3.5.8.8). The same separation of Telica samples can be made using Ba, Cr, Ni, Sr and TiO_2 (Figure 5.8). A comparison of the chemistry of these two groups shows that the phenocryst-poor samples are richer in Cr, Ni and Ti and depleted in Ba and Sr relative to the phenocryst-rich samples.

5.6 Mineral Compositions of the Telica Formation

All of the Telica Formation rocks are strongly porphyritic with phenocrysts of olivine, plagioclase, clinopyroxene, orthopyroxene and magnetite. Phenocrysts from selected samples were analysed at both core and rim with an electron microprobe (Appendix V).

Magnesium-rich olivine phenocrysts ($Fe_{81}-Fe_{64}$) are found in all members of the Telica Formation. Individual phenocrysts are continuously zoned, both normal and reverse, and exhibit only small changes in composition (Figure 5.9). Only minor amounts of TiO_2 , CaO, Al_2O_3 , MnO, Na_2O , Cr_2O_3 and NiO_2 are present in the olivines which are within the range of normal olivines (Deer et al., 1966). Both Cr_2O_3 and Ni_2O contents of the Telica olivines are surprisingly low considering the relatively high concentrations of these oxides in the

Stratigraphic
Position

Stratigraphic
Position

Figure 5.8 Changes in composition of Telica Formation rocks with increasing stratigraphic position. Phenocryst-rich samples lie within the shaded area. Oxides in wt % and trace elements in ppm. Samples subdivided into tephra (triangles), flank eruptions (squares) and flows (circles).

Figure 5.9 Olivine phenocryst compositional variations for the Telica Formation.

Figure 5.10 Plagioclase phenocryst compositional variations for the Telica Formation.

rocks (Table V-1). The olivines from the Basal Tephra Member are slightly more magnesium-rich than olivines from the Upper Tephra Member (Figure 5.9). Overall the olivines have similar compositions to a typical island arc olivine (Table V-1), and are very similar to an olivine from the Nejapa cinder cone, Nicaragua (#5, p.319, Walker, 1984).

Plagioclase (An_{55} to An_{85}) is the most abundant phenocryst in Telica Member rocks. Most plagioclases show normal zonation and vary up to 10 % in An content from core to rim (Figure 5.10). They contain minor amounts of K_2O , FeO_{total} , TiO_2 and Ni_2O and are similar in composition to normal plagioclase (Deer et al., 1966). No compositional differences exist between plagioclase phenocrysts from the two tephra members of the Telica Formation. Telica plagioclases are virtually identical in composition to plagioclases from the Granada and Nejapa cinder cones in Nicaragua (Walker, 1984) and a typical island arc plagioclase (Table V-2).

Clinopyroxene phenocrysts are abundant in all Telica Formation members and range in composition from augite to ferro-augite. Individual phenocrysts change very little in composition from core to rim (Table V-3). Even the less abundant oxides, Al_2O_3 , TiO_2 , MnO , Na_2O and Cr_2O_3 , show little variation in abundance and their values fall within the ranges of published analyses (Deer et al., 1966). Analyses of clinopyroxenes from the Nejapa and Granada cinder cones in Nicaragua show greater compositional variation and contain up to twice as much Al_2O_3 and three times as much Cr_2O_3 (Walker, 1984) as Telica clinopyroxenes. The latter are similar to typical island arc clinopyroxenes but contain less Cr_2O_3 (Table V-3).

Hypersthene phenocrysts, found only in rocks of the Upper

-2-

Tephra Member, show normal and reverse zonation. Their MgO and FeO contents are fairly uniform from rim to core. In addition, only minor amounts of TiO_2 , Al_2O_3 , MnO, CaO and Na_2O were found in the phenocrysts. The principal opaque phase in the Telica rocks is titaniferous magnetite that contains from 8 to 10 wt % TiO_2 as well as variable amounts of Al_2O_3 , Cr_2O_3 , V and MgO. Titaniferous magnetite from the Nejapa cinder cone contains up to 15.38 % TiO_2 (Walker, 1984).

5.7 Strontium Isotope Chemistry

Strontium isotope data are useful in evaluating possible sources of volcanic rocks. Previous strontium isotope ratios from Central American volcanic rocks show that they all have average $^{87}\text{Sr}/^{86}\text{Sr}$ ratios fairly close to 0.7040 (Pushkar, 1968; Leeman, 1983). These ratios range from 0.7031 to 0.7046 and are similar to values thought to be typical of modern convergent boundaries (Gill, 1981). A study of Costa Rican lavas from Arenal and Poas shows slight but "significant" variations within the range of 0.7036 to 0.7042 from each volcano that Thorpe et al. (1979) attributed to processes within a magma chamber.

Four samples from the Telica Complex, with the greatest range of Rb/Sr ratios (1.06 to 8.44), were chosen for Sr isotope measurements. Their $^{87}\text{Sr}/^{86}\text{Sr}$ ratios range from 0.70381 to 0.70392 (Table 5.4). Uniform strontium isotope ratios, such as these for Telica rocks, are consistent with their island arc origin and indicate that they were derived from a common parent magma or from a source of uniform composition.

Table 5.4 Strontium isotope analyses

Rock Type	Sample #	Unit	K ₂ O %	Rb ppm	Sr ppm	Rb/Sr weight	⁸⁷ Sr/ ⁸⁶ Sr*
Basalt tephra	15	8c	1.2	26	505	5.15	0.70381
Basalt lava	45	8b	0.83	19	465	4.09	0.70384
Andesite lava	250	2	1.9	38	450	8.44	0.70392
Basalt lava	300	1	0.59	8	755	1.06	0.70385

*-- Normalized to a ⁸⁶Sr/⁸⁸Sr ratio of 0.1194. The Eimer and Amend standard during the course of this study was 0.70801. Reproducibility is considered to be 5 parts in 70,000 at the two sigma level.

5.8 Magma Type

Previous workers have described rocks of the Telica Complex as iron-rich basaltic andesites (McBirney and Williams, 1965), that belong to the Central American calc-alkaline suite (Carr et al., 1982). Telica Complex rocks have high $\text{Na}_2\text{O}/\text{K}_2\text{O}$ and K/Rb ratios which vary from 4 to 6 and 500-1300 respectively. Normative ilmenite is found in all of the Telica Complex rocks, but none contains hydrated minerals such as amphibole. These are features characteristic of younger island arc tholeiitic suites such as the Tonga-Kermadec arc in the Pacific Ocean (Gill, 1981).

Using a variety of variation diagrams the data from the Telica Complex show affinity with tholeiitic suites. On a SiO_2 vs $\text{FeO}_{\text{total}}/\text{MgO}$ variation diagram the Telica Complex volcanic rocks lie wholly within the tholeiitic field defined by Miyashiro (1974) due primarily to their relatively high iron contents (Figure 5.11). On AFM (Figure 5.12), MgO versus $\text{FeO}_{\text{total}}$ (Figure 5.13) and total alkalis versus SiO_2 diagrams (Figure 5.14) most of the Telica Complex rocks plot within the tholeiitic fields. Only the andesites from La Ceiba, Cerro de Aguero and unit 7 lie within the high-alumina field shown in Figure 5.14.

Both typical analyses and classification by variation diagrams show quite clearly that rocks of the Telica Complex belong to an island arc tholeiitic suite, in spite of the fact that some of the andesites exhibit alkali-enrichment.

Figure 5.11. FeO^* versus SiO_2 diagram of the Tellica Complex rocks. All rocks plot within Miyashiro's tholeiitic field.

Figure 6.13. On an $\text{FeO}^{\text{total}}$ versus MgO variation diagram the Tellica Complex volcanic rocks closely parallel the trend of island arc tholeiites.

Figure 6.15. MgO vs. Tellica Complex volcanic rocks. (From William Knaflitz, 1960) The Tellica field on the NaFy versus total alkali variation diagram.

Figure 5.12 AFM diagram of the Felica Complex, showing Tholeiitic and Calc-alkaline fields. The samples lie within the Tholeiitic field.

6. Petrogenesis of Telica

6.1 Introduction

Numerous models have been proposed for the formation of island arc magmas. Until recently most involved a single stage process usually related to the subduction of oceanic crust and associated sediments (Yoder, 1976; Yoder, 1979). Carr et al. (1982) pointed out that the simple derivation of basaltic magma from a subducted oceanic slab does not easily explain the varying Ni, Cr, Rb and Sr abundances of active Central American volcanoes. Now some workers, such as Gill (1981) and Carr (1984), invoke a two-stage model, deriving an initial magma by partial melting from the upper mantle and modifying the magma during its ascent prior to eruption (Figure 6.1). Carr (1984) explained the variation in both physical and chemical characteristics of Central American volcanoes as a function of crustal thickness and magma density.

In this study only the second stage involving the modification of the magma during its ascent is examined because the Telica Complex rocks have changed substantially from their parent magma compositions. Crystal fractionation is emphasized because it appears to be the dominant process affecting magmas feeding Central American Quaternary volcanoes (Carr et al., 1981; Rose et al., 1978).

6.2 Vertically-Zoned Magma Chamber

Although there is no simple relationship between stratigraphic position and composition of Telica basaltic rocks, the older tephra and lava flows contain fewer phenocrysts than the younger flows and tephra (section 3.5.8.8). The phenocryst-poor extrusive rocks have higher

Figure 6.1 Schematic cross-section of the magma reservoir system of a medium-sized stratovolcano (from Gill, 1981).

contents of compatible elements (Cr, Ni and Ti) and are depleted in Ba, K and Sr relative to the more differentiated phenocryst-rich basalt (section 5.4). The distribution of the two types of basalt is most easily explained by eruptions from a vertically-zoned magma reservoir with an upper phenocryst-poor portion and a lower phenocryst-rich portion. Several examples of pyroclastic flows tapping vertically-zoned magma chambers have been described (Smith, 1979; Hildreth, 1979; Smith and Bailey, 1966). MacDonald (1944) has documented vertical zoning in the magma reservoir for the 1840 eruption of Kilauea in Hawaii. Initial olivine-free flows from Kilauea poured out of vents high up on the volcano. Fissures then extended downslope from these vents and olivine-rich basalts effused 600 m lower down the flanks of the volcano.

In the case of volcanoes with a central cone, such as Kilauea or Telica, the magma reservoir can be at such shallow depths within the edifice that magma can easily effuse from different levels of the reservoir. Telica's magma reservoir must have been open at the top because tephra and minor lavas clearly escaped from the vent. In addition lava flows erupted laterally from the volcano and tapped both the top and sides of the magma column.

6.3 Eruption Model

Based on a vertically-zoned magma chamber, a possible eruption model can be deduced from the spatial relationships of the Telica Formation rocks to the volcanic edifice (Map 3). During Telica's initial stages, magma rose from depth and intruded the edifices of La Ceiba and Cerro Los Portillos volcanoes. Eventually phenocryst-poor magma erupted explosively from a new volcanic vent (Figure 6.2a) to form

Figure 6.2 A schematic eruption model of Talica. Phenocryst-rich magma is shown by parallel lines starting to the left of the page.

the lowermost beds of the Basal Tephra Member and to construct much of Telica's cone (Figure 6.2a). As the magma continued to rise it eventually intruded the walls of the conduit at the base of the cone (Figure 6.2b). As the explosive volcanic activity at the central vent began to decline, phenocryst-poor magma erupted on the flanks of Telica near the base of the cone to form the San Rafael, Los Cadales and Los Cedros flows. By this time virtually all of the phenocryst-poor magma had erupted and only the underlying phenocryst-rich magma remained in the conduit. Pyroclastic activity may have ceased at about this time.

As the magma continued to rise, phenocryst-rich magma erupted at higher elevations on Telica's cone to form the El Arenal and Santa Elena flows (Figure 6.2c). Eventually some of the phenocryst-rich magma flowed over the rim of the crater or erupted high on the flanks of Telica to form the Terminal Lava Member flows. A similar sequence of upward migration of eruptive vents occurred in 1914 on the flanks of Sakurajima volcano in Japan (Taneda, 1961).

At this time, the top of the magma column probably stopped rising. There are no large lava flows on the uppermost slopes of Telica. There followed a period of limited duration when the weight of the magma column was equal to the pressure of the rising magma and phenocryst-rich magma continued to erupt from the lateral vents.

Once the pressure of the rising magma had dropped, the magma column began to recede. The change in magma-pressure led to a drop in the pressure on the effusing lava flows and the La Guanabo, La Guatuza, Telica Este and El Azucenal flows began to accumulate on top of existing flows (Figure 6.2d). Eventually the phenocryst-rich magma

receded beyond the feeding fractures for all the flank lavas and effusive activity finally came to a halt (Figure 6.2e).

A period of quiescence followed and dikes were formed by the cooling magma that plugged any fractures in the conduit. At some later stage the magma column started ascending within the conduit of the volcano and started erupting the Upper Tephra Member (Figure 6.2f). This last stage of Telica's volcanic activity continues at present.

Explosive activity could also be attributed to phreatomagmatic eruptions initiated by the influx of meteoric water (Rose, personal communication, 1985). More detailed textural studies of the tephra may help to unravel the mechanisms involved in the production of the pyroclastic rocks.

6.4 Parent Magma

The strongly porphyritic nature and low MgO (<10 wt %) and Ni values (<200 ppm) of rocks from Telica indicate that the volcanic rocks must have come from an evolved parent magma (Basaltic Volcanism Study Project, 1981). Weyl and Pichler (1973) have noted that Telica and nearby Cerro Negro are characterized by less differentiated melts than other Quaternary volcanoes in Nicaragua or Central America. Telica, in particular, has a high compatible element content which suggests that the Telica volcanic rocks are among the least differentiated of the Quaternary rocks of Central America.

Primary magmas commonly have values of $Mg/Mg+Fe^{2+}$ of 0.72 to 0.74 (Study of Basaltic Volcanism, 1981). The $Mg/Mg+Fe^{2+}$ ratios for Telica volcanic rocks are lower (0.40 to 0.61) which suggests these lavas have evolved from a more primary magma.

6.5 Differentiation of Telica's Parent Magma

The dominant processes in the evolution of magma chambers are magma mixing, vapour fractionation and crystal fractionation. Because there is no evidence of magma mixing in the Telica rocks, this mechanism will not be discussed further. Magmas rich in volatiles can transfer elements such as K, Fe, Mn, Na, Si and Zn and volatiles by vapour fractionation or gas transfer (Gill, 1981). Vapour fractionation can lead to depletion of certain elements in the lower parts of the magma reservoir and enrichment of the upper levels in these elements. Minor transfer of H_2O by vapour fractionation may have taken place in the Telica magma chamber. However, many of the marked variations between older and younger Telica volcanic rocks, involve elements such as Cr, Ni and Ti, that are not usually transported by vapour fractionation.

Crystal fractionation has long been considered as one of the principal controls on the evolution of the composition of magmas during their ascent to the surface (Bowen, 1928). The most common type of crystal fractionation is gravity settling of crystals from the magma, a mechanism controlled principally by the density contrast between the liquid and each mineral, crystal size and viscosity of the liquid.

Many of the changes in composition of Telica rocks can be most easily explained by crystal fractionation of the phenocryst phases present in the lavas.

6.6 Crystal fractionation Model for Telica

A computer programme (Appendix VI) was used to calculate evolving liquid compositions as phenocrysts are theoretically removed from an assumed parent liquid. The composition of the most primitive basalt from Telica was used as an approximation to the composition of the

parent magma (sample # 329, Table 6.1); the average composition of the Upper Tephra Member was taken as the most differentiated end member. Phenocryst modal abundances and compositions are utilized as parameters in the programme, and mineral compositions are changed from one iteration to the next to more closely simulate crystal fractionation.

The constant values of (i) the modal abundances of normative plagioclase, clinopyroxene, orthoclase and ilmenite (Table I-4), (ii) the differentiation index, and (iii) the normative An content in rocks of the Telica Formation indicate that differentiation within Telica's magma reservoir must have been caused by changes in ferromagnesian and oxide mineral contents.

The amount of crystalline phases initially removed during the fractional crystallization model (13 %) was calculated from the increase in the average potassium content, an incompatible element, between the Basal Tephra and Terminal lavas (15 % gain in K_2O value). A "best fit" solution required extraction of 9.6 wt % of a crystal mixture of 28 % plagioclase, 27 % olivine, 11 % magnetite, 11 % clinopyroxene, 13 % orthopyroxene, 9 % ilmenite and 1 % apatite (Appendix VI). The resulting composition is close to the average composition of the Upper Tephra samples (Table 6.1).

The major discrepancies of .11 % less FeO_{total} and 54 % more MgO in the calculated daughter composition relative to the average analysis of the Upper Tephra Member. These discrepancies may reflect settling of olivine phenocrysts more Mg-rich than those from Telica during the initial stages of crystal fractionation.

Table 6.1 Results of crystal fractionation model for Telica

	Oxides									
	<u>SiO₂</u>	<u>TiO₂</u>	<u>Al₂O₃</u>	<u>FeO*</u>	<u>MgO</u>	<u>CaO</u>	<u>Na₂O</u>	<u>K₂O</u>	<u>P₂O₅</u>	<u>H₂O_{total}</u>
Parent	50.7	1.4	16.7	6.7	6.1	9.8	2.8	1.1	0.19	0.32
Daughter ⁺	52.3	1.4	16.5	9.00	6.3	10.2	3.0	1.2	0.13	0.36
Tephra*	52.2	0.9	16.3	10.1	4.1	10.4	2.7	1.2	0.13	0.46

parent composition, sample #329

+ - calculated composition of fractionated daughter,
see text for further details

* - average composition of Upper Tephra

Table 6.2 Results of crystal fractionation model for Telica Complex

	<u>SiO₂</u>	<u>TiO₂</u>	<u>Al₂O₃</u>	<u>FeO*</u>	<u>MgO</u>	<u>CaO</u>	<u>Na₂O</u>	<u>K₂O</u>
Parent	50.7	1.4	16.7	6.7	6.1	9.8	2.8	1.1
Daughter+	56.3	0.7	16.9	6.6	3.3	8.2	3.6	2.0
Andesite@	55.4	0.7	17.8	7.2	2.5	7.2	3.3	2.1

parent composition, sample #329

+ - calculated composition of fractionated daughter,
see text for further details

@ - average of samples #255 and #311

Ilmenite was used as a phenocryst phase in the first two iterations of the crystal fractionation model in order to produce reasonable changes in TiO_2 and FeO_{Total} contents. Ilmenite is a common mineral in island arc volcanic rocks and occurs in the norms of the Telica rocks (Table 1-7). The absence of ilmenite in the Telica rocks suggests that the ilmenite, like the Mg-rich olivine, settled beyond the level of the magma reservoir tapped by the effusive rocks of Telica.

Anorthositic blocks observed on the slopes of Telica could be fragments of cumulates produced by fractional crystallization of the magma reservoir. Olivine-rich blocks have yet to be observed.

• 6.7 Crystal Fractionation Model for the Telica Complex

Crystal fractionation of the phenocryst phases present in the Telica Complex lavas (olivine, pyroxene, plagioclase and magnetite) plus ilmenite and trace apatite can explain the principal changes in composition of all the effusive rocks in the Complex. The removal by crystal settling of 35 wt % mixture of plagioclase, clinopyroxene, magnetite, orthopyroxene, olivine and ilmenite mixture can change a magma from the most primitive basalt found on Telica to one with an andesitic composition (Table 6.2), similar to the most siliceous flows in the Telica Complex.

7. Regional Geochemistry of Volcanic Rocks of Northwestern Nicaragua

7.1 Introduction

Volcanic rocks of the Tamarindo Group, Lower Coyol Group, Upper Coyol Group and Marrabños Range volcanoes occur within the study area (Map 1). A description of these rocks is given in Chapter 1 (section 1.6). During the course of the present study samples of these volcanic successions were collected to enable a comparison to be made with rocks from the Mina El Limón area and the Telica Complex. Whole-rock analyses were made of 10 Tamarindo Group, 3 San Cristobal and 3 Cerro Negro samples (Table I-6). The Coyol Group was not sampled because a representative suite of analyses already exists (McBirney and Williams, 1965; Catastro, 1972a).

7.2 Lower Coyol Group

The Lower Coyol Group, consisting of basaltic to rhyolitic lavas, breccias and ashflows (Catastro, 1972a), outcrops near the eastern margin of the Nicaraguan Depression (Map 1).

Average chemical analyses of the mafic Lower Coyol Group rocks, given in Table 7.1, are similar to those of tholeiitic, medium-K, basic andesites (Table 4.3). An average analysis of felsic Lower Coyol Group rocks has oxide contents that fall between those of a typical island arc dacite and rhyolite (Table 4.3). The scattered data points on the variation diagrams (Figures 7.1 to 7.6) may reflect secondary alteration effects.

The Lower Coyol Group samples lie within, or nearly within, the calc-alkaline field on an AFM (Figure 7.1), SiO_2 versus FeO^*/MgO (Figure 7.3), and a K_2O versus SiO_2 (Figure 7.6) diagrams. On a total alkali

Table 7.1 Average analyses of the Tamarindo and Coyoil Groups

	Tamarindo		Lower Coyoil		Upper Coyoil		
	Mafic	Felsic	Mafic	Felsic	Mafic	Felsic	Basalts
	T5	T4	T7	T6	T3	T2	T1
n	3	7	3+	5+	7+	7+	1+
	wt %						
SiO ₂	55.2	72.3	55.1	70.71	57.0	69.1	53.6
TiO ₂	1.2	0.54	.77	0.39	0.82	0.42	0.90
Al ₂ O ₃	15.5	13.6	19.37	14.46	17.0	15.63	17.5
Fe ₂ O ₃ *	7.4	2.0	3.35	2.33	3.53	1.77	5.41
FeO*	4.75	0.68	3.74	0.17	3.35	0.66	3.72
MnO	0.16	0.06	0.08	0.02	0.08	0.02	0.12
MgO	3.3	0.43	2.63	0.8	2.97	0.70	2.90
CaO	7.1	2.25	7.22	2.18	7.56	1.96	7.26
Na ₂ O	3.1	3.5	2.88	3.07	2.62	3.61	2.35
K ₂ O	0.60	2.5	1.71	2.53	1.88	3.52	1.38
P ₂ O ₅	0.17	0.07	0.20	0.21	0.17	0.10	0.25
H ₂ OT	1.34	1.3	-	-	-	-	-
CO ₂	0.34	0.25	-	-	-	-	-
	ppm						
Ba	475	934	-	-	-	-	-
Cr	20	8	-	-	-	-	-
Cu	186	16	-	-	-	-	-
Ga*	21	18	-	-	-	-	-
Nb	4	5	-	-	-	-	-
Ni	12	5	-	-	-	-	-
Pb*	-	5	-	-	-	-	-
Rb*	9	44	-	-	-	-	-
S*	-	-	-	-	-	-	-
Sr	338	192	-	-	-	-	-
V*	375	79	-	-	-	-	-
Y	31	37	-	-	-	-	-
Zn	92	50	-	-	-	-	-
Zr	97	162	-	-	-	-	-

* - only available for some samples

+ - analyses from Table IV (Catastro, 1972a)

n - number of samples

versus silica variation diagram all of the Lower Coyol samples plot in the tholeiitic field (Figure 7.4) because of their relatively low total alkali values at a given SiO_2 content. Therefore, the Lower Coyol Group is considered to be a calc-alkaline succession with minor affinities to island arc tholeiites.

The Lower Coyol Group rocks are different geochemically from the correlative Mina El Limon area Tertiary rocks (Tables 4.2 and 7.1); the latter contains less Al_2O_3 and more K_2O at equivalent SiO_2 values. There are no tholeiitic lavas in the Lower Coyol Group while tholeiitic unit 1 lavas form the base of the volcanic succession in the Mina El Limon area.

7.3 Tamarindo Group

The Tamarindo Group consists of Tertiary andesitic and dacitic lavas, breccias, tuffs and ignimbrites which are correlated with the Lower Coyol Group (Catastro, 1972a). These two groups outcrop on opposite sides of the Nicaraguan Depression, the Tamarindo Group on the western side and the Lower Coyol Group on the eastern side (Map 1).

Tamarindo Group rocks have a bimodal distribution of SiO_2 values; a gap exists between 58.3 % and 66 % SiO_2 (Figure 7.5). Although the average analyses of mafic and felsic Tamarindo Group rocks (Table 7.1) show similarities to tholeiitic, medium-K, basic andesites and calc-alkaline dacites, respectively (Table 4.3), they generally have higher TiO_2 contents at a given SiO_2 content. Some of the felsic Tamarindo Group rocks contain SiO_2 contents typical of rhyolites.

Figure 7.1. TAS diagram of the volcanic rocks of northern Cerro Negro, showing shift from the calc-alkaline to the tholeiitic field (Irvine and Barager, 1921).

Figure 7.2. MgO vs. FeO total variation diagram for the volcanic rocks of northern Cerro Negro.

Figure 7.1 Total FeO versus SiO_2 variation for samples from the northernmost to southernmost volcanic rock group from the calc-alkaline and tholeiitic fields.

Figure 7.2 Total Al₂O₃ versus SiO_2 variation for samples from the northernmost to southernmost volcanic rocks.

Figure 7.5 TiO_2 Harker diagram of the Tertiary volcanic rocks showing the high titanium contents of the bimodal Tamarindo Group.

Figure 7.6 K_2O versus SiO_2 Harker diagram. Symbols explained on Figure 7.4. Boundaries between fields from Pecerillo and Taylor (1976).

A comparison of trace element abundances among the Tamarindo Group and representative analyses of island arc volcanic rocks (Table 4.3) shows that Nb, Rb, Sr and Zr values are similar for given SiO_2 contents while Ba (350-1080 ppm) and Y (17-69 ppm) values are higher and Cr (1-31 ppm) and Ni (1-16 ppm) contents lower. Similar trace element compositions are reported for Quaternary volcanic rocks from northern Central America (Carr et al, 1982). The relatively high Y and lower Cr and Ni values for a given SiO_2 content suggest Central American Quaternary lavas are more differentiated than the island arc sequences listed in Table 4.3.

Virtually all the Tamarindo Group rocks belong to one of two groups when the data are plotted on an AFM diagram. Mafic rocks fall within the tholeiitic field, while most of the felsic rocks fall in the calc-alkaline field (Figure 7.1). Using Irvine and Baragar's classification (1975) half of the samples from the Tamarindo Group are defined as tholeiitic basalts to dacites and the remaining samples as calc-alkaline basalts to rhyolites (Table I-7). The tholeiitic nature of the Tamarindo Group can be clearly shown using other variation diagrams (Figures 7.3 and 7.4).

Tamarindo Group rocks have higher $\text{FeO}_{\text{total}}$ and TiO_2 and lower Al_2O_3 values than the correlative Lower Cuyol Group rocks with similar SiO_2 contents (Tables 7.1 and 4.2). Mafic Tamarindo Group rocks also contain less K_2O than basalts and andesites of the Lower Cuyol Group. The remaining oxides for the two groups are virtually identical. Although the Tamarindo and Lower Cuyol Groups have been correlated on a geological basis (Catastro, 1972a), they are geochemically different.

The Mina El Limon area and Tamarindo Group rocks have similar oxide and trace element compositions but the latter contain more TiO_2 and exhibit a wider range of K_2O values. Tholeiitic basalts occur at the base of both sequences. Although not identical in composition, the Mina El Limon area and Tamarindo Group rocks are quite similar in terms of chemical composition.

7.4 Upper Coyol Group

The Upper Coyol Group consists of basaltic to rhyolitic lavas, breccias and ashflows and outcrops east of the Nicaraguan Depression (Map 1). Rocks from this group show a wide range of SiO_2 values (49.5 % to 72.5 %). Average analyses of mafic rocks of the Upper Coyol Group (Table 7.1) are similar to tholeiitic, medium-K andesites (Table 4.3), while the composition for an average felsic rock falls between the analyses for typical island arc dacite and rhyolite. The Upper Coyol values display considerable scatter on various variation diagrams, probably the result of secondary alteration (Figures 7.1 to 7.4).

Almost all analyses of the Upper Coyol Group plot within the calc-alkaline field on an AFM diagram (Figure 7.1). Plots of MgO versus $\text{FeO}_{\text{total}}$, SiO_2 versus $\text{FeO}_{\text{total}}/\text{MgO}$ and $\text{Na}_2\text{O}+\text{K}_2\text{O}$ versus SiO_2 show that the Upper Coyol Group samples plot in both the tholeiitic and calc-alkaline fields (Figures 7.2 to 7.4). On a K_2O versus SiO_2 variation diagram data from Upper Coyol samples lie within the calc-alkaline field.

The analyses of the Upper Coyol Group display more geochemical variation than all other volcanic successions of Northwestern Nicaragua, except those from the Mina El Limon area. Comparison of analyses from rocks of the Upper and Lower Coyol Groups shows that rocks of the

Upper Coyol contain more K_2O and exhibit more variation in total alkali content than the Lower Coyol (Figures 7.4 and 7.6). In addition, tholeiitic rocks are found in the Upper Coyol Group but not in the Lower Coyol Group.

Although stratigraphically correlated with the Lower Coyol, the Mina El Limon area volcanic rocks exhibit more chemical similarities to the Upper Coyol Group rocks. Average chemical analyses are extremely similar (Tables 4.2 and 7.1) and tholeiitic lavas similar to unit 1 lavas from the Mina El Limon area are contained within the Upper Coyol Group.

The Tamarindo Group rocks are different in composition from the the Upper Coyol Group rocks; the latter generally contain more K_2O and Al_2O_3 and less TiO_2 and FeO_{total} at a specific SiO_2 content.

7.5 Marrabios Range Volcanoes

Volcanoes of the Marrabios Range form a linear chain on the western side of the Nicaraguan Depression (Map 1). They consist mainly of basalt and andesite lavas and tephra with relatively minor amounts of dacitic extrusive rocks. Several new chemical analyses of rocks from Cerro Negro and San Cristobal are given in Table I-6.

The basic character of the rocks from the Marrabios Range is shown by the low average SiO_2 contents ($< 53\%$; Table 7.2). Average analyses of Cerro Negro and San Cristobal (Table 7.2) are similar to high-alumina basalts, except for more Ba and Sr and less Cr and Ni in the latter (Table 4.3; pg 206, Study of Basaltic Volcanism Project, 1981). High Sr values are not found in Tertiary volcanic rocks within the study area but similar abundances are found in other volcanoes in Central America

Table 7.2 Average analyses of active volcanoes in the Marrabios Range, northwestern Nicaragua

	Cosequina	San Cristobal	Telica	Cerro Negro	Momotombo	
n	1@	5+	2	29 wt %	3	1#
SiO ₂	57.84	51.6	50.7	50.86	49.9	52.81
TiO ₂	0.69	0.97	0.9	1.11	0.78	0.83
Al ₂ O ₃	17.76	17.5	19.4	17.22	17.7	17.14
Fe ₂ O ₃ *	2.05	2.3	3.6	2.27	3.17	3.53
FeO*	5.48	7.0	7.5	7.41	7.87	7.35
MnO	0.23	0.20	0.21	0.18	0.19	0.21
MgO	2.31	4.68	3.8	4.98	5.87	4.60
CaO	7.82	10.86	10.7	10.51	11.97	9.29
Na ₂ O	3.86	2.68	2.9	2.71	2.1	2.69
K ₂ O	1.18	0.71	0.73	1.06	0.46	0.80
P ₂ O ₅	0.05	0.05	0.20	0.14	0.08	0.28
H ₂ O ^T	0.45	--	0.29	0.47	0.03	0.09
CO ₂	--	--	0.18	0.17	0.14	0.14
LOI	--	0.2	--	--	--	--
				ppm		
Ba	--	--	487	615	322	--
Cr	--	--	8	59	29	--
Cu	--	--	182	163	143	--
Ga*	--	--	23	21	22	--
Nb	--	--	5	7	5	--
Ni	--	--	1	37	17	--
Pb*	--	--	4	1	9	--
Rb	--	--	14	23	6	--
S*	--	--	--	600	--	--
Sr	--	--	545	452	447	--
V*	--	--	253	241	255	--
Y	--	--	27	23	21	--
Zn	--	--	86	83	21	--
Zr	--	--	91	101	68	--

* - only available for some samples

@ - andesite bomb from 1835 ejecta, Williams (1953)

+ - Hazlett (1977)

- 1905 lava, McBirney and Williams (1965)

(Carr, 1984). The low Cr and Ni contents could reflect the degree of differentiation of the Cerro Negro and San Cristobal magmas.

Data from San Cristobal and Cerro Negro fall completely within the tholeiitic field on an AFM plot (Figure 7.1) and SiO_2 versus $\text{FeO}_{\text{total}}/\text{MgO}$ variation diagram (Figure 7.3). The same holds true for other variation diagrams (Figures 7.2 and 7.4). However, on a K_2O versus SiO_2 diagram (Figure 7.6), the data from Cerro Negro, San Cristobal and the Telica Complex lie within the calc-alkaline field (Figure 5.5). This reflects the high K_2O contents of these rocks at a given SiO_2 content, rather than a truly calc-alkaline chemical signature.

All rocks of the Marrabios Range, including those from the Telica Complex (Table 5.2), are tholeiites. They are similar in composition, not only to each other, but also to the mafic rocks of the Tertiary Tamarindo Group. The Marrabios Range volcanoes typically contain less SiO_2 and K_2O (at a given SiO_2) content than the Miocene Coyoil Group rocks.

7.6 Conclusions

There have been no major changes in the composition of the volcanic rocks erupted in northwestern Nicaragua since the Miocene and it appears that all belong to the same igneous rock suite. In terms of chemical composition this suite falls near the boundary between island arc tholeiites and calc-alkaline volcanics. Mafic volcanic rocks can be found in all areas; felsic volcanic rocks are relatively insignificant in post-Miocene eruptions.

It is interesting to note from the data presented in this chapter that the Mina El Limon area rocks show greater geochemical similarities

to the Upper Coyol Group rocks than the stratigraphically correlative Lower Coyol Group. Furthermore, tholeiitic rocks outcrop on the western side of the Nicaraguan Depression, while the predominantly calc-alkaline Coyol Groups are found near the eastern margin.

8. Groundwater

8.1 Introduction

In many young volcanic terrains, such as Yellowstone National Park, USA; Wairakei, New Zealand; and Kráfla, Iceland, movement of large quantities of water through the country rock is aided by relatively high heat flow. Convective circulation of these waters results in numerous geothermal features such as hot springs and fumaroles. Various studies have shown that the geochemistry and stable isotopic composition of these waters can be used to deduce the source of the water and the extent of its interaction with the country rock (Craig, 1963; Taylor, 1973; Taylor, 1974; Faure, 1977). In this study water samples from hot springs, wells and Lake Managua in western Nicaragua were examined in an attempt to determine their source and compositional variation (Appendix IV).

8.2 Oxygen and Hydrogen Isotopes

The stable isotopes of oxygen and hydrogen are commonly used to determine the source of groundwater (see Appendix IV). Waters from magmatic and metamorphic sources have characteristic oxygen and hydrogen stable isotope compositions. Magmatic waters are believed to have values of $+6$ to $+8$ $\delta^{18}\text{O}$ and -50 to -80 δD , while metamorphic waters commonly fall between $+5$ to $+25$ $\delta^{18}\text{O}$ and -20 to -65 δD (Taylor, 1974). Meteoric waters have different oxygen and hydrogen stable isotope values which can be approximated by the Craig-Epstein meteoric-water line equation (Appendix IV).

8.3 Northwestern Nicaragua

The surface waters of the Pacific Coastal Plain, the northern portion of the Marrabios Range and the northern Nicaraguan Depression drain into the Pacific Ocean. South of this area the continental divide passes from the Nicaraguan Highlands across the Nicaraguan Depression from Santa Lucia to Malpaisillo (Figure 8.1), then follows the crest of the southern portion of the Marrabios Range and passes to the west of Lake Managua. To the south and east of this divide, the surface waters drain into Lake Managua which is part of the Atlantic Ocean watershed.

8.4 Mina El Limon Area

Within the Mina El Limon area the moderate relief of up to 300 m has resulted in a poorly-developed dendritic drainage pattern that is part of the Pacific watershed. The rainfall totals between 200 and 225 cm annually and most of this falls in the rainy season during the months of September, October and November (Gleason, 1977). The water table is commonly several metres to tens of metres beneath the land surface, though two springs occur in the northern half of the map area (Table IV-1). Generally the water table is deeper in the northern part of the map area than the southern part.

The Mina El Limon and Atravesada underground workings are quite dry with a low rate of inflow of groundwater. The small amounts of groundwater probably reflect the higher elevation of these two areas. However, at the Panteon Mine in the mid-1970's, 1800 gallons of water per minute were being pumped from the workings (Gleason, 1977). The water enters the mine on all levels, but the greatest rate of inflow is

Figure 8.1 Locality map of water samples collected during study.

encountered in the 600, 800 and 1000 foot levels. The groundwater temperature ranges from 35⁰ to 70⁰ C (Gleason, 1977). The large volume of groundwater encountered underground at the Panteon Mine reflects the high permeability of the country rocks provided by the numerous fractures and unplugged diamond drill holes.

8.4.1 Geochemistry of Groundwater

The few available analyses of groundwater from the Mina El Limon are from samples collected at the Panteon Mine (Table 8.1; Gleason, 1977, Table 9). These samples are characterized by:

- i) high total dissolved solids contents (>1000 equivalents per million);
- ii) alkaline nature, pH between 6.5 and 8.6; and
- iii) high concentrations of SO₄, Ca, Na, F, and Cl.

Panteon Mine waters are very different in overall chemistry from the local rainfall which has a neutral pH and extremely small concentrations of cations (Gleason, 1977). The surface waters of the Nicaraguan Depression, such as Lake Nicaragua, are also quite different as they have less than one tenth the concentrations of Ca, Na, SO₄ and total dissolved solids found in Panteon Mine groundwater (Figure 8.2).

The composition of the Mine groundwaters result from interaction with the surrounding country rock. The breakdown of feldspars and pyroxenes in the mafic wall rocks to the clay minerals, chlorite and sericite, by hot alkaline water would result in the high Ca, Na and total dissolved solids concentrations such as are found in the Panteon Mine groundwater.

The alkaline nature and chemistry of the mine waters are similar to

Table 5.1. Chemical Analyses[#] of Ground and Lake Water, Nicaragua

	1. Lago de Managua	2. Lago de Managua	3. San Jacinto	4. San Jacinto	5. Santa Pancha	6. Santa Pancha
SiO ₂	13	75	300	155	80	ND
Ca	6	8	80	40	106	100
Mg	22	20	126	14	4	9.7
Na	280	280	70	37	210	211
K	46	50	18	16	13	ND
CO ₃	48	45	0	0	6	7.7
HCO ₃	531	525	0	62	43	4.4
SO ₄	12	22	180	180	430	850
Cl	180	207	0	14	174	71
F	6.8	0.8	0.4	0.5	2.6	2.4
NO ₃	6	1.8	8	3	4	0
PO ₄	0	0	1.2	0.15	0.05	ND
B	0.5	0.2	0.4	0	0	0.8
TDS*	766	782	3407	370	1604	1245
pH	8.9	8.8	3.3	6.1	8.4	8.6
T°C	30	31	100	61.5	61.5	60.6

- in equivalent ppm

* - total dissolved solids

ND - not determined

1. Lago de Managua, west of Mateare; Catastro, 1972a.

2. Lago de Managua, Puerto Momotombo; Catastro, 1972a.

3. red pool, San Jacinto, Catastro; 1972a.

4. mud pot, San Jacinto, Catastro; 1972a.

5. Mina Santa Pancha, Catastro; 1972a.

6. Shaft 6, 1070 level, Mina Santa Pancha; analysis for Empresa Minera de el Gerentirion.

Figure 8.2 Stiff diagram of groundwater compositions from northwestern Nicaragua. Concentrations of four cations are plotted to the left of zero line and likewise four anion concentrations are plotted to the right of zero (after Hem, 1970).

waters in the Wairakei geothermal area of New Zealand (Table 8.2).

The larger ion concentrations in Wairakei groundwaters may be due to the higher temperatures (boiling) of these waters relative to the Panteon Mine groundwater ($<70^{\circ}\text{C}$).

8.4.2 Stable Isotope Chemistry

Water samples from two springs and from various levels of Panteon Mine were analysed to determine their oxygen and hydrogen isotopic compositions. The $\delta^{18}\text{O}$ contents of samples from the Mina El Limon area range between -5.5 and -8.7 per mil while δD values range from -50 to -59 per mil (Table IV-1). The most negative $\delta^{18}\text{O}$ and δD values in the area, -6.4 to -8.6 per mil and -58 and -59 per mil respectively, are associated with the Panteon mine waters.

The Panteon Mine groundwaters have stable isotope compositions of oxygen and hydrogen that are very similar to water samples taken from local springs and wells. A plot of the standard δD vs $\delta^{18}\text{O}$ diagram shows that all the Mina El Limon area samples plot close to the Craig-Epstein meteoric water line (Figure 8.3).

The marked concentration of ^{16}O and ^1H in the Panteon Mine waters is the result of its meteoric origin. This interpretation is consistent with results from other geothermal fields, indicating the circulation of meteoric water through hot country rock (Taylor, 1974).

The small oxygen shift in the Panteon Mine groundwaters may be due to the limited interaction of water with the wall rock. According to Taylor (1974), reduced interaction between groundwater and the country rock can result from rapid circulation or depletion of the ^{18}O content of the wall rock by a geothermal system active for a long period of

Table 1. Chemical composition of ground and lake water

	1. Dead Sea	2. Eagle Lake	3. Lago de Nicaragua	4. Hot water south of Volcan Momotombo	5. Yellowstone National park	6. Green Dragon Spring	7. Wairakei
SiO ₂	ND	10	23	135	302	369	386
Ca	14	4.5	16	104	4	6.5	26
Mg	36	49	--	10	3	--	<0.1
Na	32	220	12	2560	48	243	1130
K	6	59	5.5	228	30	61	146
CO ₃	--	--	0	0	ND	ND	0
HCO ₃	0.18	70	92	49	--	--	35
SO ₄	0.34	1.6	4	100	1100	454	35
Cl	178	22	21	4616	5	408	1930
F	ND	7.0	0.3	1	--	ND	6.2
NO ₃	ND	2.2	0	0.80	ND	ND	ND
PO ₄	ND	ND	0.05	0.75	ND	ND	ND
B	ND	0.03	0	12.7	2.5	6.9	26
TDS	ND	1250	112	6452	1850	ND	3750
pH	ND	ND	6.9	7.8	3	2.5	8.6
T°C	22	ND	25	101	ND	87	boiling

- in equivalent ppm

TDS - total dissolved solids

ND - not determined

1. Dead Sea, Degans & Ross (1969)
2. Closed basin, Eagle Lake near Susanville, California, Livingstone, (1963)
3. Lago de Nicaragua, Puerto Diaz, Catastro, (1972a)
4. Hot water, south of Volcan Momotombo, Catastro, (1972a)
5. Spring 33, Norris Geyser Basin, Yellowstone National Park; Hem (1970)
6. Green Dragon Spring, southern part of Norris Basin, Yellowstone National Park, White et al. (1963)
7. Drillhole 4, 1245 ft deep, about 3000 feet southeast of Geyser Valley, Wairakei, North Island, New Zealand, White et al. (1963)

time. At the Panteon Mine the latter explanation is favoured because there is widespread propylitic alteration of the country rocks which was produced by higher temperature geothermal fluids. However, more complicated groundwater systems such as those described by Bethle and Robert (1979) may also be applicable.

8.4.3 Conclusions

All water in the Mina El Limon area, regardless of temperature, is meteoric in origin. The composition of the groundwater from the Panteon Mine can best be explained by limited interaction of mafic volcanic wall rock with the hot alkaline waters. The source of heat is presumed to be an intrusive body cooling at some depth nearby. The geothermal system at the Panteon Mine may represent either a degrading geothermal system which deposited the gold-bearing quartz veins or a genetically distinct, later geothermal system.

8.5 Telica Complex

The Telica Complex is an area of moderate to high relief with variations in elevation of up to 1200 m. The volcanic edifices within the Complex exhibit a radial surface drainage pattern which is part of the Pacific watershed. Leon, immediately to the south, receives an average of 164 cm of rainfall annually and most of it falls during the rainy season (Aid Resources Center, 1966); the rainfall on the Telica Complex probably exceeds this amount because of its pronounced relief. The water table in the Telica Complex typically varies from tens of metres to over 180 m below the surface. There are eight areas where a shallow water table and high heat-flow combine to form hot springs and/or fumaroles (Table 3.2).

8.5.1 Geochemistry of Groundwater

The only published analyses of groundwater from the Telica Complex are from the San Jacinto hot springs (Table 8.1). This water has a low pH, high concentrations of sulfate and dissolved silica, and surprisingly small amounts of chloride. The overall chemistry of the San Jacinto water samples resembles analyses from acid springs in the Norris Basin, Yellowstone National Park (Table 8.2). The Stiff diagram (Figure 8.2) shows that San Jacinto water has a different composition from Pantéon Mine water and surface waters from the Nicaraguan Depression (Lake Nicaragua and Lake Managua).

The only geothermal field in Nicaragua which has been drilled extensively is on the flanks of Momotombo volcano, north of Lake Managua. In contrast to water from the Momotombo geothermal field (Table 8.2), the San Jacinto hot springs contain low concentrations of boron which is derived primarily from volcanic gases (Hem, 1970). Therefore, it would seem that volcanic gases are not important in the geochemical evolution of the San Jacinto hot springs.

8.5.2 Stable Isotope Geochemistry

Water samples from a San Jacinto mud pot, El Najo hot spring, El Carol spring and six wells in the Telica Complex were analysed to determine their isotopic composition (Appendix IV). The $\delta^{18}O$ values vary between -4.7 and -6.3 per mil except for the San Jacinto mud pot which has a +1.2 per mil value. The water samples from El Najo, San Jacinto and a well northeast of the town of Telica have δD concentrations of

-49, -35 and -59 per mil respectively.

Both the δD and $\delta^{18}O$ values of the Telica Complex water samples are different from the values reported for metamorphic and magmatic waters (Taylor, 1974) and are close to values for meteoric water. The availability of meteoric water probably controls the cyclic, seasonal activity of springs and fumaroles associated with the Telica Complex. activity peaks during or following the rainy season because of the greater flow of groundwater at these times.

The water from the mud pot at San Jacinto has higher values of $\delta^{18}O$ (1.2 per mil) and δD (-35 per mil) than the other samples. The San Jacinto hot-springs range in temperature from 60⁰ to 108⁰ C (Catastro, 1972a) and are associated with a number of fumaroles. The area has been investigated for its geothermal power potential (Fergusson, personal communication, 1977) but has not been developed. The positive $\delta^{18}O$ value in the mud pot water is thought to be due to exchange between the hot groundwater and country rock. The δD value of the mud pot sample is higher than δD values of water elsewhere in the Telica Complex. This is attributed to deuterium enrichment by non-equilibrium evaporation of steam, a feature common in acid geothermal systems (Taylor, 1974).

8.5.3 Conclusions

The water associated with the Telica Complex is meteoric in origin and derives heat from interaction with wall rock heated by sub-volcanic processes. Only the composition of the San Jacinto sample has been

significantly affected by wall-rock interaction. The San Jacinto geothermal field is the only near-surface area in the Telica Complex which has the potential to produce substantial amounts of geothermal power.

The Mina El Limon and Telica Complex water samples are very similar in stable isotope composition except for the San Jacinto sample. The differences in chemical composition, no doubt reflect the different subterranean paths of these groundwaters. The lower elevations in both areas derive their groundwater, at least in part, from the same catchment basin.

8.6 Lake Managua

The central and southern portions of the Nicaragua Depression drain into Lake Managua and Lake Nicaragua, which belong to the Atlantic Ocean watershed. Lake Managua covers 1049 square km and is fed by a drainage area of 6277 square kilometers (Catastro, 1972b). There is only limited outflow from Lake Managua.

Water samples were taken from Lake Managua in an attempt to determine the source of the lake water and its relationship to groundwater in northwestern Nicaragua. The lake waters are essentially a solution of sodium bicarbonate with high total dissolved solids compared to most surface waters (Table 8.1). The boron, fluoride and chloride concentrations are also high for surficial fresh water. The overall water composition is similar to Eagle Lake, a closed basin in California (Table 6.2).

Two water samples from Lake Managua collected at Puerto Momotombo and Cafe Ali Negro (Figure 8.2) were analysed to determine their stable

isotope ratios. The resulting values were $\delta^{18}O$ contents of 1.2 and 1.3 per mil respectively and δD contents of -11 per mil which are similar to isotopic compositions of waters from closed basins and the Red Sea (Faure, 1977).

A high evaporation rate coupled with limited outflow could explain the high salinity and the unusual oxygen and hydrogen isotopic compositions of water from Lake Managua.

The waters of Lake Managua are enriched in D and ^{18}O relative to to groundwater from the Telica Complex and the Mina El Limon area.

Because this difference in stable isotopic composition would be even more pronounced if the waters of Lake Managua interacted with silicate wall rock and/or magmatic and metamorphic waters, it seems unlikely that water from Lake Managua is feeding the Telica Complex or Mina El Limon area groundwater systems.

9. Geological History of the Mina El Limon Area and the Telica Complex

9.1 Mina El Limon Area

The mafic volcanic rocks at the base of the Mina El Limon volcanic succession were erupted from a Miocene volcano located to the south or east of the present position of Mina El Limon. This volcano shed lahars (unit 1) and effused basaltic and andesitic lavas (units 1 and 2) onto the adjacent plain much like the Recent volcanoes in western Nicaragua. These mafic volcanic rocks were deposited distal to the volcano in a predominantly subaerial environment. Minor intercalated conglomerates, sandstones and siltstones were derived from the same volcanoes. These epiclastic rocks probably formed from mudflows and streams.

Later in the Miocene, unit 3 dacite lavas erupted subaerially on the flanks of the volcano to form domes. In the Mina El Limon area domes formed at Tres Cerritos, Cerro Los Natos and north of Cerro Tigra. Felsic talus breccias and lahars derived from the domes piled up on the flanks of these domes, while volcanic breccias and conglomerates were deposited farther away. Some of the conglomerates formed in streams.

Unit 4 proximal to distal andesite and dacite flows erupted from a vent at Cerro Penasca and possibly others in the Mina El Limon area. These flows were deposited subaerially and completely covered the dacite domes.

The volcanic sequence was cut during the Miocene by dacitic intrusions, some as old as the co-magmatic dacite lavas and domes (unit 3), others younger than unit 4 andesite and dacite lavas. The dacite intrusions probably came from a high-level felsic magma chamber in the

Mina El Limon area.

The mafic dikes (unit 6) are presumed to be younger than all the conformable rocks (units 1, 2, 3 and 4) because they are mineralogically similar to Pliocene basalts and andesites which outcrop to the north and east of the Mina El Limon area. Any volcanic rocks related to these dikes have been eroded in the Mina El Limon area.

North- and northeast-trending normal faults formed after the extrusion of unit 4 flows in the Late Miocene or Pliocene. Dacite dikes intruded along some of these faults. The same set of faults also served as conduits for hydrothermal fluids which deposited auriferous quartz veins and altered the wall-rock. A second set of generally younger east-trending faults developed in the Mina El Limon area as well.

The most recent geological event in the Mina El Limon area has been the deposition of Pleistocene to Recent tephra and alluvium.

9.2 Telica Complex

The Telica Complex is composed of six volcanoes: Cerro Los Portillos, La Ceiba, San Jacinto, Cerro de Aguero, Santa Clara, and Telica. They range in age from Pli-Pleistocene to Recent.

The first volcano, Cerro Los Portillos, erupted high-alumina basalt lava in the present region of Cerro Los Portillos and Cerro Montosa (Figure 10.1a). Little is known about this volcano which has suffered extensive erosion and is covered by younger tephra deposits. The Cerro Los Portillos volcano is thought to be significantly older than the other volcanoes of the Telica Complex because it has no visible crater.

a) Cerro Los Portillos

b) La Celba

c) El Najo

d) Cerro de Agüero and Santa Clara

e) San Jacinto and Santa Clara

f) Tellica

La Ceiba, the next volcano to form, erupted basic andesite lavas which are believed to have come from the La Ceiba crater. The lavas spread to the north, east and south of the crater (Figure 10.1b) and now underly several of the younger volcanoes of the Telica Complex (cross-sections, Map 3). At roughly the same time, high-alumina El Najo basalts from the San Jacinto crater and flowed primarily to the north and east (Figure 10.1c).

Either Cerro de Aguero or Santa Clara was next to erupt. It is possible that these two volcanoes were active simultaneously (Figure 10.1d). Both volcanoes have experienced very little erosion and both have produced flows and tephra. The basic andesite flows and tephra from Cerro de Aguero were deposited on the flanks of this small volcano. Although high-alumina basalt flows from Santa Clara are pre-historic, Santa Clara exhibited solfateric activity as recently as the sixteenth century and may have been active for a considerable time.

High-alumina basalt lapillistone and ash erupted during the following stage from the San Jacinto crater (Figure 10.1e). This eruption may have been similar in character to the 1835 plinian explosions of Cosequina (Williams, 1952) and eruptions from Pelona and Monte Galan near San Cristobal volcano (Hazlett, 1977).

Telica, the last volcano to erupt in the Telica Complex, produced high-alumina basalt tephra and flows. A detailed eruption model for Telica is given in section 6.3. A phase of weak explosive activity has continued to the present day interspersed with periods of solfateric exhalations. Telica's most recent tephra eruption was in 1982.

10. Conclusions

10.1 Mina El Limon Area

The important findings from the Mina El Limon area are:

- 1) The 400 m thick volcanic succession consists of basal tholeiitic basalts and andesites overlain by calc-alkaline andesites and dacites.
- 2) The succession is made up of the following map units (listed in order of decreasing age):
 - unit 1) basalt and andesite volcanoclastic rocks and lavas;
 - unit 2) two-pyroxene andesite porphyry flows;
 - unit 3) dacite domes, flows and volcanoclastic rocks;
 - unit 4) andesite and dacite flows.
 - unit 5) dacite dikes and stocks
 - unit 6) mafic dikes
- 3) The volcanic succession is divided by two sets of faults into fault-bounded blocks of shallowly-dipping volcanic rocks. One set, trending north- and northeast, is associated with quartz veins and dacite dikes. A second set of east-trending faults offsets some of the north- to northeast-trending faults.
- 4) The volcanic succession is cross-cut by steeply-dipping quartz veins, many of which contain gold and silver. Quartz is the principal vein mineral; pyrite, carbonate, chalcopyrite and sphalerite are minor constituents.

5) Quartz veins, ubiquitous in the area, are enveloped by hydrothermal wall-rock alteration. In mafic volcanic rocks the alteration grades outward from the veins, passing first into a sericite-adularia zone, then an argillic zone and finally into a propylitic zone. Silicification related to the east-trending faults and potassium metasomatism have also affected parts of the volcanic succession.

6) Exploration criteria for locating auriferous quartz veins in the Mina El Limon area are:

- i) north- and northeast-trending faults, veins and dacitic dikes;
- ii) quartz veins with a nearly complete volcanic succession in the hanging wall; and
- iii) areas of argillic and sericite-adularia alteration.

7) Although the Mina El Limon area volcanic succession is stratigraphically correlated with the Lower Coyol Group (Hodgson, 1972), it is geochemically more similar to the Upper Coyol Group.

10.2 Telica Complex

The important findings from the Telica Complex are:

- 1) The Telica Complex is made up of lavas, tephra, alluvium, lahars and intrusive rocks. Listed in order of decreasing age these units are:

- unit 1 - Cerro Los Portillos Formation
- unit 2 - La Ceiba Formation
- unit 3 - El Najo Formation
- unit 4 - Cerro de Aguero Formation
- unit 5 - Santa Clara Formation
- unit 6 - San Jacinto Formation
- unit 7 - Coral Falso andesite lava
- unit 8 - Telica Formation
- unit 9 - alluvium and colluvium

- 2) The youngest volcano, Telica, is composed of pyroxene basalt porphyry tephra and lava (Telica Formation) which outcrop on the western half of the Telica Complex. The Telica Formation is subdivided into the following members:

- i) Basal Tephra Member;
- ii) El Porvenir Lava Member;
- iii) El Pegon Lava Member;
- iv) La Martinez Lava Member;
- v) Los Ranchos Lava Member;
- vi) Terminal Lava Member; and
- vii) Upper Tephra Member.

- 3) The Telica Complex igneous rocks on the basis of chemical composition are considered island arc tholeiites. Uniform $\frac{87}{86} \text{Sr/Sr}$ ratios from the Telica Complex suggest that these rocks came from a common parent magma or were derived from a relatively uniform source.

- 4) High-alumina basalts and basic andesites are the two important rock types of the Telica Complex. The basalts have lower Ba (< 700 ppm) and SiO_2 (< 54 %) contents and higher CaO , FeO_{total} and MgO values than the andesites.
- 5) High-alumina basalts make up the Cerro Los Portillos, El Najo, Santa Clara and Telica Formations, while basic andesites form the La Ceiba Formation and Corral Falso lavas. Both high-alumina basalts and basic andesites have erupted from Cerro de Aguero. San Jacinto Formation tephra consists of altered, high-alumina basalt.
- 6) The volcanoes Cerro Los Portillos, La Ceiba, Santa Clara and Telica each possess unique chemical criteria which can be used to distinguish them from the other volcanoes in the Telica Complex.
- 7) There are no systematic variations in composition among volcanoes.
- 8) The distribution and compositional variations of Telica rocks is best explained by tapping a vertically-zoned magma chamber at different levels.
- 9) Crystal fractionation of the phenocryst phases present in the Telica Complex rocks (olivine, plagioclase, orthopyroxene, clinopyroxene and magnetite) plus ilmenite could have produced the range of oxide compositions seen in both Telica and Telica Complex rocks.
- 10) Explosive eruptions from Telica or Santa Clara tephra are the principal volcanic hazard in the area.

10.3 Volcanic Rocks of Northwestern Nicaragua

New chemical analyses of rocks from the Tamarindo Group and volcanoes from the Marrabios Range and published analyses of rocks from the Coyol Group enable comparisons to be made with rocks from the Mina El Limon area and Telica Complex. The significant findings are:

- 1) There have been no major changes in composition of the volcanic rocks erupted in northwestern Nicaragua since the Miocene.
- 2) The Lower and Upper Coyol Groups have different geochemical compositions.
- 3) The Mina El Limon area rocks are similar in composition to rocks from the Upper Coyol Group.
- 4) Tamarindo Group volcanics contain more $\text{FeO}_{\text{total}}$ and TiO_2 less Al_2O_3 than the stratigraphically correlative Lower Coyol Group.
- 5) The mafic rocks from Cerro Negro, San Cristobal, the Telica Complex and the Tamarindo Group are similar in composition.

10.4 Waters of Northwestern Nicaragua

The stable isotope and chemical compositions of water from the study area support the following conclusions:

- 1) The water is meteoric.
- 2) The geothermal waters at San Jacinto exhibit a strong oxygen shift.
- 3) Lake Managua has stable isotopic ratios characteristic of a closed basin in an arid region.

10.5 Summary

Two areas in Northwestern Nicaragua, one near Mina El Limon and the other centred on the volcano Telica, have been studied in detail. The Mina El Limon area is generally representative of the Miocene and Pliocene-Coyol Group rocks, while the the Telica Complex is an excellent example of the Pliocene to Recent volcanoes forming the Marrabios Range. Mafic rocks of the ~~Miocene~~ Tamarindo Group are compositionally equivalent to the Telica Complex rocks.

These two areas have both similarities and differences. The main similarities are:

- 1) the mafic rocks are petrologically similar with abundant phenocrysts of plagioclase and pyroxene;
- 2) high-alumina basalts and medium-K andesites are common;
- 3) the mafic volcanic rocks erupted from large stratovolcanoes;
- 4) volcanic activity led to groundwater circulation; and
- 5) east- and north-trending structures are common.

The main differences are:

- 1) extensive alteration occurred in the Mina El Limon area;
- 2) hydrothermal activity in the Mina El Limon area produced auriferous quartz veins;
- 3) felsic rocks are not found in the Telica Complex; and
- 4) most volcanic rocks in the Mina El Limon area are calc-alkaline; those in the Telica Complex are tholeiitic.

Both the nature and composition of the Cenozoic mafic volcanic rocks in northwestern Nicaragua show that the character of volcanism has not changed greatly from the Miocene to the present.

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Appendix I

Lithogeochemical Analyses

Introduction

One hundred volcanic and intrusive rocks from Northwestern Nicaragua were analysed for the following oxides and trace elements: SiO_2 , TiO_2 , Al_2O_3 , MnO , MgO , CaO , Na_2O , K_2O , P_2O_5 , H_2O total (L.O.I. minus CO_2), CO_2 , Ba, Cr, Cu, Nb, Ni, Rb, Sr, Y, Zn, and Zr. Iron was analysed as $\text{FeO}_{\text{total}}$ or Fe_2O_3 and FeO . Several samples were also analysed for Ga, Pb, V and S.

All weathered surfaces were removed from the samples prior to crushing. The samples were then broken into pea-sized chips using a core-splitter and rock hammer. The chips were powdered in a tungsten carbide Bleuler mill to minus 200 mesh. All equipment was washed with distilled water and acetone between samples to minimize contamination. The tungsten carbide mill was periodically cleaned by grinding quartz.

The powders were submitted in five batches to Durham Science Laboratories at the University of Durham, Durham, England (under the supervision of Dr. G. Holland) and Memorial University, St. John's, Newfoundland (analyst, D. Press). Seven samples were included in more than one batch to determine precision.

Both precision and accuracy of the analytical results are discussed below. Precision is the "degree of agreement or uniformity of repeated measurements of a quantity" and "relates to the quality of the operation by which the result is obtained" (Bates et al., 1980). Accuracy is defined as the degree of perfection attained in a measurement.

Durham Science Laboratories

The samples were analysed by X-ray fluorescence and the oxide results recalculated to 100%. All iron was determined as FeO. The Durham analyses are precise to the first or second decimal place for the major elements and to about 1-2 ppm for most trace elements (G. Holland, personal communication, 1978). More specifically he reports precisions for the trace elements as follows:

Ba - 4-5 ppm
Cr - 2 ppm
Nb - 1-2 ppm
Zr, Y, Sr, Rb - 1 ppm
Zn, Cu, Ni - 1 ppm

A comparison of analyses from Durham Science Laboratories and published analyses for U.S.G.S. standards is presented in Table I.1.

Memorial University

The oxides were analysed by atomic absorption using a Perkin-Elmer 360 instrument at Memorial University, Newfoundland. The sample (0.1 gm) was dissolved in 5.0 ml of hydrofluoric acid and 50 ml of saturated boric acid solution and made up to 200 ml with distilled water. The samples were compared with a suite of standards with approximately the same concentrations as the samples.

The trace elements Ba, Cr, Cu, Ga, Nb, Ni, Pb, Rb, Sr, V, Y, Zn and Zr were analysed on a Phillips 1450 automatic X-ray fluorescence unit. The peak intensities were compared with those obtained from U.S.G.S. rock standards. The correction for mass absorption was based on measurements of the Compton scatter peak of the silver tube.

Appendix II

Petrographic Descriptions

Introduction

Representative samples with whole rock analyses from Mina El Limon and the Telica Complex were studied petrographically to determine their mineralogy, texture, degree of alteration and mode (Tables II-2 and II-3). More complete descriptions of the petrography of each unit are given in chapters 2 and 3.

Modal Analysis

Modal analyses were made on a 0.5 mm by 0.5 mm grid using an automatic Swift counter and stage. One thousand or more counts were taken for each sample (Chayes, 1956; Galehouse, 1971); for several smaller sections only 500 to 999 counts were made. Estimated modes are indicated by an asterisk after the sample number.

The statistical uncertainty associated with point counting has been determined by Nentwich (personal communication, 1980) after Kelley (1971). Multinomial distribution curves using a poisson distribution below 5 volume % and a bimodal distribution over 5 volume % (Figure II-1) can be used to determine the probable error at a 75% confidence level in point counting. For example, three times out of four for 1000 counts the probable error is less than the following:

<u>Volume Percentage</u>	<u>Probable Error(+/-)</u>
1%	0.36%
10%	1.1%
20%	1.5%
50%	1.8%

Table I-1. Comparison of Chemical Analyses with U.S.G.S. Standards

	AGV-1			GSP-1			PCC-1				
	Durh.	Publ.	Mem.	σ	Durh.	Publ.	Mem.	σ	Durh.	Publ.	Mem.
SiO ₂		59.0	59.63	0.90(3)		67.38	68.65	0.60(7)		41.90	42.0
TiO ₂		1.04	1.08	0.11(3)		0.66	0.60	0.08(7)		0.015	0.0
Al ₂ O ₃		17.25	17.13	0.23(4)		15.25	14.77	0.22(7)		0.74	0.3
Fe ₂ O ₃		4.51	6.70	0.33(4)		1.77	4.22	0.07(8)		2.85	2.13
FeO		2.05	*	*		2.31	*	*		5.24	5.20
MnO		0.097	0.10	0.00(4)		0.042	0.04	0.01(8)		0.042	0.11
MgO		1.53	1.47	0.07(4)		0.96	0.96	0.03(7)		43.18	43.10
CaO		4.90	4.78	0.16(4)		2.02	1.94	0.07(8)		0.51	0.0
Na ₂ O		4.26	4.06	0.12(4)		2.80	2.74	0.06(8)		0.006	0.0
K ₂ O		2.89	2.88	0.10(3)		5.53	5.44	0.12(6)		0.004	0.0
P ₂ O ₅		0.49				0.28				4.70	4.7
H ₂ O total		0.81				0.57				0.12	0.0
CO ₂		0.06				0.15				99.89	99.89
Total		99.91				99.84					
Ba	1204	1208	1218	27(10)	1297	1300	1288	13(6)	<5	1.2	1.5
Cr		12/2	12	3(10)		12.5	13	2(6)			
Cu		59.7	64	2(10)		33.3	38	2(6)			
Ga		20.5	23	2(10)		22	24	2(6)			
Nb	17	15	12	1(10)	29	29	21	2(6)	2	0.4	
Ni		18.5	13	3(10)		12.5	8	4(6)			
Pb		35.1	37	5(10)		51.3	56	4(6)			
Rb	69	67	70	3(10)	260	254	252	3(6)	1	0.063	
S		<10	ND	ND		162	ND	ND		10	
Sr	657	657	687	11(10)	236	233	237	5(6)	1	0.41	
V		125	129	5(10)		52.9	60	5(6)		30	33
Y	20	21.3	22	1(11)	30	30.4	25	2(11)	1	5	10
Zn	88	84	87	2(10)	103	98	102	2(6)	40	36	43
Zr	230	225	233	3(10)	530	500	471	2(6)	6	7	5

Durh. - Durham Science Laboratories Mem. - Memorial University σ - one standard deviation
 Publ. - value published in Flanagan, 1973. * - all iron determined as Fe₂O₃ (6) - number of samples

The precision of the Memorial analyses as determined from Table I-2 for 3 duplicate samples is better than or equal to:

	Plus or Minus
TiO ₂ , Fe ₂ O ₃ , MnO, K ₂ O	0.03%
MgO, CaO, FeO	0.10%
SiO ₂ , H ₂ O total	0.15%
Al ₂ O ₃	0.20%
Na ₂ O, P ₂ O ₅	0.23%
Nb, Ni, Pb, Rb, Y	1 ppm
Gr	2 ppm
Zn	2.5 ppm
Cu, V	4 ppm
Cr, Zr	6 ppm
Sr	9 ppm
Ba	16 ppm

Analyses of three U.S.G.S. standards at Memorial University compare favourably with reported values (Flanagan, 1973).

Repeat analyses of MgO, Na₂O, Cr, Cu and Zr from Memorial University show more variation than was found for the same elements for the U.S.G.S. standards. This suggests better results could have been obtained through multiple analyses of the same sample or adoption of another analytical technique.

Interlaboratory Comparison

Seven identical samples were analysed by both laboratories (Table I-2). The difference and correlation between results for the oxides and trace elements is presented in Table I-3. The correlation between the

Table I-2. Comparison of Chemical Analyses from Durham Science Laboratories and Memorial University

	40			43			58			88			98
	D-2	M-1	M-3	D-2	M-3	D-2	M-1	D-1	M-2	D-1	M-2	D-1	M-1
SiO ₂	50.3	50.61	50.80	51.4	51.7	43.01	43.82	73.8	73.5	73.8	73.5	80.3	80.3
TiO ₂	1.7	1.49	1.45	0.91	0.82	0.35	0.37	0.62	0.20	0.62	0.20	0.17	0.17
Al ₂ O ₃	16.6	16.66	16.30	17.2	17.8	17.22	17.85	13.1	12.4	13.1	12.4	11.3	11.3
Fe ₂ O ₃	2.55	2.55	2.55		3.54		3.54		1.57		1.57		
FeO*	11.0	7.87	7.85	10.3	6.32	9.57	5.68	1.7	0.14	1.7	0.14	0.99	0.99
MnO	0.17	0.16	0.17	0.19	0.18	0.11	0.12	0.02	0.01	0.02	0.01	0.03	0.03
MgO	5.1	6.09	6.26	4.0	4.52	11.21	11.49	0.41	0.33	0.41	0.33	0.13	0.13
CaO	10.8	10.14	10.27	10.8	10.20	17.29	16.87	0.58	0.67	0.58	0.67	0.28	0.28
Na ₂ O	2.7	3.05	2.61	2.6	2.68	0.30	0.51	1.7	1.84	1.7	1.84	0.49	0.49
K ₂ O	0.81	0.87	0.87	1.1	1.19	0.13	0.00	4.5	4.71	4.5	4.71	6.0	6.0
P ₂ O ₅	0.13	0.18	0.14	0.11	0.11	0.02	0.02	0.01	0.01	0.01	0.01	---	---
H ₂ O total	0.69	0.87	0.54	0.80	0.49	0.54	---	2.9	3.46	2.9	3.46	0.39	0.39
CO ₂	---	0.0	0.28	0.64	0.30	---	0.50	0.7	---	0.7	---	---	---
Total	100.0	100.54	99.82	100.1	99.85	99.75	100.77	100.0	98.84	100.0	98.84	100.1	100.1
Ra	420	424	417	720	703	40	30	1560	1930	1560	1930	1170	1170
Cr	165	109	97	36	14	240	148	12	---	12	---	9	9
Cu	135	110	102	230	189	20	8	20	30	20	30	7	7
Ga	ND	17	20	ND	21	ND	16	ND	18	ND	18	ND	ND
Nb	15	10	11	6	5	3	3	8	8	8	8	3	3
Ni	86	71	67	20	2	75	61	9	9	9	9	10	10
Pb	ND	2	4	ND	---	ND	2	ND	12	ND	12	ND	ND
Rb	16	16	17	25	25	2	2	140	127	140	127	120	120
S	300	ND	ND	200	ND	200	ND	500	ND	500	ND	400	400
Sr	410	408	390	485	466	369	359	90	82	90	82	83	83
V	ND	250	252	ND	275	ND	177	ND	12	ND	12	ND	ND
Y	23	23	25	23	26	4	7	43	39	43	39	24	24
Zn	90	94	89	68	85	32	43	44	45	44	45	19	19
Zr	100	103	114	82	102	2	21	210	167	210	167	103	103

D - Durham Science Laboratories, M - Memorial University FeO* - all iron as FeO, --- not detected

Table I-2 Continued.

	98		119		125		250		364	
	M-1	D-1	M-1	D-1	M-1	D-1	M-2	M-2	M-2	M-2
SiO ₂	79.11	57.23	58.45	61.58	63.06	63.06	56.3	56.0	76.5	76.8
TiO ₂	0.12	0.86	0.82	0.74	0.64	0.64	0.78	0.76	0.50	0.54
Al ₂ O ₃	10.52	17.63	16.41	15.76	14.83	14.83	17.4	17.1	14.2	14.6
Fe ₂ O ₃	0.72		2.55		2.62	2.62	3.57	3.54	0.10	0.05
FeO	0.12	8.82	6.18	6.29	3.55	3.55	4.64	4.74	0.05	0.09
MnO	0.02	0.26	0.26	0.15	0.14	0.14	0.18	0.19	0.003	0.004
MgO	0.08	4.93	3.49	2.90	2.11	2.11	2.82	2.82	0.00	0.0
CaO	0.41	1.50	1.40	3.21	3.02	3.02	7.14	7.11	0.00	0.02
Na ₂ O	0.60	4.12	4.92	3.88	3.98	3.98	3.37	3.33	0.015	0.45
K ₂ O	6.22	0.19	0.18	1.41	1.25	1.25	1.88	1.90	0.04	0.04
P ₂ O ₅	0.0	0.21	0.15	0.13	0.13	0.13	0.13	0.18	0.19	0.64
H ₂ O total	1.11	3.17	2.78	3.40	3.46	3.46	0.40	0.57	6.17	6.06
CO ₂	0.48	0.77	1.54	---	0.59	0.59	---	0.07	0.32	0.07
Total	100.04	99.69	100.57	99.45	99.38	99.38	98.61	98.31	98.09	99.36
Ba	1175	138	129	1893	2405	2405	1100	1131	608	624
Cr	---	69	19	8	1	1	5	1	5	9
Cu	4	27	26	73	60	60	162	159	26	24
Ga	10	ND	18	ND	15	15	19	23	25	27
Nb	4	4	3	3	3	3	4	6	3	2
NI	3	18	7	8	3	3	4	2	---	---
Pb	9	ND	1	ND	3	3	---	---	1	---
Rb	109	6	6	23	23	23	38	39	4	3
S	ND	2000	ND	1500	ND	ND	ND	ND	ND	ND
Sr	76	428	396	363	331	331	451	453	723	716
V	11	ND	286	ND	141	141	195	192	155	163
Y	19	29	28	31	27	27	29	29	12	13
Zn	23	174	136	77	66	66	88	90	13	12
Zr	84	89	88	122	109	109	140	141	142	141

Table I-3. Variation and Correlation for Seven Samples Analysed by
Durnam Science Laboratories and Memorial University

	<u>Maximum Variation</u>	<u>Common Variation (5 Samples)</u>	<u>Correlation</u>
	<u>Oxides (wt. %)</u>		
SiO ₂	1.5	< 0.5	0.999
TiO ₂	< 0.40	< 0.10	0.952
Al ₂ O ₃	< 0.80	< 0.50	0.969
MnO	< 0.01	< 0.01	0.996
MgO	< 1.44	< 0.55	0.977
CaO	< 0.70	< 0.50	1.00
Na ₂ O	< 0.80	< 0.20	0.990
K ₂ O	< 0.22	< 0.15	0.999
P ₂ O ₅	< 0.06	< 0.01	0.915
H ₂ O total	< 0.72	< 0.45	0.941
CO ₂	< 0.87	< 0.60	0.241
	<u>Trace Elements (ppm)</u>		
Ba	< 600	< 10	0.992
Cr	< 92	< 50	0.804
Cu	< 41	< 15	0.960
Nb	< 5	< 3	0.931
Ni	< 19	< 15	0.914
Rb	< 13	< 2	1.00
Sr	< 32	< 22	0.994
Y	< 5	< 4	0.963
Zn	< 38	< 20	0.961
Zr	< 43	< 25	0.968

@ between two samples

two sets of results is greater than .9 except for CO_2 and Cr. Cr values from Durham Science Laboratories were consistently higher (50% or more) than results obtained from Memorial University.

Data Presentation

The analyses for the Nicaraguan samples are listed in Tables I-4, I-5 and I-6. The oxides are reported to two figures for concentrations less than 10% and to three figures for values greater than 10%. Trace element concentrations greater than 100 and 1000 ppm respectively, are rounded off to the nearest 5 and 10 ppm respectively. The CIPW normative mineralogy and ~~rock name~~ (Table 1.7) were determined using a computer programme that recalculates the oxide values to total 100% without volatiles (Irvine and Baragar, 1971). The Differentiation Index (Thorton and Tuttle, 1960) is the sum of the weight percentages of normative quartz, orthoclase, albite, nepheline, leucite and kalsilite.

Specific Gravity

Specific gravity was determined for selected samples from the Mina El Limon area. Fourteen determinations were made with a Model 930 Beckman Air Comparison Pycnometer at the University of Waterloo, Ontario using rock powders. A balance at the Geological Survey of Canada was used for 20 fist-sized rock samples to determine their specific gravity by weighing first in air, and then in water. The latter results are always lower than those from the pycnometer.

Table 1.3a Specific gravity determinations for Mina El Limon samples

Pycnometer	Balance	Difference
28	2.44, 2.45	
31	2.42, 2.42	
88	2.14, 2.16	
93	2.58, 2.60	
98	2.18, 2.19	
104	2.42, 2.42	
119	2.81, 2.76, 2.77	
120	3.36, 3.25, 3.30	
121	2.82	
122	2.85	
125	2.62, 2.72, 2.68	
129	2.80	
130	2.77	
132	2.85, 2.90, 2.88	
149	2.95	
173	2.60	
209	2.42, 2.42, 2.43	.33, .33, .34
210	2.70, 2.70, 2.70	
226	2.60	
284	2.84	.10
286	2.60	
363	1.89, 1.96	
364	2.38, 2.38	.24, .24
371	2.72, 2.70	
395	2.43, 2.44	
410	2.78	
416	2.30, 2.30	.37, .37
439	2.45	
440	2.72	

296 2.79 sample from Telica

Legend for Tables I-4, I-5 and I-6.

Form. - Formation

Mem. - Member

ND - not determined

--- - not detected

D.I. - Differentiation Index

* - analysis by Durham Science Laboratories

Norm - CIPW norm determined from analyses
recalculated to 100 % and "excess" Fe_2O_3 ,
anything greater than $\text{TiO} \% + 1.5 \%$, is
converted to FeO (Irvine and Baragar,
1971).

Table 1-4 Chemical Composition and Normative Mineralogy of Volcanic and Plutonic Rocks from the Toluca Complex, Nicaragua

Sample	Cerro Los Portillos			La Ceiba		El Najo	Unit 7		S. Clara
	flows	flows	flows	flows	flows	flow	flows	flow	flow
	77-300	76-56*	76-57	77-311	77-467	77-464	76-80*	77-302	77-552
Oxides (wt. %)									
SiO ₂	49.5	51.6	51.3	54.6	60.0	51.7	53.6	54.7	43.8
TiO ₂	0.88	0.93	0.87	0.80	0.54	0.74	0.97	0.76	0.95
Al ₂ O ₃	20.1	18.9	20.4	18.3	16.5	16.8	17.4	17.8	20.0
Fe ₂ O ₃	4.4	ND	3.9	3.4	2.3	4.0	ND	3.8	8.6
FeO	5.6	9.6	5.6	4.4	3.4	6.1	10.2	4.2	3.8
MnO	0.21	0.20	0.20	0.17	0.16	0.20	0.24	0.18	0.24
MgO	3.7	2.9	3.2	2.1	1.7	5.1	2.8	2.7	4.5
CaO	10.2	10.9	10.0	7.8	4.9	10.5	9.6	7.6	10.2
Na ₂ O	3.1	3.1	3.3	3.3	3.6	2.4	3.6	3.3	2.3
K ₂ O	0.59	0.61	0.63	2.9	2.6	1.2	0.91	2.6	0.26
P ₂ O ₅	0.13	0.15	0.15	0.16	0.16	0.14	0.18	0.16	0.13
H ₂ O total	0.56	0.73	0.19	1.2	1.8	0.49	0.50	1.15	7.7
CO ₂	---	0.42	0.15	---	0.59	0.52	---	0.14	0.85
Total	99.0	100.0	100.0	99.1	98.3	99.9	100.0	99.1	98.3
Trace Elements (ppm)									
Ba	590	515	630	995	2446	740	710	1180	830
Cr	25	21	3	---	6	13	24	5	7
Cu	270	230	200	130	44	125	250	125	300
Ga	19	ND	1	21	22	20	ND	20	24
Nb	2	4	1	4	4	4	5	---	3
Ni	---	9	1	4	3	6	1	6	8
Pb	1	ND	1	2	2	---	ND	---	9
Rb	8	7	11	28	47	21	17	24	7
S	ND	100	ND	ND	ND	ND	300	ND	ND
Sr	755	770	735	485	465	455	560	560	555
V	210	ND	190	145	69	230	ND	145	365
Y	21	23	25	32	38	24	26	30	20
Zn	74	64	71	84	63	82	96	76	100
Zr	93	38	67	140	165	96	65	115	92
CIPW Norm (wt. %)									
Q		0.53	1.6	4.5	16.2	2.4	0.62	5.1	
Or	3.6	3.7	3.8	17.7	15.9	7.2	5.4	15.5	1.6
Ab	26.3	26.1	28.1	28.1	31.7	21.0	30.9	28.2	20.3
An	40.2	36.5	39.2	27.3	22.1	31.8	28.7	27.1	46.5
Ne									
Di	4.4	4.9	3.9	4.4	1.0	9.3	4.8	4.4	2.4
He	4.4	9.8	4.2	5.0	0.69	7.4	10.7	4.3	2.6
En	7.3	5.0	6.3	3.3	3.9	8.4	4.7	4.8	4.6
Fs	8.3	11.4	7.6	4.4	3.0	7.7	11.9	5.3	5.8
Fo	0.05								4.3
Fa	0.07								5.9
Mt	3.5		3.5	3.4	3.4	3.3		3.4	1.8
Ln									
Hm									
Il	1.7	1.8	1.7	1.6	1.7	1.4	1.9	1.5	1.9
Ru									
Ap	0.31	0.35	0.35	0.38	0.39	0.42	0.42	0.38	0.32
Po									
D.I. #	29.9	30.3	33.4	50.3	63.8	30.5	36.9	48.9	21.9

Table 1-4 Continued

Sample	Santa Clara flows		Cerro de Agüero flows			La Cebalga flows			San Jacinto tuff
	76-96*	77-450	76-60*	77-348	77-349	77-250	77-255	77-263	77-457
Oxides (wt. %)									
SiO ₂	49.4	48.8	56.8	51.7	52.2	56.3	56.1	49.8	42.5
TiO ₂	0.82	0.80	0.71	0.82	0.88	0.78	0.76	0.76	0.88
Al ₂ O ₃	19.8	20.2	16.9	18.8	18.6	17.4	17.3	19.6	21.2
Fe ₂ O ₃	ND	4.1	ND	9.9	3.6	3.6	3.5	9.2	8.2
FeO	9.3	5.9	7.6	1.5	6.8	4.6	4.7	0.06	3.5
MnO	0.19	0.20	0.21	0.27	0.22	0.18	0.18	0.18	0.23
MgO	2.9	3.9	1.5	3.5	3.3	2.8	2.8	3.2	4.5
CaO	11.9	11.7	6.5	9.3	9.8	7.1	7.3	9.1	6.9
Na ₂ O	2.9	2.2	4.4	2.9	2.9	3.4	3.3	3.0	1.7
K ₂ O	0.64	0.53	1.4	0.74	0.90	1.9	1.8	1.1	0.43
P ₂ O ₅	0.19	0.09	0.27	0.12	0.14	0.13	0.14	0.16	0.14
H ₂ O total	2.0	--	3.1	0.83	0.34	0.50	0.32	1.6	8.2
CO ₂	0.10	0.82	0.65	0.18	0.37	--	0.34	0.14	1.5
Total	100.1	99.2	100.0	100.6	100.1	98.3	98.5	97.9	99.9
Trace Elements (ppm)									
Ba	600	515	1130	740	750	1100	1140	820	535
Cr	15	6	6	4	2	5	6	5	3
Cu	270	215	72	105	245	160	165	420	180
Ga	ND	23	ND	21	24	19	18	23	25
Nb	4	2	4	4	3	4	6	6	4
Ni	1	8	9	--	--	4	--	1	4
Pb	ND	--	ND	--	--	--	11	4	2
Rb	10	9	21	9	17	38	43	23	10
S	100	ND	ND	ND	ND	ND	ND	ND	ND
Si	610	580	510	515	520	450	460	520	355
V	ND	295	ND	230	230	195	185	165	325
Y	17	19	31	30	26	29	29	24	26
Zn	72	82	90	91	95	88	85	82	92
Zr	40	84	76	92	90	140	110	110	80
CIPW Norm (wt. %)									
Q		1.2	6.9	3.8	3.9	8.7	8.8	3.9	4.3
C									6.4
Or	3.9	3.2	8.4	4.4	5.4	11.3	11.0	6.5	2.8
Ab	24.8	19.2	38.3	24.4	24.6	29.1	28.6	26.9	16.2
An	40.0	44.3	23.3	36.8	35.4	27.3	27.6	38.5	37.2
Ne									
Di	5.6	5.9	1.7	3.4	4.8	3.3	3.6	3.3	
He	10.7	5.8	5.2	4.3	5.8	3.2	3.5	3.1	
En	1.8	7.2	3.2	7.2	6.1	5.7	5.5	6.9	12.6
Fs	4.0	8.0	11.0	10.4	8.5	6.3	6.2	7.6	14.6
Fo	2.1								
Fe	5.2								
Mt		3.4		3.4	3.5	3.4	3.4	3.4	3.9
Il									
Ru	1.6	1.6	1.4	1.6	1.7	1.5	1.5	1.5	1.9
Ap	0.45	0.21	0.65	0.28	0.33	0.34	0.33	0.39	0.36
Po									
D.L. #	28.6	23.6	53.7	32.7	33.9	49.1	48.5	35.3	23.3

Table I-4 Continued

A13

Sample	San Jacinto	Tellica			Tellica				
	ruff	Basal Tephra			El Porvenir Lava Member				
	77-466	76-49*	77-329	76-48*	76-55*	77-214	77-245	76-18*	77-328
Oxides (wt. %)									
SiO ₂	42.7	50.0	50.7	50.2	51.3	49.5	51.2	51.5	53.2
TiO ₂	0.97	1.6	1.4	1.6	1.6	1.4	0.91	1.3	0.95
Al ₂ O ₃	19.1	17.1	16.7	17.2	16.9	16.6	17.0	17.0	17.2
FeO	8.5	ND	8.6	ND	ND	2.8	3.4	ND	2.3
MnO	5.4	10.6	2.8	10.3	10.1	7.7	6.4	10.3	6.8
MgO	0.23	0.17	0.17	0.15	0.16	0.17	0.18	0.17	0.18
CaO	5.3	5.6	6.1	5.6	5.0	6.8	5.1	4.5	4.8
Na ₂ O	5.3	10.6	9.8	10.6	10.7	10.4	9.9	10.8	9.6
K ₂ O	1.1	2.9	2.8	3.0	3.0	2.7	2.7	2.8	2.8
P ₂ O ₅	0.80	0.77	1.4	0.80	0.83	0.82	1.3	1.0	1.4
H ₂ O total	0.06	0.15	0.19	0.13	0.14	0.12	0.12	0.13	0.19
CO ₂	8.9	0.50	0.32	0.49	0.30	0.38	0.11	0.03	0.51
Total	1.1	--	0.13	--	--	--	0.21	0.28	--
Total	99.5	100.0	100.8	100.1	100.0	99.4	98.5	99.8	99.9
Trace Elements (ppm)									
Ba	740	465	505	450	400	400	715	640	800
Cr	13	155	98	150	155	110	28	74	26
Cu	125	100	150	130	120	145	170	175	190
Ga	20	ND	23	ND	ND	18	20	ND	19
Nb	4	9	10	2	13	8	4	11	5
Ni	6	87	72	89	86	68	19	40	16
Pb	--	ND	3	ND	ND	2	1	ND	--
Rb	21	18	22	18	16	17	32	22	29
S	ND	100	ND	--	100	ND	ND	100	ND
Sr	455	425	400	415	420	415	450	455	455
V	230	ND	230	ND	ND	230	230	ND	215
Y	24	23	28	24	22	26	19	24	26
Zn	82	95	97	93	81	91	81	83	74
Zr	96	99	120	100	100	110	115	105	125
IPW Norm (wt. %)									
Q	7.3	--	--	--	--	--	1.4	--	3.7
C	7.8	--	--	--	--	--	--	--	--
Or	5.3	4.6	6.4	4.8	4.9	4.9	7.6	6.2	8.6
Ab	10.6	24.5	23.8	25.1	25.4	22.8	23.3	23.8	23.4
An	29.2	31.5	29.9	31.4	30.4	31.2	31.2	30.9	30.5
Ne	--	--	--	--	--	--	--	--	--
Di	--	8.3	9.1	8.5	8.4	10.9	8.8	8.0	7.9
Hc	--	8.8	5.3	8.7	9.6	5.4	6.1	10.6	5.4
En	14.9	3.7	10.8	3.2	5.4	8.8	8.9	5.4	8.4
Fs	18.8	4.5	7.3	3.8	7.2	5.0	7.1	8.2	6.6
Ed	--	4.6	0.15	4.8	2.2	2.3	--	1.5	--
Fa	--	6.2	0.11	6.3	3.2	1.5	--	2.6	--
Mt	4.0	--	4.2	--	--	4.1	3.6	--	3.3
Ln	--	--	--	--	--	--	--	--	--
Hm	--	--	--	--	--	--	--	--	--
Il	2.1	3.1	2.6	3.0	3.0	2.8	1.8	2.5	1.8
Ru	--	--	--	--	--	--	--	--	--
Ap	0.16	0.35	0.44	0.30	0.33	0.28	0.28	0.30	0.44
Po	--	--	--	--	--	--	--	--	--
D.I. #	23.2	29.4	30.1	29.9	30.3	27.7	32.3	30.0	35.7

Table 1-4 Continued

A14-

Sample	El Pegon Lava Member				Tellico Martinez Lava Member		Los Ranchos Flow	Terminal Lavas	
	77-248	77-261	77-268	77-293	77-279	76-45*	76-59*	76-54*	76-40
	Oxides (wt. %)								
SiO ₂	49.8	48.7	50.0	48.8	49.6	47.7	49.7	52.5	50.8
TiO ₂	1.5	0.97	1.2	0.99	0.97	1.0	0.89	0.67	1.5
Al ₂ O ₃	16.4	18.1	17.4	17.5	17.3	17.9	18.8	17.6	16.3
Fe ₂ O ₃	3.5	3.3	3.0	3.7	3.7	ND	ND	ND	2.6
FeO	7.0	6.7	6.7	6.5	6.5	10.2	10.1	10.0	7.6
MnO	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.19	0.17
MgO	6.3	5.9	5.5	5.7	5.4	4.7	4.6	3.8	6.3
CaO	10.1	11.2	10.1	10.9	10.9	11.4	11.8	10.7	10.3
Na ₂ O	2.7	2.4	2.7	2.5	2.5	2.6	2.4	2.8	2.6
K ₂ O	0.89	0.94	1.1	0.96	1.0	0.83	0.89	1.1	0.87
P ₂ O ₅	0.14	0.13	0.14	0.12	0.13	0.14	0.13	0.10	0.14
H ₂ O total	--	0.26	0.31	0.21	0.24	2.44	0.53	0.40	0.54
CO ₂	0.36	--	--	--	--	0.96	--	0.00	0.28
Total	98.8	98.8	98.3	98.1	98.4	100.1	100.0	100.0	99.82
Trace Elements (ppm)									
Ba	415	515	585	495	520	575	650	720	415
Cr	98	34	--	26	37	48	45	32	97
Cu	135	180	155	160	165	165	130	160	100
Ga	22	22	20	27	21	ND	ND	ND	20
Nb	9	8	7	8	5	6	3	4	11
Ni	67	24	35	28	18	32	27	17	67
Pb	--	--	--	1	--	ND	ND	ND	4
Rb	17	20	21	19	19	19	19	26	17
S	ND	ND	ND	ND	ND	100	200	400	ND
Si	420	510	455	475	475	465	430	475	390
V	225	255	220	260	260	ND	ND	ND	250
Y	23	23	24	20	22	20	21	23	25
Zn	88	79	77	88	76	80	80	76	89
Zr	120	105	120	105	105	76	69	83	115
CIPW Norm (wt. %)									
Q	0.35	--	0.36	--	--	--	--	0.18	1.2
C	--	--	--	--	--	--	--	--	--
Or	5.4	5.7	6.8	5.8	6.2	5.1	5.3	6.7	5.2
Ab	22.8	20.3	22.9	21.2	21.5	22.8	20.6	23.8	22.3
An	30.8	36.6	32.9	34.7	33.6	35.9	38.0	37.1	30.5
Ne	--	--	--	--	--	--	--	--	--
Di	10.4	9.6	9.0	9.8	10.1	7.8	7.3	6.7	10.7
Hc	5.3	6.0	5.1	6.4	6.9	10.1	9.7	10.8	5.8
En	11.1	6.6	9.9	7.1	8.3	0.49	3.1	6.1	10.8
Fs	6.4	4.7	6.5	5.3	6.5	0.32	4.7	11.6	6.8
Fe	--	2.7	--	2.0	0.57	5.6	3.5	--	--
En	--	2.2	--	1.7	0.49	9.2	5.9	--	--
Mt	4.4	3.6	4.0	3.7	3.7	--	--	--	3.7
In	--	--	--	--	--	--	--	--	--
Ilm	--	--	--	--	--	--	--	--	--
Il	2.8	1.9	2.3	1.9	1.9	2.0	1.7	1.7	2.8
Ru	--	--	--	--	--	--	--	--	--
Ap	0.33	0.31	0.33	0.29	0.31	0.34	0.30	0.23	0.33
Po	--	--	--	--	--	--	--	--	--
D.L.	28.5	25.9	30.1	27.0	27.7	27.8	25.9	30.0	28.7

Table 1-4 Continued

A15

Tefica

Sample	Terminal Lava Member				Upper Tephra Member				
	76-41*	76-46*	77-289	77-330	76-10*	76-14*	76-15*	76-17*	76-43
					Oxides (wt. %)				
SiO ₂	49.0	50.8	50.4	51.0	51.4	51.1	52.7	51.7	51.7
TiO ₂	1.5	1.1	1.1	0.88	0.89	0.92	0.92	0.93	0.82
Al ₂ O ₃	17.4	16.9	17.1	17.2	16.7	16.3	14.1	16.8	17.8
Fe ₂ O ₃	ND	ND	3.0	4.5	ND	ND	ND	ND	3.5
FeO	10.5	10.3	6.6	5.9	10.1	10.5	10.0	10.6	6.3
MnO	0.16	0.18	0.17	0.19	0.19	0.18	0.18	0.19	0.18
MgO	5.1	4.3	5.4	5.3	3.7	4.8	3.9	4.4	4.5
CaO	10.6	11.0	10.0	10.0	10.0	10.7	10.7	10.6	10.2
Na ₂ O	2.9	2.7	2.7	2.6	2.7	2.6	2.7	2.6	2.7
K ₂ O	0.84	1.1	1.1	1.3	1.4	1.1	1.2	1.1	1.2
P ₂ O ₅	0.15	0.13	0.13	0.13	0.14	0.13	0.15	0.12	0.11
H ₂ O total	0.46	1.3	0.32	0.19	0.24	0.63	0.37	0.41	0.59
CO ₂	1.5	0.33	--	0.42	0.49	--	--	0.45	0.30
Total	100.1	100.1	98.0	99.6	100.0	100.0	100.0	99.9	99.9
					Trace Elements (ppm)				
Ba	525	655	575	725	845	720	700	700	705
Ca	140	56	55	28	38	31	32	31	14
Cu	145	190	155	160	125	260	220	205	190
Ga	ND	ND	21	22	ND	ND	ND	ND	21
Nb	10	9	9	3	6	6	4	6	5
Ni	74	26	37	18	20	19	17	19	2
Pb	ND	ND	--	--	ND	ND	ND	ND	--
Rb	19	25	21	25	35	21	26	28	25
S	100	200	ND	ND	200	5800	100	200	ND
Sr	420	465	445	450	455	485	505	475	465
V	ND	ND	230	235	ND	ND	ND	ND	275
Y	21	21	24	23	25	22	23	24	26
Zn	95	76	86	78	77	82	75	88	85
Zr	99	92	120	115	105	80	81	86	100
					CIPW Norm (wt. %)				
Q	--	--	1.1	0.66	1.9	0.84	1.0	--	2.1
C	--	--	--	--	--	--	--	--	--
Or	5.1	6.5	6.9	8.0	8.3	6.3	7.0	6.5	7.1
Ab	24.7	24.3	22.9	22.0	23.3	22.3	23.2	22.5	22.9
An	32.7	31.7	32.1	31.9	29.3	29.7	31.1	31.1	33.4
Ne	--	--	--	--	--	--	--	--	--
Di	7.7	8.1	9.2	8.3	6.4	8.8	6.9	7.3	7.7
He	9.0	11.5	5.4	6.2	10.4	10.0	10.6	10.6	6.4
En	1.9	5.0	9.6	9.5	6.4	7.9	6.5	6.8	7.8
Fs	2.5	8.2	6.4	8.1	12.0	10.4	11.5	11.3	7.4
Fo	5.2	1.5	--	--	--	--	--	0.64	--
Fa	7.8	2.7	--	--	--	--	--	1.2	--
Mt	--	--	3.9	3.5	--	--	--	--	3.4
Ln	--	--	--	--	--	--	--	--	--
Hm	--	--	--	--	--	--	--	--	--
Il	2.9	2.1	2.2	1.7	1.7	1.7	1.8	1.8	1.6
Ru	--	--	--	--	--	--	--	--	--
Ap	0.36	0.31	0.31	0.31	0.33	0.30	0.35	0.28	0.26
Po	--	--	--	--	--	1.7	--	--	--
D.I. *	29.8	29.2	30.9	30.7	33.5	29.5	31.2	29.0	32.1

Table 1-4 Continued

A16

Tephra

Sample	Upper Tephra Member			intrusive fragment 76.58	E1 Na 10 How 77.324
	76.45*	76.51*	76.52*		
	Oxide (wt. %)				
SiO ₂	51.9	51.9	53.1	43.8	50.2
TiO ₂	0.86	0.89	0.81	0.37	0.69
Al ₂ O ₃	17.5	17.3	18.5	17.9	17.3
Fe ₂ O ₃	ND	ND	ND	3.5	3.9
FeO	9.7	10.3	9.2	5.7	6.3
MnO	0.19	0.19	0.18	0.12	0.18
MgO	3.9	4.0	3.5	11.5	5.0
CaO	10.2	10.8	10.2	16.9	10.5
Na ₂ O	2.9	2.6	3.0	0.51	2.4
K ₂ O	1.3	1.1	1.3	--	1.1
P ₂ O ₅	0.15	0.13	0.13	0.02	0.10
H ₂ O total	0.47	0.76	0.39	--	0.38
CO ₂	0.98	0.11	0.04	0.50	0.10
Total	100.1	100.1	100.1	100.8	91.02
	Trace Elements (ppm)				
Ba	810	765	865	30	505
Cr	26	31	22	150	8
Cu	175	190	105	8	170
Ga	ND	ND	ND	26	21
Nb	4	4	3	3	75
Ni	18	13	17	61	9
Pb	ND	ND	ND	2	8
Rb	30	27	29	2	21
S	100	400	1000	ND	ND
Sr	455	465	455	360	455
V	ND	ND	ND	175	240
Y	24	22	22	7	24
Zn	85	83	72	43	82
Zr	93	87	88	21	100
	UPW Norm (wt. %)				
Q		0.12	0.98		1.0
Or	7.9	6.8	7.6		6.5
Ab	24.7	21.9	25.4		21.0
An	31.3	32.6	32.0	46.4	34.1
Ne				2.3	
Di	6.5	6.9	5.6	21.1	8.3
He	9.6	10.6	8.7	7.2	7.0
In	5.8	6.9	6.1		8.7
Fs	9.9	12.2	10.9		8.3
Fo	0.81			13.2	
Fa	145			5.7	
Mt				2.7	3.3
In				0.61	
Hm					
	1.7	1.7	1.6	0.70	1.4
Ru					
Ap	0.35	0.30	0.30	0.05	0.24
Po			0.28		
D.I.	32.6	28.8	34.0	2.3	28.6

Table 1-5 Chemical Composition and Normative Mineralogy of Volcanic and Plutonic Rocks from the Mina El Limon Area, Nicaragua

Sample	Mina El Limon mafic flows					Santa Pancha mafic flows				
	76-93*	76-149	77-284	77-286	77-479	76-119	76-120*	76-121*	76-122*	
	Oxides (wt. %)									
SiO ₂	62.1	54.2	56.7	56.5	55.6	58.5	58.3	54.4	59.5	
TiO ₂	1.0	0.91	0.59	0.57	0.76	0.82	0.82	0.74	0.74	
Al ₂ O ₃	15.3	16.4	17.4	17.2	15.0	16.4	19.4	15.6	16.4	
Fe ₂ O ₃	ND	6.7	3.2	2.9	3.8	2.6	ND	6.0	ND	
FeO	6.9	2.2	4.2	4.3	2.6	6.2	9.4	8.1	8.9	
MnO	0.15	0.14	0.15	0.16	0.14	0.26	0.13	0.18	0.24	
MgO	1.7	1.2	4.0	3.8	1.8	3.5	3.7	5.9	8.0	
CaO	5.6	7.1	8.5	8.5	4.7	1.4	1.6	8.0	7.7	
Na ₂ O	4.0	2.4	3.0	2.8	2.1	4.9	1.4	2.7	2.4	
K ₂ O	1.8	2.4	0.79	0.9	2.8	0.18	0.80	0.16	0.08	
P ₂ O ₅	0.27	0.22	0.09	0.07	0.20	0.15	0.14	0.10	0.10	
H ₂ O total	1.2	4.2	1.3	2.1	8.1	2.9	4.1	3.9	6.1	
CO ₂	---	2.0	0.60	0.35	1.7	1.5	0.25	0.48	---	
Total	100.0	100.1	100.5	100.2	99.3	100.6	100.0	100.2	100.1	
	Trace Elements (ppm)									
Ba	440	875	550	605	1070	130	430	440	390	
Cr	6	30	13	12	7	19	32	29	32	
Cu	62	51	87	88	105	26	100	37	98	
Ga	ND	21	20	22	18	18	ND	ND	ND	
Nb	4	5	2	4	6	3	1	3	5	
Ni	7	13	1	2	2	7	13	17	14	
Pb	ND	---	---	2	2	1	ND	ND	ND	
Rb	50	60	8	13	66	6	21	2	3	
Sr	100	ND	ND	ND	ND	ND	600	1700	1600	
Si	385	330	390	495	140	395	245	405	355	
V	ND	220	235	215	145	285	ND	ND	ND	
Y	44	38	22	20	34	28	26	22	22	
Zn	92	67	69	70	69	135	110	75	100	
Zr	225	145	76	86	145	88	81	79	82	
	CIPW Norm (wt. %)									
Q	14.7	13.4	11.4	12.6	20.6	18.3	32.7	9.0	2.0	
C					0.48	6.3	14.2			
Or	10.6	14.9	4.7	5.5	18.3	1.1	5.0	0.99	0.51	
Ab	34.5	21.9	26.7	23.9	20.2	43.9	12.5	23.7	20.3	
An	18.7	28.8	32.2	32.7	24.6	6.3	7.4	31.4	36.6	
Ne										
Di	2.0	1.9	5.0	5.0				4.1	1.7	
Hc	4.6	4.3	3.2	3.2				3.2	1.1	
En	3.4	2.4	7.7	7.3	5.0	9.2	9.7	13.3	20.5	
Fs	9.1	6.3	5.6	5.4	5.0	9.4	16.4	12.0	15.0	
Fo										
En										
Mi		3.7	3.7	3.1	3.7	3.7				
Il										
Il	1.9	1.8	1.1	1.1	1.6	1.7	1.6	1.5	1.5	
Ru										
Ap	0.63	0.55	0.21	0.17	0.52	0.37	0.34	0.24	0.25	
Po							0.29	0.57	0.59	
D.F.	59.8	50.1	41.8	42.0	59.1	63.3	50.1	33.7	27.8	

Table 1-5 Continued

Sample	Santa Pancha mafic flows					Limon intrusive		S. Pancha s. flow	
	76-125	76-129*	76-130*	76-132*	77-210	77-226	77-365	77-410	77-209
Oxides (wt. %)									
SiO ₂	63.1	49.9	50.0	46.9	57.3	60.2	53.2	53.3	71.2
TiO ₂	0.64	0.79	0.89	0.77	0.56	0.80	0.76	0.82	0.48
Al ₂ O ₃	14.8	15.7	16.8	19.8	17.1	16.3	18.1	17.3	14.3
Fe ₂ O ₃	2.6	ND	ND	ND	3.6	4.0	4.8	4.6	0.96
FeO	3.6	9.1	10.0	11.5	4.0	1.7	4.1	4.1	0.16
MnO	0.14	0.22	0.38	0.56	0.18	0.11	0.19	0.17	---
MgO	2.1	7.0	5.5	8.3	3.3	2.1	3.6	4.6	0.02
CaO	4.0	8.6	11.4	5.9	7.3	5.1	9.3	8.9	0.04
Na ₂ O	4.0	3.1	2.5	2.6	3.4	4.2	3.1	3.0	0.10
K ₂ O	4.3	0.62	0.15	0.66	0.76	1.7	0.69	0.8	0.55
P ₂ O ₅	0.13	0.12	0.13	0.12	0.11	0.18	0.11	0.11	0.17
H ₂ O total	3.5	2.9	2.1	2.0	0.59	1.9	1.3	1.4	9.2
CO ₂	0.59	1.9	0.18	1.1	0.26	---	0.53	0.34	0.40
Total	100.1	100.0	100.0	100.2	98.5	98.3	99.8	99.4	97.6
Trace Elements (ppm)									
Ba	2410	860	360	350	760	1120	495	545	1640
Cr	1	35	37	32	1	4	9	14	5
Cu	60	28	180	130	60	61	170	110	71
Ga	15	ND	ND	ND	18	21	22	21	14
Nb	3	2	3	3	2	4	4	3	2
Ni	3	7	14	20	---	4	2	5	---
Pb	3	ND	ND	ND	2	9	---	1	11
Rb	23	10	2	15	13	42	8	14	6
S	ND	500	2000	7800	ND	ND	ND	ND	ND
Sr	330	470	400	390	525	425	425	390	595
V	140	ND	ND	ND	150	120	245	220	82
Y	27	19	20	19	24	43	23	25	15
Zn	66	83	79	255	72	72	71	67	12
Zr	110	56	56	44	85	155	74	81	180
CIPW Norm (wt. %)									
Q	24.9				12.9	15.8	6.0	6.0	78.4
C	1.9			4.6					15.9
Or	7.8	3.9	0.91	4.0	4.6	0.4	4.2	4.9	3.7
Ab	35.4	27.9	21.4	22.4	29.1	37.0	27.2	26.0	0.96
An	14.7	28.2	34.9	29.0	30.2	21.5	34.0	32.2	-1.3
Ne									
Di		7.4	8.7		2.9	2.0	5.6	6.2	
Hc		5.7	9.3		2.3	0.96	4.7	4.0	
En	5.5	8.6	9.6	14.5	7.0	4.5	6.7	8.8	
Fs	5.0	7.6	11.8	12.3	6.5	2.5	6.5	6.5	
Ed		4.4	0.28	4.7					
Fa		4.3	0.38	4.4					
Mt	3.3				3.1	3.5	3.4	3.5	
Il									
Hm									1.1
Pl	1.3	1.6	1.7	1.5	1.1	1.6	1.5	1.6	0.38
Ru									0.34
Ap	0.32	0.29	0.31	0.29	0.26	0.43	0.26	0.26	0.45
Po		0.29	0.31	2.3					
D. L. #	68.0	31.7	22.3	26.4	46.7	63.2	37.4	37.1	83.1

Table I-5 Continued

A19

Sample	Santa Pancha silicified flow		Mina El Limon Felsic flows				Felsic flows		Limon intrusive	
	77-364	77-416	76-414*	77-173	76-28*	76-88*	77-395	77-440	76-105*	
			Oxides (wt. %)							
SiO ₂	76.5	59.5	66.2	65.2	70.0	73.5	62.5	71.7	66.0	
TiO ₂	0.50	0.81	0.55	0.80	0.64	0.20	0.88	0.28	0.72	
Al ₂ O ₃	14.2	25.9	15.5	14.2	14.2	12.4	15.5	13.7	14.5	
Fe ₂ O ₃	0.10	3.1	ND	4.6	ND	1.6	5.4	1.9	ND	
FeO	0.05	---	4.5	0.74	3.0	0.14	0.41	0.20	4.7	
MnO	---	0.07	0.09	0.15	0.03	0.01	0.09	0.03	0.09	
MgO	---	---	1.5	0.71	0.45	0.33	0.78	0.30	1.5	
CaO	---	0.18	4.5	3.7	2.2	0.67	3.9	0.40	4.3	
Na ₂ O	0.02	0.01	3.3	3.4	3.4	1.8	3.6	1.8	3.2	
K ₂ O	0.04	0.02	1.6	3.3	3.9	4.7	3.4	6.7	3.1	
P ₂ O ₅	0.19	0.17	0.14	0.18	0.10	0.01	0.22	0.02	0.22	
H ₂ O total	6.2	10.1	1.6	1.6	1.9	3.5	1.8	2.6	1.8	
CO ₂	0.32	0.22	---	---	0.30	---	---	---	---	
Total	98.1	100.1	100.0	98.6	100.1	98.9	98.5	99.6	100.1	
	Trace Elements (ppm)									
Ba	610	435	860	1530	1550	1930	1560	2240	1320	
Cr	5	15	150	8	27	---	10	4	14	
Cu	26	52	34	110	20	30	58	23	135	
Ga	25	22	ND	18	ND	18	19	16	ND	
Nb	3	2	6	6	8	8	5	6	5	
Ni	---	---	12	6	7	9	12	6	24	
Pb	1	3	ND	11	ND	12	---	6	ND	
Rh	4	2	29	81	100	125	95	165	77	
S	ND	ND	400	ND	200	ND	ND	ND	400	
Sr	725	505	335	280	260	52	305	110	310	
V	155	230	ND	100	ND	12	125	12	ND	
Y	12	16	25	40	57	39	47	63	46	
Zn	13	15	68	57	73	45	85	52	49	
Zr	140	140	140	245	385	465	230	290	295	
	CIPW Norm (wt. %)									
Q	83.8	66.3	26.8	25.1	29.7	45.2	20.0	35.5	22.6	
C	16.0	28.9	0.57	---	0.75	3.3	---	2.9	---	
Or	0.26	0.13	9.5	20.1	23.3	29.2	20.7	40.3	18.7	
Ab	0.19	0.09	28.4	29.3	29.2	15.9	31.3	16.1	27.2	
An	-1.4	-0.13	21.9	14.5	10.5	3.4	17.0	1.9	16.4	
Ne	---	---	---	1.3	---	---	0.64	---	1.2	
Di	---	---	---	1.5	---	---	0.69	---	2.1	
He	---	---	---	---	---	---	---	---	---	
En	---	---	3.8	1.2	1.2	0.86	1.7	0.77	3.3	
Fs	---	---	7.6	1.6	4.6	---	2.1	---	6.6	
Fe	---	---	---	---	---	---	---	---	---	
Fa	---	---	---	---	---	---	---	---	---	
Mt	---	0.03	---	3.5	---	---	3.6	0.32	---	
Ln	---	---	---	---	---	---	---	---	---	
Ilm	0.11	2.6	---	---	---	1.7	---	1.6	---	
Il	0.12	1.7	1.1	1.6	1.2	0.33	1.7	0.55	1.4	
Ru	0.49	---	---	---	---	0.04	---	---	---	
Ap	0.48	0.44	0.33	0.43	0.24	0.09	0.53	0.05	0.52	
Po	---	---	---	---	---	---	---	---	---	
D.I. #	84.3	66.5	64.7	74.5	81.6	90.4	72.0	91.9	68.5	

Table 1-5 Continued

Sample	Mina 11, Timon, and Santa Pancha felsic rocks					
	Intrusive 77-371	76-952	76-98	77-363	77-400	77-439
	Oxides (wt. %)					
SiO ₂	51.4	71.3	79.1	74.7	78.2	72.5
TiO ₂	0.80	0.26	0.12	0.14	0.20	0.30
Al ₂ O ₃	19.4	15.0	10.5	12.6	11.4	13.2
Fe ₂ O ₃	4.9	ND	0.77	1.4	1.1	1.9
FeO	3.5	1.9	0.17	---	0.39	0.32
MnO	0.18	0.04	0.02	0.02	0.02	0.05
MgO	3.8	0.63	0.08	0.34	0.25	0.35
CaO	9.0	0.93	0.41	0.5	---	1.3
Na ₂ O	3.4	2.5	0.60	2.1	0.76	3.5
K ₂ O	0.57	4.4	6.2	4.5	6.6	4.0
P ₂ O ₅	0.13	0.03	---	---	0.02	0.01
H ₂ O total	2.8	3.1	1.1	3.4	0.90	1.3
CO ₂	0.20	---	0.48	0.28	0.54	0.13
Total	100.1	100.1	99.5	100.0	100.4	98.9
	Trace Element (ppm)					
Ba	645	1420	1150	1710	1890	1980
Cr	5	27	---	3	13	4
Cu	130	15	4	24	28	27
Ga	16	ND	10	20	13	13
Nb	1	8	4	7	6	8
Ni	---	1	3	5	4	1
Pb	---	ND	9	15	4	6
Rb	7	120	110	10	165	97
S	ND	6ND	ND	ND	ND	ND
Sr	595	76	97	53	165	---
V	220	ND	11	8	22	12
Y	16	44	19	16	26	43
Zn	79	45	23	43	28	46
Zr	85	260	84	160	105	280
	CIPW Norm (wt. %)					
Q	3.2	37.3	51.9	45.6	48.9	34.1
C	---	4.7	2.0	3.6	3.1	0.69
Or	3.5	26.9	37.6	27.3	39.2	24.5
Ab	29.6	21.4	5.2	18.5	6.5	30.6
An	37.3	4.4	2.0	2.6	-0.13	6.6
Ne	---	---	---	---	---	---
Di	3.8	1.6	---	---	---	---
He	2.7	2.8	---	---	---	---
En	8.1	---	0.20	0.88	0.63	0.90
Fs	6.6	---	---	---	---	---
Fe	---	---	---	---	---	---
Mt	---	---	---	---	---	---
Ln	3.5	---	0.11	---	0.75	0.54
Hm	---	---	0.71	1.5	0.59	1.5
Il	1.6	0.51	0.23	0.04	0.38	0.59
Ru	---	---	---	0.12	---	---
Ap	0.31	0.07	---	---	0.05	0.02
Po	---	0.28	---	---	---	---
D.I.	36.2	85.6	94.6	91.4	94.6	89.2

Table 1-6 Chemical Composition and Normative Mineralogy of Volcanic Rocks from the Tamarindo Group, Coyol Group and Marrales Range, Nicaragua

Sample	Tamarindo Group			Tamarindo Group						
	mafic flows			felsic flows						
	77 189	77 489	77 490	76 101*	77 186	77 188	77 483	77 484	77 486	77 487
	oxide (wt %)									
SiO ₂	56.0	58.3	51.4	74.7	73.1	78.2	68.9	66.6	72.6	65.5
TiO ₂	1.2	1.2	1.3	0.31	0.61	0.34	0.78	0.84	0.38	0.41
Al ₂ O ₃	15.7	14.5	16.5	13.2	13.4	11.8	14.8	14.8	14.0	13.0
Fe ₂ O ₃	3.9	11.1	4.3	ND	1.6	0.73	4.1	3.2	1.7	10.86
FeO	6.6	0.95	7.1	1.8	0.06	0.21	0.50	1.4	10.66	0.2
MnO	0.18	0.11	0.20	0.05	0.05	0.02	0.11	0.14	0.03	0.0
MgO	3.7	1.4	4.7	0.56	0.13	0.08	6.67	1.1	0.29	0.19
CaO	7.9	6.7	9.6	2.0	1.3	0.92	2.8	3.7	2.3	2.7
Na ₂ O	3.4	3.0	2.8	2.7	3.9	2.9	4.1	4.2	3.7	3.7
K ₂ O	0.77	0.56	0.48	3.1	3.2	3.2	2.1	2.0	2.6	1.1
P ₂ O ₅	0.19	0.17	0.16	0.02	0.06	0.05	0.14	0.14	0.04	0.0
H ₂ O total	0.81	2.7	0.50	1.5	0.99	0.73	2.1	1.4	1.2	1.0
CO ₂	0.23	0.64	0.14	--	0.24	0.29	0.24	0.62	0.15	0.04
Total	100.6	100.8	99.2	99.9	99.6	99.5	99.2	100.1	99.9	98.7
	Trace Elements (ppm)									
Ba	375	700	350	990	1080	880	925	795	1070	800
Cr	10	19	31	6	1	30	7	7	5	2
Cu	230	74	255	21	3	9	12	26	17	7
Ga	18	20	25	ND	20	15	17	21	16	17
Nb	4	4	4	3	5	8	4	8	4	5
Ni	6	16	14	9	4	--	1	--	4	--
Pb	--	1	--	ND	7	2	7	5	1	11
Rb	14	10	2	68	51	51	36	30	42	32
S	ND	ND	ND	600	ND	ND	ND	ND	ND	ND
Sr	325	360	330	220	160	82	220	215	195	240
V	355	360	410	ND	33	220	81	75	56	19
Y	34	29	30	17	48	31	33	41	69	22
Zn	94	82	100	32	73	42	59	62	51	29
Zr	110	89	91	98	190	175	175	180	165	150
	CIPW Norm (wt. %)									
Q	9.5	20.5	4.5	41.5	36.9	47.8	29.5	25.8	46.8	44.4
C				1.8	1.3	2.1	1.2		1.1	0.82
Or	4.6	3.4	2.9	18.4	19.0	19.5	13.0	12.1	15.5	6.9
Ab	28.8	25.8	24.1	23.5	33.8	24.8	35.3	36.5	31.6	32.4
An	25.5	25.3	31.6	10.0	6.2	4.2	13.4	15.8	11.4	43.4
Ne										
Di	5.4	1.9	7.1					1.3		
He	5.2	5.0	6.0					0.11		
En	6.8	2.8	8.5	1.4	0.33	0.20	1.7	2.4	0.74	0.58
Fs	7.5	8.6	8.4	2.6			0.75	0.67		
Fo										
Fa										
Mt	4.0	4.1	4.1				3.4	3.5	1.1	
Ilm										
Il	2.3	2.4	2.5	0.60	1.6	0.74			0.95	0.88
Ru					0.24	0.49	1.5	1.6	0.73	0.56
Ap	0.44	0.41	0.38		0.50	0.09				0.02
Po				0.05	0.14	0.12	0.34	0.33	0.09	0.10
				0.28						
D.I.	43.0	49.7	31.5	83.3	89.7	92.1	77.7	74.4	83.9	81.7

Table 1-6 Continued

	Cerro Negro			San Cristobal			Coyol Group
Sample	flow	leptira	flow	flows			flow
	76-2	76-67	76-70	76-25	76-62	76-63	76-35*
	Oxides (wt.%)						
SiO ₂	48.7	50.1	50.9	49.7	62.9	51.7	54.3
TiO ₂	0.84	0.73	0.78	0.80	0.76	1.0	0.79
Al ₂ O ₃	19.5	16.4	20.1	19.9	15.9	18.8	17.3
Fe ₂ O ₃	3.0	2.8	3.7	4.0	1.9	3.1	ND
FeO	7.1	7.9	5.6	6.1	5.4	7.4	7.9
MnO	0.19	0.20	0.17	0.19	0.23	0.22	0.15
MgO	5.1	8.5	4.0	3.9	1.7	3.7	4.1
CaO	12.1	11.8	12.0	11.4	4.9	10.0	8.4
Na ₂ O ₅	2.2	1.9	2.3	2.6	4.7	3.1	3.3
K ₂ O	0.5	0.39	0.49	0.62	1.7	0.83	1.2
P ₂ O ₅	0.11	0.06	0.08	0.18	0.15	0.22	0.12
H ₂ O total	0.06	---	0.03	0.31	0.51	0.26	1.9
CO	0.05	0.26	0.11	0.19	---	0.16	0.71
Total	99.5	101.0	100.3	99.9	101.0	100.5	99.9
	Trace Elements (ppm)						
Ba	330	300	335	385	1190	580	605
Cr	8	67	12	8	4	3	27
Cu	155	135	140	160	27	205	59
Ga	24	19	24	23	22	22	ND
Nb	5	5	5	5	5	4	4
Ni	6	38	7	1	---	---	25
Pb	---	---	---	---	4	8	ND
Rb	4	5	10	10	29	18	28
S	ND	ND	ND	ND	ND	ND	600
Sr	475	385	480	550	435	540	472
V	245	265	255	250	53	255	ND
Y	23	20	21	26	40	28	19
Zn	75	79	78	80	100	92	84
Zr	69	61	75	85	135	96	86
	CIPM Norm (wt. %)						
Q			3.3	0.77	14.5	1.9	3.5
C							
Or	2.8	2.3	2.9	3.7	10.2	4.9	7.5
Ab	18.4	15.7	19.4	21.8	39.5	26.3	28.8
An	42.5	35.0	43.2	41.4	17.1	34.9	29.5
Ne							
Di	8.1	12.2	7.1	6.0	1.6	5.4	4.4
He	6.2	6.4	6.0	6.0	2.5	5.7	4.3
En	8.7	13.3	6.7	7.0	3.5	6.7	9.4
Fs	7.7	8.0	6.5	8.1	6.1	8.1	9.0
Fo	0.14	1.5					
Fa	0.14	1.0					
Mt	3.4	3.2	3.3	3.4	2.8	3.7	
Ln							
Ilm							
Il	1.6	1.4	1.5	1.5	1.4	1.9	1.5
Ru							
Ap	0.26	0.14	0.19	0.42	0.81	0.51	0.29
Po							0.28
D.I.	21.2	18.0	25.6	26.2	64.2	33.2	39.9

Table 1.7 Rock names derived from Irvine and Baragar classification (1976)

Sample #	Rock Name	K ₂ O Content
2	calc-alkaline (high-alumina) basalt	K-rich
10	calc-alkaline (high-alumina) basalt	K-rich
14	tholeiitic basalt	K-rich
15	calc-alkaline (high-alumina) basalt	K-rich
17	calc-alkaline (high-alumina) basalt	K-rich
18	calc-alkaline (high-alumina) basalt	K-rich
25	calc-alkaline (high-alumina) basalt	K-rich
28	calc-alkaline dacite	K-rich
31	calc-alkaline (high-alumina) andesite	average
35	calc-alkaline (high-alumina) basalt	K-rich
40	tholeiitic basalt	K-rich
41	calc-alkaline (high alumina) basalt	average
43	calc-alkaline (high-alumina) basalt	K-rich
44	calc-alkaline (high-alumina) basalt	K-rich
45	calc-alkaline (high-alumina) basalt	K-rich
46	calc-alkaline (high-alumina) basalt	K-rich
48	calc-alkaline (high alumina) basalt	average
49	calc-alkaline (high alumina) basalt	average
51	calc-alkaline (high-alumina) basalt	K-rich
52	calc-alkaline (high-alumina) basalt	K-rich
54	calc-alkaline (high-alumina) basalt	K-rich
55	calc-alkaline (high alumina) basalt	average
56	calc-alkaline (high alumina) basalt	average
57	calc-alkaline (high alumina) basalt	average
58	anorthositic block	
59	calc-alkaline (high-alumina) basalt	K-rich
60	tholeiitic andesite	average
62	tholeiitic andesite	average
63	calc-alkaline (high alumina) basalt	average
67	tholeiitic basalt	K-rich
70	calc-alkaline (high-alumina) basalt	K-rich
80	calc-alkaline (high alumina) basalt	average
88	calc-alkaline dacite	K-rich
93	tholeiitic andesite	average
95	calc-alkaline dacite	K-rich
96	calc-alkaline (high alumina) basalt	average
98	calc-alkaline dacite	K-poor
101	calc-alkaline dacite	K-rich
104	tholeiitic andesite	K-rich
119	tholeiitic andesite	K-poor
120	tholeiitic andesite	average
121	tholeiitic basalt	K-poor

Table 1.7. cont. Rock names derived from Irvine and Baragar classification

Sample #	Rock Name	K ₂ O Content
122	calc-alkaline (high alumina) basalt	K-poor
125	tholeiitic andesite	K-poor
129	calc-alkaline (high alumina) basalt	average
130	calc-alkaline (high alumina) basalt	K-poor
132	calc-alkaline (high alumina) basalt	average
149	calc-alkaline (high-alumina) basalt	K-rich
173	tholeiitic dacite	K-rich
186	calc-alkaline rhyolite	average
188	calc-alkaline rhyolite	K-poor
189	tholeiitic basalt	average
209	tholeiitic basalt	K-poor
210	calc-alkaline (high alumina) basalt	average
214	calc-alkaline (high-alumina) basalt	K-rich
226	tholeiitic andesite	average
245	calc-alkaline (high-alumina) basalt	K-rich
248	calc-alkaline (high-alumina) basalt	K-rich
250	calc-alkaline (high alumina) andesite	K-rich
255	calc-alkaline (high alumina) andesite	K-rich
261	calc-alkaline (high alumina) andesite	K-rich
263	calc-alkaline (high-alumina) basalt	K-rich
268	calc-alkaline (high-alumina) basalt	K-rich
279	calc-alkaline (high-alumina) basalt	K-rich
284	calc-alkaline (high alumina) basalt	average
286	calc-alkaline (high-alumina) basalt	K-rich
289	calc-alkaline (high-alumina) basalt	K-rich
293	calc-alkaline (high-alumina) basalt	K-rich
300	calc-alkaline (high alumina) basalt	average
302	calc-alkaline (high alumina) andesite	K-rich
311	calc-alkaline (high alumina) andesite	K-rich
324	calc-alkaline (high-alumina) basalt	K-rich
328	calc-alkaline (high-alumina) basalt	K-rich
329	calc-alkaline (high-alumina) basalt	K-rich
330	calc-alkaline (high-alumina) basalt	K-rich
348	calc-alkaline (high-alumina) basalt	K-rich
349	calc-alkaline (high-alumina) basalt	K-rich
363	calc-alkaline rhyolite	K-rich
364	tholeiitic basalt	K-poor
365	calc-alkaline (high alumina) basalt	average
371	calc-alkaline (high alumina) basalt	average
395	tholeiitic andesite	K-rich

Table I.7 cont. Rock names derived from Irvine and Baragatti classification.

Sample #	Rock Name	K ₂ O Content
400	calc-alkaline rhyolite	K-poor
410	calc-alkaline (high alumina) basalt	average
416	tholeiitic basalt	K-poor
439	calc-alkaline dacite	K-poor
440	calc-alkaline rhyolite	K-poor
450	calc-alkaline (high-alumina) basalt	K-rich
452	calc-alkaline (high alumina) basalt	average
457	calc-alkaline (high-alumina) basalt	K-rich
464	calc-alkaline (high-alumina) basalt	K-rich
466	calc-alkaline (high-alumina) basalt	K-rich
467	calc-alkaline (high alumina) andesite	K-rich
479	calc-alkaline (high-alumina) basalt	K-rich
483	tholeiitic dacite	average
484	tholeiitic dacite	average
486	tholeiitic dacite	average
487	calc-alkaline dacite	K-poor
489	tholeiitic andesite	average
490	calc-alkaline (high alumina) basalt	average

Appendix II

Petrographic Descriptions

Introduction

Representative samples with whole rock analyses from Mina El Limon and the Telica Complex were studied petrographically to determine their mineralogy, texture, degree of alteration and mode (Tables II-2 and II-3). More complete descriptions of the petrography of each unit are given in chapters 2 and 3.

Modal Analysis

Modal analyses were made on a 0.5 mm by 0.5 mm grid using an automatic Swift counter and stage. One thousand or more counts were taken for each sample (Chayes, 1956; Galehouse, 1971); for several smaller sections only 500 to 999 counts were made. Estimated modes are indicated by an asterisk after the sample number.

The statistical uncertainty associated with point counting has been determined by Nentwich (personal communication, 1980) after Kelley (1971). Multinomial distribution curves using a poisson distribution below 5 volume % and a bimodal distribution over 5 volume % (Figure II-1) can be used to determine the probable error at a 75% confidence level in point counting. For example, three times out of four for 1000 counts the probable error is less than the following:

<u>Volume Percentage</u>	<u>Probable Error(+/-)</u>
1%	0.36%
10%	1.1%
20%	1.5%
50%	1.8%

Figure- 11.1

Probable errors in point counts
(from Nentwich, personal communication, 1980)

Hall (1979) has shown that the error in point counting determinations for pore spaces (e.g. vesicles in volcanic rocks) is greater than for the crystalline phases.

In the modal analysis tables, the last significant digit is the first digit after the decimal for minerals with abundances less than 1 volume % and the first digit before the decimal for minerals present in greater amounts.

The vesicle volume percentages are the relative percentage of the entire section. The other volume percentages are recalculated in the mode to represent volume percent of the solid material (after Rose et al., 1978). This permits comparison of phenocryst abundances without the added complexity of variable gas content. The vesicularity in a single Telica flow commonly varies from 1 to 5 % in the core to over 25 % in the flow top scoria.

A glassy groundmass is marked by (g) in the modal analysis tables. Minerals in trace amounts are indicated by tr.

Petrography

A binocular Leitz microscope with a horizontal stage was used for the petrographic study. Plagioclase compositions are expressed in terms of anorthite percentages rounded off to the nearest 5%. The method used to determine plagioclase composition is given by the number in brackets following the composition. The methods are:

- 1) Carlsbad-albite twins
- 2) perpendicular to a
- 3) perpendicular to x
- 4) Michel Levy
- 5) microlite statistical method (parallel to a)
- 6) perpendicular to Z

Olivine compositions are expressed in terms of forsterite (to the nearest 5%) based on determinations of 2V and optical sign. Pyroxene and amphibole compositions were determined from appearance, 2V, optic sign and extinction angle. Abbreviations used in the tables are given in Table II-1. The type of alteration is indicated by the number within the brackets following the alteration mineral(s). The types of alteration are:

- 1) confined to vesicles
- 2) confined to fractures
- 3) confined to phenocrysts
- 4) throughout the groundmass
- 5) throughout the sample

Table 11-1. Abbreviations of mineral names and textures used in Tables 11-2 and 11-3.

Minerals		Textures	
apatite	AP	diptytaxitic	DKXC
augite	AG	flow layering	FWLG
bronzite	BZ	fluidal	FLDL
carbonate	CB	glomeroporphyritic	GLPC
chlorite	CL	holocrystalline	HLCR
enstatite	EN	holohyaline	HLLN
heulandite	HE		
hematite	HM	hyalophitic	HLPC
hornblende	HB	hyalopilitic	HPLC
hypersthene	HP	hypocrystalline	HPCS
iddingsite	IG	intergranular	IRGR
montmorillonite	MM	intersertal	IRSR
palagonite	PG	massive	MSSV
prehnite	PR		
quartz	QZ	micro-ophitic	MCOP
sericite	SC	pilotaxitic	PLXC
		porphyritic	PPRC
		pseudomorphic	PDRP
		seriate	SRIT
		spherulitic	PHRL
		vitrophyric	VRRC
		xenolith-bearing	XNLT

Abbreviations based on a slashing code developed by J. Franklin of the Geological Survey of Canada (personal communication; 1980).

- 1) Retain first letter of each component word.
e.g. BLACK SHALE = BS
- 2) Eliminate letters from right to left using the order A, E, I, O, U, W, H, Y, double letters, T, N, R, S, L, D, C, M, F, G, P, K, V, X, J, Q, Z.
e.g. BLACK SHALE = BCKS
- 3) If an abbreviation is generated which duplicates an abbreviation already used, replace the nearest letter to the first letter with a letter which will avoid duplication of another abbreviation.
e.g. BLACK SHALE = BCKS
BLACK SLATE = BLKS

TABLE II-2. Modal and petrographic characteristics of the volcanic rocks from the line El Limon area, Nicaragua.

Unit*	1	1	1	1	1
Sample #	30	119	120	121	122
MODE (vol. %)					
PHENOCRYSTS					
quartz					
plagioclase	25	12.9	14.7	25.1	20.2
clinopyrox.	5			4.1	
orthopyrox.					
olivine					
amphibole					
biotite					
opaques	3	tr	0.6	0.8	0.6
pseudomorphs		1.4	9.8		
MATRIX					
groundmass	67	85.7	74.8	70.0	79.2
amygdules		16.7	4.2	0.6	7.2
MINERALOGICAL DESCRIPTION					
PHENOCRYSTS				70-80(1)	
plagioclase					
olivine					
clinopyrox.	AG?			AG	
orthopyrox.					
amphibole					
MATRIX					
plagioclase				50(5)	
TEXTURE	HLCR PDRP GLPC	HLRC PPRC	HLRC PPRC	HLRC PPRC PLXC GLPC	HLRC PPRC
ALTERATION	SC(5) CL(4)	CL(1,5) SC(3) HM(1) CB(1)	CL(3,5) CB(1,3)	CB(3,4) CL(3,4) HM(2,5)	QZ(1) CB(5) CL(4)
ROCK NAME	BASALT	ALTERED MAFIC VOLCANIC	MAFIC VOLCANIC	BASALT PORPHYRY	MAFIC VOLCANIC PORPHYRY

* - see Table III-1 for explanation of different unit numbers

TABLE 11-2 cont. Modal and petrographic characteristics of the volcanic rocks from the Mine El Limon area, Nicaragua.

Unit Sample #	1 125	1 129	1 130	1 132	1 149
	MODE (vol. %)				
PHENOCRYSTS					
quartz					
plagioclase	25.1	13.1	13.9	21.4	26.6
clinopyrox.		1.4	0.8		
orthopyrox.					
olivine					
amphibole					
biotite					
opaques	1.4	0.2		tr	1.7
pseudomorphs	0.7	tr		2.0	7.4
MATRIX					
groundmass	72.8	85.3	85.3	76.6	64.3
amygdules	2.3	7.0		4.3	4.4
	MINERALOGICAL DESCRIPTION:				
PHENOCRYSTS					
plagioclase			75(1)		65- 55(1)
olivine					
clinopyrox.		AG			
orthopyrox.					
amphibole					
MATRIX					
plagioclase		53(5)	55(1)		
TEXTURE	PPRC HLRC	HLRC PLXC PDRP SRIT	HLRC SRIT PLXC	HLRC PPRC	HLRC GLPC
ALTERATION	CL(5) CB(3) QZ(1,2)	QZ(1) CL(1,3) CB(1,3)	CB(2,5) QZ(2)	CB(3) QZ(1) CL(5)	QZ(2) HM(5) CL(5)
ROCK NAME	MAFIC VOLCANIC PORPHYRY	BASALT	BASALT	MAFIC VOLCANIC PORPHYRY	ALTERED MAFIC VOLCANIC PORPHYRY

TABLE II-2 cont. Modal and petrographic characteristics of the volcanic rocks from the Mine El Lirio area, Nicaragua.

Unit	1	2	2	2	2
Sample #	158*	72*	226	284	286
			MODE (vol. %)		
PHENOCRYSTS					
quartz					
plagioclase	26	30	12.5	17.6	34.0
clinopyrox.		7	0.7	4.2	
orthopyrox.			1.9	5.8	3.4
olivine					
amphibole					
biotite					
opakes	3	1	0.6	1.3	0.6
pseudomorphs	<1				0.9
MATRIX					
groundmass	70	62	84.3	70.6	61.1
amygdules	7				

MINERALOGICAL DESCRIPTION

PHENOCRYSTS					
plagioclase		65(1)	60(1)		
olivine					
clinopyrox.		AG	AG?		
orthopyrox.			HP		
amphibole					
MATRIX					
plagioclase					
TEXTURE	HLRC PPRC	HLRC GLPC	HLRC PPRC PLXC	PPRC	HLRC PPRC
ALTERATION	QZ(5) CB(3) CL(3,4) HM(5)	SC(3) CL(3)	HM(2)		SC(3) CL(3) CB(4)
ROCK NAME	ALTERED MAFIC VOLCANIC SANDSTONE	ANDESITE PORPHYRY	ANDESITE PORPHYRY	ANDESITE PORPHYRY	ANDESITE PORPHYRY

TABLE 11-2 cont. Modal and petrographic characteristics of the volcanic rocks from the Mine El Limon area, Nicaragua.

Unit	2	3	3	3	3
Sample #	365	74*	98	400	440*
	MODE (vol. %)				
PHENOCRYSTS					
quartz		7	0.2	13.5	
plagioclase	28.0	12	0.9	5.6	1.86
clinopyrox.	0.4				
orthopyrox.	3.5				
olivine					
amphibole					
biotite		3	0.2	0.6	
opakes	1.4	2	tr	0.5	
pseudomorphs	1.4				
MATRIX					
groundmass	65.3	64	98.7	79.8	98.14
amygdules	5.2				

MINERALOGICAL DESCRIPTION

PHENOCRYSTS	
plagioclase	55(2)
olivine	
clinopyrox.	HP
orthopyrox.	
amphibole	
MATRIX	
plagioclase	

TEXTURE	GLPC HLCR	HLCR	HLCR FWLG PHRL XNLT	PPRC HLCR	FWLG HLCR
ALTERATION	CB(3) QZ?(3) HM(4) CL(3)	SC(3) CB(5) HM(?)	HM(4) CL?(4)	SC(3)	HM(3) MM?
ROCK NAME	ANDESITE PORPHYRY	ALTERED ANDESITE PORPHYRY	ALTERED DACITE PORPHYRY	DACITE PORPHYRY	DACITE FLOW

TABLE II-2 cont. Modal and petrographic characteristics of the volcanic rocks from the Mine El Limon area, Nicaragua.

Unit Sample #	3 71*	3 209*	3 364	3 416*	4 28
	MODE (vol. %)				
PHENOCRYSTS					
quartz					0.2
plagioclase	5	12	3.6	25	2.0
clinopyrox.	<1				
orthopyrox.					
olivine					
amphibole					
biotite	tr				
opakes	1.0	1			0.5
pseudomorphs	1.0				0.3
MATRIX					
groundmass	91	87	96.4	75	97(G)
amygdules					

MINERALOGICAL DESCRIPTION

PHENOCRYSTS
 plagioclase
 olivine
 clinopyrox.
 orthopyrox.
 amphibole
 MATRIX
 plagioclase

TEXTURE	PPRC FWLG HLCR	PPRC FLDL VRRC	PPRC VRRC FLDL	VVRC	FWLG PPRC PHRL HLCR
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ALTERATION	HM(5) SC(?)		QZ(5)	QZ(4) HM(4)	SC(3) CL(3) MM?
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ROCK NAME	ANDESITE FLOW	SILICIFIED PLAGIOCLASE VITROPHYRE BRECCIA	DACITE VITROPHYRE
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TABLE 11-2 cont. Modal and petrographic characteristics of the volcanic rocks from the Mine El Limon area, Nicaragua.

Unit	4	4	4	4	4
Sample #	31	93	104	143	173
	MODE (vol. %)				
PHENOCRYSTS					
quartz					
plagioclase	20.2	0.8	25.6	18	15.2
clinopyrox.	0.7		2.6	3	3.2
orthopyrox.		0.5	1.4		
olivine					
amphibole					
biotite					
opaques			2.0	2	1.6
pseudomorphs	2.5				1.4
MATRIX					
groundmass	76.6(G)	98.7	68.4	77	78.6(G)
amygdules					
	MINERALOGICAL DESCRIPTION				
PHENOCRYSTS					
plagioclase	55(1)		60-55(1)	65(3)	80-65(1,6)
olivine					
clinopyrox.					
orthopyrox.					
amphibole					
MATRIX					
plagioclase					
TEXTURE	VVRC PHRL	FWLG HLRC XNLT	GLPC	PPRC HLRC	FWLG GLPC
ALTERATION	CL(3) HM(4) SC(3)		HM(5) CL?(4)	HM CL(3) HE?	HM(5) SC(3)
ROCK NAME	ANDESITE PORPHYRY	ANDESITE	ANDESITE PORPHYRY	ANDESITE PORPHYRY	ANDESITE VITROPHYRE

TABLE II-2 cont. Modal and petrographic characteristics of the volcanic rocks from the Mine El Limon area, Nicaragua.

Unit	4	4	4	4	4
Sample #	210	35	395	479	88*
	MODE (vol. %)				
PHENOCRYSTS					
quartz					
plagioclase	31.0	30	15.6	20.5	5
clinopyrox.	1.5	8	1.1		
orthopyrox.	5.0	2			
olivine					
amphibole					
biotite					
opakes	2.8	2	3.6	0.6	1
pseudomorphs			2.9	1.8	
MATRIX					
groundmass	59.7	58	78.8	77.1	94(G)
amygdules				1.5	

MINERALOGICAL DESCRIPTION

PHENOCRYSTS					
plagioclase		70(?)		70?	
olivine					
clinopyrox.		AU	AU		
orthopyrox.		EN			
amphibole					
MATRIX					
plagioclase		65(5)			

TEXTURE	GLPC HLRC	HLPC GLPC HPCS	PPRC HLRC	GLPC	FWLG PPRC HPCS
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ALTERATION			HM(3) CL(3)?	CB(2)	HM(4)
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ROCK NAME	PYROXENE ANDESITE PORPHYRY	ANDESITE PORPHYRY	ANDESITE PORPHYRY	ANDESITE	FELSIC VITROPHYRE
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TABLE II-2 cont. Modal and petrographic characteristics of the volcanic rocks from the Mine El Limon area, Nicaragua.

Unit Sample #	5 95	5 363	5 439	6 371	6 410
	MODE (vol. %)				
PHENOCRYSTS					
quartz					
plagioclase	5.9	tr	2.1	26.0	72
clinopyrox.				tr	14
orthopyrox.					6
olivine					
amphibole					
biotite					
opaques	0.1	0.1		0.8	5.0
pseudomorphs		0.4	tr		3.0
MATRIX					
groundmass	94.0	99.5	97.9	73.2	
amygdules					

MINERALOGICAL DESCRIPTION

PHENOCRYSTS	
plagioclase	40(1)
olivine	
clinopyrox.	
orthopyrox.	
amphibole	
MATRIX	
plagioclase	60(5)

TEXTURE	FWLG PPRC	FWLG HLLN	HPCS FLWG	PPRC HPCS	SRIT HLCR
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ALTERATION	CH(4)		HM(4)	CB(4) CL?(4) PR?(5)	CB(3) HM(4)
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ROCK NAME	DACITE BOSS	DEVETRIF. FELSIC VOLCANIC	INTERMED. VOLCANIC	HYPABYSSAL ANDESITE	GABBRO
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Table II-3. Modal and Petrographic Characteristics of the Volcanic and Hypabyssal Rocks from the Tellica Complex, Nicaragua

Unit Sample	1				2				7				
	76.56	76.57	77.300	77.250	77.255	77.263	77.311	77.467	76.80				
Mode (vol. %)													
Phenocrysts													
Plagioclase	46.0	42.1	47.8	9.8	13.1	13.2	20.6	33.5	17.5				
Clinopyroxene	1.7		tr										
Orthopyroxene	3.0	2.5	3.0	0.7	0.4	0.9	1.1	4.8	1.0				
Olivine				tr			tr						
Amphibole	0.8	0.7	0.8	0.3	0.4	1.0	0.5	1.3	0.2				
Opaques													
Matrix	48.5	54.7	48.4	89.2	86.1	84.9	77.8	60.4	81.3				
Groundmass	14.6	0.7	1.3	0.7	5.8	7.9	7.4	7.6	tr				
Vesicle													
Mineral Characteristics													
Phenocrysts													
Plagioclase (ZAn)	70-65(1)	85-60(2,6)	75-70(1)		85(1)	85-70(1,2)	80-70(2)	65(1)	75-70(1,2)				
Olivine (ZFo)	85	95	95						85				
Clinopyroxene	AG												
Orthopyroxene				BZ	BZ	BZ	BZ	HP	HB				
Amphibole													
Matrix													
Plagioclase (ZAn)	70(4)	55(4,5)	70(4)	55(5)		45(5)	50-45(4,5)	35(5)	55(5)				
Texture													
	MSSV, HLCR	MSSV, HPCS	MSSV, HPCS	FNLG, HPCS	FNLG, HPCS	HPCS, PPRC	FNLG, HPCS	MSSV, HPCS	HPCS, FLDC				
	PPRC, IRGR	PPRC, IRGR	PPRC, IRGR	PPRC, HPLC	PPRC, HPLC	PPRC, HPLC	PPRC, HPLC	PPRC, HPLC	PPRC, IRGR				
Alteration													
	IG(3)	IG(3)	IG(3)	IG(3)		HM(4), CL(1)	AM(1)	AM(1)	ID(3)				
Rock Name													
	Olivine basalt porphyry										Pyroxene Andesite		
											Andesite porphyry		

Unit Sample	7*	3	4
Mode (vol. %)	77.302	77.324	77.348
Phenocrysts			
Plagioclase	26.3	22.6	20.6
Clinopyroxene	3.3	9.7	-
Orthopyroxene	0.2	-	tr
Olivine	-	2.2	0.5
Amphibole	-	-	-
Opakes	0.9	1.1	0.3
Matrix			
Groundmass	69.3	64.4	78.6
Vesicle	2.1	7.0	2.4

Phenocrysts								
Plagioclase (%An)	85-65(1)	85-75(1)	80(1)	75-70(1,2)	80(1)	75-70(1)	75-70(1)	
Olivine (%Fo)		70	85	75		75	80	
Clinopyroxene	AG	AG	AG				AG	
Orthopyroxene	BZ							
Amphibole								
Matrix								
Plagioclase (%An)		60(4,5)	55(5)	60-55(4,5)	55(5)	55(5)	65-60(4,5)	55(5)

HPCS	,PPRC HPCS,	PPRC HPCS,		HPCS	,PPRC HPCS,	PPRC HLGR,	PPRC HPCS,	PPRC VRCC
FDDL	,GLPC FDDL,HPLC IRSR	.HLPC	.	GLPC,HPLC GLPC,IRCR	GLPC,IRGR	GLPC,IRGR		
IRGR				PORP	*		* FLDL	

AM(1)	CL(1)	HM(3)	HM(5)	IG(3)	IG(3)	IG(3)
	CB(1)		IG(3)	HM(3)		
			SC(3)			

Andesite	Olivine Pyroxene	Olivine Basalt porphyry	Olivine basalt porphyry
porphyry basalt porphyry			

Table II-3. Modal and Petrographic Characteristics of the Volcanic and Hypabyssal Rocks from the Telica Complex, Nicaragua

Unit Sample	6		8a		8b	
	77.457	77.466	76.48*	76.49	77.329	76.53
Mode (vol. %)						
Phenocrysts						
Plagioclase		22.1	21.0	19.3	32.0	23.8
Clinopyroxene		3.0	1.6	7.0	9.6	2.5
Orthopyroxene				0.9	1.9	tr
Olivine					0.3	4.8
Amphibole				0.5	1.5	tr
Opaques		2.9	1.6			
Matrix						
Groundmass		72.0(g)	75.8(g)	72.3(g)	54.2	70.0
Vesicle		32.0	38.0	42.8	15.9	12.6
						13.3
						72.2
						64.1
						24.4
Mineral Characteristics						
Phenocrysts						
Plagioclase (%An)		75-70(1)	80-70(1,2)	75(1)	65(1)	65(6)
Olivine (%Fo)				95	85	85
Clinopyroxene		AG	AG	AG	AG	AG
Orthopyroxene				BZ		
Amphibole						
Matrix						
Plagioclase (%An)		55(5)	55(5)	50(5)	50(5)	55(5)
Texture						
	VRRC	PPRC, HPCS HPLC, PDRP	PPRC, HPCS HPLC	PPRC, HPCS HPLC	HPLC, GLPC HPCS	HPLC PPRC, HPCS IRSR
					GLPC	PLXC, GLPC
Alteration						
	PG(5)	HM(3)	HM(3)	HM(3)	IG(3)	
Rock Name						
	Andesite tuff					
		Pyroxene basalt tephra				
						Pyroxene basalt porphyry lava

Table II-3. Modal and Petrographic Characteristics of the Volcanic and Hypabyssal Rocks from the Telica Complex, Nicaragua

Unit	77-328	77-248	77-261	77-268	77-293	76-59	76-5*	77-259	76-40
Sample									
Mode (vol. %)									
Phenocrysts									
Plagioclase	29.4	17.9	36.1	28.5	27.6	32.7	32.6	33.4	18.8
Clinopyroxene	11.6	2.0	5.9	5.6	5.4	7.4	7.6	5.5	4.7
Orthopyroxene	trace		trace			trace			trace
Olivine	3.7	4.2	2.7	2.9	3.2	3.7	3.4	2.8	3.5
Amphibole									
Opagues	2.3	trace	0.8	0.3	0.4	0.4	0.8	0.5	trace
Matrix									
Groundmass	53.0	75.9	54.5	62.7	63.4	55.8	55.6	57.8	73.0
Vesicle	8.2	10.4	13.1	10.2	8.0	17.9	11.0	5.7	15.1
Mineral Characteristics									
Phenocrysts									
Plagioclase (%An)	75-65(1)	70(1)		similar	similar	80-75(1)	85(1)	65(1)	85(2)
Olivine (%Fo)			90	to	to	80	80	85	90-85
Clinopyroxene	AG	AG	AG	261	261	AG	AG	AG	AG
Orthopyroxene			BZ			BZ			
Amphibole									
Matrix									
Plagioclase (%An)	60(5)	55(5)				55(5)	55(5)	55(5)	50(5)
Texture									
	GLPC	GLPC	GLPC	GLPC PPRC, HPCS	GLPC PPRC, HPCS	GLPC PPRC, HPCS	GLPC PPRC, HPLS	GLPC	GLPC
	HPCS, IRSR	HPCS, PLXC	HPCS, IRSR	PLXC	PLXC	HPCS, PLXC	IRSR	HPCS, IRGR	HPCS, PLXC
Alteration									
Rock Name									

Table II-3. Modal and Petrographic Characteristics of the Volcanic and Hypabyssal Rocks from the Telica Complex, Nicaragua

Unit Sample	8c					
	76.41	76.46	76.54	77.289	77.330	76.10* 76.15 76.17*
Mode (vol. %)						
Phenocrysts						
Plagioclase ³	21.7	27.9	25.0	31.4	26.9	29.3 22.5 29.9 25.7
Clinopyroxene	1.8	10.2	12.0	5.2	13.0	5.6 5.5 6.0 7.6
Orthopyroxene		trace			trace	trace trace
Olivine	4.5	2.8	1.6	3.3	2.1	2.8 3.6 1.5
Amphibole						
Opakes	0.6	2.1	1.9	0.5	2.4	1.4 1.0 1.1 1.5
Matrix	71.4	57.0	59.5	59.6	55.6	60.9(g) 63.7(g)
Groundmass	38.7	32.3	26.1	9.5	17.7	28.3 3.6 33.9
Vesicle						
Mineral Characteristics						
Phenocrysts						
Plagioclase (%An)	similar	85-80(1)	similar	similar	60(1)	70(1) 85(1) similar
Olivine (%Fo)	to 40	to 46	to 54	to 54	85 AG	75 AG to 10
Clinopyroxene		AG			AG BZ	AG BZ
Orthopyroxene						
Amphibole						
Matrix						
Plagioclase (%An)		50(5)				55(5) 55(5)
Texture						
	PPRC, PLXC, HPLC	PPRC, HPCS, PPRC, HPCS	HPLC	HPCS, IRSR, HPCS	GLPC, IRSR, HPCS, HPLC	GLPC, PPRC, HPCS, HPLC, IRSR, HCCR, IRGR, HPLC
Alteration						
						10(3) 10(3)
						HM(5)
Rock Name						
						Pyroxene basalt; porphyry lava

Table II-3. Modal and Petrographic Characteristics of the Volcanic and Hypabyssal Rocks from the Telica Complex, Nicaragua

Unit	8c		xenolith	
Sample	76.43	76.44	76.51	76.58
Mode (vol. %)				
Phenocrysts				
Plagioclase	25.4	27.2	27.7	26.8
Clinopyroxene	6.0	6.0	4.9	10.3
Orthopyroxene	2.1	trace		
Olivine		1.7	0.9	1.4
Amphibole				
Opakes	0.7	2.2	trace	1.0
Matrix				
Groundmass	65.9(g)	62.9(g)	66.5(g)	60.8
Vesicle	26.0	32.0	38.2	2.1
Mineral Characteristics				
Phenocrysts				
Plagioclase (%An)	similar	65(6)	similar	60
Olivine (%Fo)	to 85	to 44	to 15	
Clinopyroxene	44	BZ		
Orthopyroxene				
Amphibole				
Matrix				
Plagioclase (%An)				
Texture	PPRC, HPCS HPLC	PPRC, HPCS HPLC	PPRC HPCS, HPLC, HLCR, IRGR	GPLC HPCS, GRNR
Alteration				
Rock Name	pyroxene basalt porphyry tephra			anorthosite

Appendix III

Sample Unit and Location

Table LII-1. Rock samples from the Mina El Limon area

Unit 6 - Basalt and Andesite Dikes

92, (371)*, 375*, (410)*, 428

Unit 5 - Latite and Dacite Rhyolite Dikes and Stocks

(88)*, (95)*, 175, 182, 225, 282, (363)*, 366, 372, 373, 374,
377*, 435, (439)*, 441, 442, 477

Unit 4 - Andesite and Latite Flows

(28)*, 29*, (31)*, 91*?, (93)*, 94, (104)*, 115, 133*, 134*, 135*,
136*, 140, 141*, 142*, 143*, 144, 145, 161*?, 169, 171, 172*,
(173)*, 174*, 196, 197, 206, 207*, (210)*, 211, 212*, 223, 224,
269a, 358*, 359*, 361, 362, 382, 394, (395)*, 396, 397*, 398,
399*, 413, 414, 424, 427*, 444*, (479)*

Unit 3 - Latite and Dacite Domes, Flows and Breccias

Domes and Flows

74*, (98)*, 177, 178, 179*, 180, 185, 205, 227*, 352, 356, 378*,
379*, 393, (400)*, 425*, 429, (440)*, 443*

Breccias, Conglomerates and Tuffs

71*, 78, 89*, 90*, 103?, 137?, 138?, 139?, 146, 170*, 176, 183,
222, 223, 282, 351, 353, 354, 355, 360, 367, 368, 369, 380, 381,
426, 436

Silicified Breccias

114*, (209)*, 213*, 283, (364)*, 370*, (416)*

Unit 2 - Clinopyroxene Orthopyroxene Andesite Porphyry Flows

72*, 147, 148*, 181, 184, 204*, 208*, 221, (226)*, 228*,
281*, (284)*, 285, (286)*, 286a, 357*, (365)*, 399*, 412*, 415,
428*, 430, 445, 480

Unit 1 - Plagioclase Clinopyroxene Basalt and Andesite Porphyry
Flows and Breccias

Flows

30*, 116*, 117*, 118*, (119)*, (120)*, (121)*, (122)*, (125)*,
(129)*, (130)*, (132)*, (149)*, 150, 151, 152, 154a, 431, 432,
438, 494*, 497*, 498*, 499, 501*

Table 111-1. cont.

breccias and Conglomerates

72*, 87*, 123*, 124*, 131*, 138*, 139*, 141, 142, 153*, 154*,
155*, 156, 157, 158*, 159, 160, 200*, 283, 388, 411, 419, 421,
437, 446, 472, 474, 475, 476, 491*, 492, 493*, 495, 496, 500

Quartz Veins

a) Mina Limon and Lino North
198, 199, 202*, 478

b) Pozo Bono
417*, 418*, 481*

c) Atrevelada
420, 422*, 423*

d) Pantheon Vein System
383*, 384, 385*, 386, 387*, 389*, 390, 391*, 392, 446*, 447*

e) Santa Pancha
433, 434, 435

f) Tecompa
473

g) Larga
376

h) Quartz vein
281*

Carbonized Wood
280

Sample numbers with chemical analyses are bracketed.
Samples with asterisks were examined in thin section.

Table III-2. Rock samples from the Telica Complex

Alluvium and Lahars (unit 9)

50*, 231*, 232, 233, 234, 235, 236*, 237, 238, 239, 273, 290, 291, 465

Telica Formation (Unit 8)

Upper Tephra Member (Unit 8c) - Black Olivine Pyroxene Basalt Porphyry Tephra

(10)*, 11*, 12*, 13*, (14)*, (15)*, 16*, (17)*, (43)*, (44)*, (51)*, (52)*, 53, 190, 191, 192*, 193*, 194, 195*, 333, 336, 337

Terminal Lava Member (Unit 8bt) - Dark Gray Olivine Pyroxene Basalt Porphyry Flows

(40)*, (41)*, (46)*, (54)*, 230*, (289)*, (330)*

Los Ranchos Lava Member (Unit 8br) - Dark Gray Olivine Pyroxene Basalt Porphyry Flows

El Azucenal Flow 346
Santa Elena Flow (59)*

La Martinez Lava Member (Unit 8bm) - Dark Gray Olivine Pyroxene Basalt Porphyry Flows

Telica Este Flow (45)*
El Arenal Flow (279)*, 294*, 453, 454

El Pegon Lava Member (Unit 8bp) - Dark Gray Olivine Pyroxene Basalt Porphyry Flows

La Guatuzza Flow (268)*, 270, 271, (293)*, 334
Los Cedros Flow (248)*, 249, 253, 256, 257*, 259, 260, (261)*, 266, 268

El Porvenir Lava Member (Unit 8bpv) - Dark Gray Olivine Pyroxene Basalt Porphyry Flows

El Guanabo Flow (18)*, 269, 296*, 297, 298, 326, 327, (328)*, 335
Los Canales Flow 216, 217*, 218, 220, 240, 241, 242, 243, 244, (245)*, 246, 262
San Rafael Flow (55)*, (214)*, 215, 219, 295*

Basal Tephra Member (Unit 8a) - Gray Pyroxene Basalt Porphyry Tephra

42*, 47*, (48)*, (49)*, 229, (329)*, 331, 332

Andesite (Unit 7) - Gray Andesite Porphyry

(80)*, 81, (302)*, 303

Table I-2. cont.

San Jacinto Formation (Unit 6) - Brown to Brownish-orange Alt. Basalt Tephra

264, 275, 310, 342, (457)*, 459*, 462, (466)*

Santa Clara Formation (Unit 5) - Gray Olivine Basalt Porphyry
(96)*, 252, 254*, 449, (450)*, 451, (452)*, 458

Cerro de Aguero Formation (Unit 4) - Purplish-gray or Gray Olivine
Andesite Porphyry
(60)*, 347, (348)*, (349)*, 350

El Najo Formation (Unit 3) - Gray Olivine Pyroxene Basalt Porphyry
247, 273, 274, 276?, 277*, 301, 304, 305, 306, 307*, 308, 309,
312, 313, 314, 315, 316*, 320, 321, 322, 323, (324)*, 325?, 343*,
344, 455, 456, 460, 463, (464)*, 468, 470*

La Ceiba Formation (Unit 2) - Gray and Red Pyroxene Andesite
(250)*, 251*, (255)*, 258, (263)*, 265, 287*, (311)*, 317, 318,
319*, 338, 339*, 340, 341, 343*, 345*, 461, (467)*, 469, 471

Cerros Los Portillos Formation (Unit 1) - Gray Olivine Basalt Porphyry
(56)*, (57)*, 299, (300)*

Xenoliths

(58)*, 232, 236*, 237, 239

Altered Sample

325

Sample numbers with chemical analyses are bracketed.

Samples with asterisks were examined in thin section.

Table III-3. Rock samples from the Maricao Range,
Pacific Coastal Plain and Nicaraguan Highlands.

Cerro Negro

Plagioclase Olivine Basalt Porphyry
1, (2)*, 3, 6*, 7, 8*, (67)*

Gray Clinopyroxene Plagioclase Olivine Basalt Porphyry Bomb
4*

Red Plagioclase Andesite Porphyry Bomb or Block
5*, 68*, 69

Vesicular Plagioclase Clinopyroxene Andesite
(70)*

San Cristobal (El Viejo)

Grey Plagioclase Olivine Basalt Porphyry Flow
9*, 19, 21, 22*, 23, 24, (25)*

Red Volcanic Andesite Bomb
20*

Plagioclase Basalt Porphyry Flow
(62)*, (63)*, 64*, 65

Tamarindo Group

Latite and Dacite Ashflows (T4)
(101)*, (186)*, 187*, (188)*, 482, (483)*, (486)*, (487)*, 488*

Latite Flow (T4)
(484)*

Andesite and Basalt Flows (T5)
100*, 102*, (189)*, (489)*, (490)*

Coyol Group

Agglomerate Lava Deposits and Lava Flows (T1)
401

Andesitic to Rhyolitic Ashflows (T2)
402, 403

Table III-3. cont.

Basalt Flows and Agglomerates (T3)

26*, 27*, 79, 404

Andesitic and Dacitic Ashflows and Tuffs (T6)

32*, 33*, 34*, 36*, 37, 76, 77, 82*, 83*, 84, 86*, 405, 406, 408, 409

Andesite Flows and Pyroclastic Deposits (T7)

(35)*, 38, 85*, 407*

Undifferentiated Matagalpa Group and Lower Coyol Group (T9)

113

Felsic Intrusives (Ta)

39*, 61*

Intermediate Intrusives (Ti)

75*, 99*

* Sample numbers with chemical analyses are bracketed.
Samples with asterisks were examined in thin section.
The locations of these samples are shown on Map 1.

Appendix IV

Groundwater Isotope Analyses

Introduction

Groundwater variations in isotopic composition of hydrogen's two isotopes ~~deuterium~~ (D) and hydrogen (H) and oxygen's three isotopes ^{16}O , ^{17}O and ^{18}O are reported as ratios related to the same ratio in a standard. The resulting values (delta) are determined as follows::

$$\delta = [(R^{\text{sample}}/R^{\text{standard}}) - 1](1,000)$$

Usually R is the ratio D/H or $^{18}\text{O}/^{16}\text{O}$. The standard used by most laboratories is ocean water, normally referred to as SMOW (standard mean ocean water; Craig, 1961). Delta is measured in per mil units and a value of +10 indicates that the sample is 10 per mil or 1% richer in deuterium or ^{18}O than the standard.

During August, 1976 and July and August 1977, water samples were collected from springs, wells and the Panteon mine levels in western Nicaragua and Lake Managua (Table IV-3). Twenty-one samples were analysed for oxygen stable isotope ratios; hydrogen isotope ratios were determined for eight of these samples.

Analytical Methods

Samples were analysed by Geochron Laboratories in Cambridge, Massachusetts. The isotopic compositions were determined by conventional mass spectrometry using a double-collector. The water samples were allowed to equilibrate with CO_2 gas at 25 degrees centigrade and the $^{18}\text{O}/^{16}\text{O}$ ratio compared to a standard gas "generated from a carbonate working standard" used by Geochron Laboratories

Table IV-1. Stable Oxygen and Hydrogen Isotope Data from Water Samples from the Telica Complex, Mina El Limon Area and Lake Managua

Sample Location	Comments	$\delta^{18}O$ (per mil)	δD (per mil)
1. foot of Redondo flow, Telica Complex	cool water, well approximately 60 metres deep	-4.7	
2. south of Colonia Agrícola Cristo Rey, Telica Complex	cool water, well approximately 180 metres deep	-6.4	
3. foot of Porvenir flow, Telica Complex	cool water, well		
4. San Jacinto, Telica Complex	scalding hot water from boiling mud pot	1.2	-35
5. Santa Isabel, Telica Complex	cool water, well approximately 30 metres deep	-6.0	
6. Piedras Quemadas, Telica Complex	cool water, well		
7. El Najo, Telica Complex	hot water spring near a fumarole field, more active in rainy season	-5.2	-49
8. Santa Elena, Telica Complex	hot water, well approximately 60 metres deep	-6.3	
9. El Carol, Telica Complex	cool water, spring	-6.3, -6.2	
10. Aqua Caliente, Mina El Limon area	hot water, well approximately 20 metres deep	-5.6	
11. El Panal, Telica Complex	cool water, well approximately 25 metres deep		
12. Los Coccos, Telica Complex	cool water, well approximately 50 metres deep	-5.0	-50

Table IV-1. Continued

13.	southwest of Santa Rosa, Mina El Limon area	cool water, well approximately 2 metres deep, previously a spring	
14.	southeast of Veta Spencer, Mina El Limon area	cool spring	6.2
15.	Puerto Momotombo, Lake Managua	shore of Lake Managua	1.2 -11
16.	San Jose, Mina El Limon area	cool water, spring	
17.	Cerro Nato, Mina El Limon area	cool water, well approximately 13 metres deep	-5.7 -50
18.	Lomas Cebadillos, Mina El Limon area	cool spring	-5.5
19.	Aparejo, Mina El Limon area	cool water, approximately 5 metres deep	
20.	Cafe Ali Negro, Lake Managua	west shore of Lake Managua	+1.3, +1.3 -11
21.	Pitahaya, Mina El Limon area	cool water, well approximately 10 metres deep	
22.	Santa Pancha, Mina El Limon area	800 level, hot ground water	-6.5 -8
23.	Santa Pancha, Mina El Limon area	600 level, hot ground water	-6.4 -9
24.	Santa Pancha, Mina El Limon area	200 level, hot ground water	
25.	Santa Clara farm, Telica Complex	hot water, well approximately 10 metres deep	
26.	Santa Pancha, Mina El Limon area	1000 level, Shalit 6, 14971	-7.7, -7.6, -7.6

Table IV-1. Continued

27.	Santa Pancha, Mina El Limon area	600 level, Shaft 6, 154° F	-7.5, -7.7
28.	Santa Pancha, Mina El Limon area	1070 level, Shaft 6, 141° F	-7.2, -7.6
29.	Santa Pancha, Mina El Limon area	1070 level, Shaft 6, 140° F	-7.4, -7.7
30.	Santa Pancha, Mina El Limon area	900 level, Shaft 6, 158° F	-7.5, -7.6

for over ten years (personal communication, R. Reesman, 1979). For the hydrogen analyses the ratio of D/H of water vapour in equilibrium with the water sample was compared to the NBS 1A working standard.

Accuracy and Precision

Reesman (personal communication, 1979) of Geochron laboratories quotes reproducibilities of better than 0.3 per mil for oxygen isotope abundances and 2 per mil for hydrogen isotope values. He considers the accuracy of the results to be better than 0.3 per mil for oxygen isotopes and approximately 2 per mil for hydrogen isotopes. These figures are consistent with accuracies of ± 0.1 per mil for $\delta^{18}O$ and ± 1 per mil for δD reported by Taylor (1974).

Interpretation

The stable isotopes of oxygen and hydrogen are commonly used to determine the source of groundwater. Oxygen has three stable isotopes - ^{16}O , ^{17}O and ^{18}O . Hydrogen has two stable isotopes 1H and 2H (deuterium), while the third 3H (tritium) is radioactive.

Isotopic fractionation can result from isotope exchange reactions, kinetic effects or physical processes. The isotope exchange reactions involve the redistribution of isotopes of an element. For equilibrium reactions, the stable isotope ratios can be used to determine the temperature of the reaction. The kinetic effects occur in unidirectional reactions where the lighter isotope moves more rapidly than the heavier isotope. Physical processes such as crystallization, melting and condensation can produce isotope fractionation which is

governed by mass differences of the individual isotopes. Stable

isotopes are fractionated by exchange reactions and physical processes.

In migration through volcanic rocks, groundwater exchanges oxygen and hydrogen with the wall-rock to varying degrees depending primarily on temperature and residence time of the water. Igneous rocks typically have higher $\delta^{18}\text{O}$ values than groundwater and therefore oxygen shifts in the groundwater to higher $\delta^{18}\text{O}$ values as the result of interaction with the wall-rock. The change in D/H ratios, however, are small even in acid geothermal systems, because volcanic rocks have low hydrogen contents (Taylor, 1974).

The oxygen and hydrogen stable isotope concentrations in meteoric waters are controlled by the physical processes of evaporation and condensation. The lighter isotopes ^{16}O and H will be concentrated in the vapour phase during evaporation and condensation. Therefore, an air mass moving over a continent will become increasingly depleted in ^{18}O and D and the resulting precipitation will also have increasingly smaller concentrations of ^{18}O and D. Because the D/H fractionation is proportional to the $^{18}\text{O}/^{16}\text{O}$ fractionation, a linear relationship exists between δD and $\delta^{18}\text{O}$ for most meteoric surface waters (Craig, 1961). This relationship can be approximated by the Craig-Epstein meteoric water line equation (Figure 8.1; Taylor, 1974):

$$\delta\text{D} = 8.0 \delta^{18}\text{O} + 5$$

The only surface waters that do not have stable isotope ratios close to the meteoric water line are those associated with closed basins in arid regions.

Telica Formation Mineral Composition

Introduction

Carleton University's Cambridge MK 5 electron microprobe was used to analyse pyroxene, olivine and plagioclase phenocrysts from four representative samples of the Telica Formation Formation. The results are listed in Table V. All analyses were carried out using a 15 kv accelerating potential and a specimen current of 0.5×10^{-7} amp. Elements were analysed in pairs such as Fe and Mg.

Standards

A calibration standard with similar element concentrations and crystal structures was used for each element for the different mineral grains. The standards used are given below:

Mineral	Standard	Elements
pyroxene	Boetcher natural pyroxene	Mg, Ca, Si
pyroxene	Smithsonian ilmenite	Ti
pyroxene	natural jadeite	Al
pyroxene	iron metal	Fe
olivine	Boetcher natural pyroxene	Mg, Si
olivine	iron metal	Fe
olivine	synthetic phlogopite	Mg
olivine	natural Mn-bearing tremolite	Mn
plagioclase	Boetcher natural pyroxene	Ca, Si
plagioclase	natural jadite	Na, Al
plagioclase	synthetic phlogopite	K
plagioclase	iron metal	Fe

The drift of the microprobe was monitored during the run by analysing standards at least once every hour. The internal standard for pyroxene and olivine was Cam natural olivine (Camargo, Mexico) and natural albite was used for plagioclase.

Quality of Analyses

The best pyroxene analyses add up to weight per cent totals that are between 99 and 101% and have 2.00 plus or minus 0.04 cations in the XY group (Aoki, 1964). Similar criteria can be applied to the olivine analyses. Y site cations should total 2.00 ± 0.04 for better quality analyses. In the case of plagioclase the Z site cations should total 16.00 ± 0.25 .

If the above criteria are applied to the probe analyses in this study there are 37 pyroxene, 16 olivine, and 7 plagioclase analyses that are high quality.

Table W.1 Representative olivine and orthopyroxene compositions from Telica

Sample#	10	10	328	328	328	329	329	10	10	Average
Unit	rim	core	incl.	rim	core	rim	core	rim	core	Island Arc Olivine*
SiO ₂	36.24	36.49	37.78	39.29	39.57	37.74	38.02	50.80	50.43	38.87
TiO ₂	0.05	0.02	0.02					0.39	0.42	---
Al ₂ O ₃	0.00	0.00	0.03					1.11	1.18	0.07
FeO	29.78	29.80	29.83	17.85	17.27	27.78	27.78	18.47	21.20	21.51
MnO	0.64	0.65	0.66	0.25	0.22	0.55	0.60	0.62	0.65	0.23
MgO	32.85	32.74	32.06	39.96	41.37	33.22	34.30	24.56	22.26	39.94
CaO	0.19	0.20	0.30					1.93	2.00	0.25
Na ₂ O	0.00	0.00	0.30					0.19	0.26	<0.00
Cr ₂ O ₃	0.03	0.03	0.02					0.01	0.00	0.00
NiO	0.04	0.05	0.02					0.01	0.00	<0.00
Total	99.82	99.99	100.7	97.35	98.42	99.29	100.62	98.08	98.44	100.34

	Number of Ions on the Basis of 4 Oxygen Atoms							6 Oxygen Atoms	
Si	0.988	0.989	1.013	1.025	1.018	1.015	1.012	1.917	1.921
Al	0.000	0.000	0.001					0.049	0.053
Ti ²⁺	0.001	0.001	0.000					0.011	0.012
Fe	0.677	0.675	0.668	0.390	0.371	0.625	0.614	0.583	0.676
Mg	1.331	1.323	1.281	1.544	1.587	1.332	1.356	1.381	1.264
Mn	0.015	0.015	0.015	0.006	0.005	0.013	0.013	0.020	0.021
Na	0.00	0.000	0.000					0.014	0.019
Ca	0.005	0.006	0.009					0.078	0.082
Cr	0.001	0.001	0.001					0.000	0.000
Ni	0.001	0.001	0.001					0.000	0.001
[Y]	2.023	2.048	1.964	1.949	1.964	1.970	1.984	1.984	1.961

Atomic Ratios

Fe ²⁺	33.7	33.8	34.3	20.1	18.9	31.9	31.2	29.7	34.9
Mg	66.3	66.2	65.7	79.9	81.1	68.1	68.8	70.3	65.1

+ - from Study of Basaltic Volcanism, 1981.

* - total iron as FeO

Table V.2 Representative plagioclase compositions from Telica

Sample #	10	10	328	328	329	329	Average
Unit	core	rim	core	rim	core	rim	Island Arc Plagioclase†
	wt %						
SiO ₂	51.63	49.78	49.53	53.19	50.13	49.52	48.70
Al ₂ O ₃ *	29.95	31.57	31.54	28.97	30.88	31.62	32.20
FeO	0.43	0.34	0.65	0.62	0.70	0.78	0.71
CaO	12.72	14.50	15.32	11.89	13.77	15.26	15.58
Na ₂ O	3.79	2.80	2.59	4.53	3.48	2.29	2.58
K ₂ O	0.26	0.14	0.16	0.29	0.17	0.13	0.19
Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.02	<0.01
TiO ₂	0.05	0.03	0.05	0.03	0.04	0.02	<0.01
NiO	0.02	0.02	0.07	0.07	0.04	0.06	<0.01
Total	98.85	99.20	99.92	99.58	99.20	99.71	100.13

Number of Ions on the Basis of 32 Oxygen Atoms

Si	9.488	9.152	9.080	9.696	9.232	9.088
Al	6.488	6.840	6.816	6.224	6.704	6.840
Fe ²⁺	0.068	0.052	0.100	0.096	0.108	0.120
Ca	2.504	2.586	3.008	2.324	2.176	3.000
Na	1.384	1.000	0.928	1.600	1.240	0.816
K	0.060	0.032	0.040	0.068	0.040	0.032
Cr	0.000	0.000	0.000	0.000	0.000	0.004
Ti	0.004	0.008	0.004	0.004	0.004	0.004
Ni	0.004	0.004	0.012	0.008	0.004	0.008

Z	15.976	15.992	15.896	15.920	15.936	15.928
X	3.988	3.920	4.096	4.190	4.112	3.984

Molecular Ratios

Ab	63.3	74.9	78.4	62.3	66.9	80.7
An	35.0	24.3	20.3	36.0	32.0	18.4
Or	1.7	0.8	1.3	1.7	1.1	0.9

† - from The Study of Basaltic Volcanism, 1981.

* - total iron as FeO

Table V.3 Representative clinopyroxene composition, from Table 1.

Sample	10	10	328	328	329	329	329	329	Average
	rim	core	rim	core	rim	core	rim	core	Island Arc
Clinopyroxene ⁺									
SiO ₂	50.59	51.35	50.63	51.23	51.47	51.77	52.06	52.67	51.31
Al ₂ O ₃	2.14	1.84	2.92	2.37	2.39	2.26	1.95	2.11	2.83
TiO ₂	0.54	0.55	0.80	0.67	0.77	0.43	0.38	0.33	0.47
FeO*	11.01	10.57	10.21	9.81	9.02	9.48	11.26	11.11	11.15
MnO	0.46	0.40	0.34	0.33	0.27	0.31	0.44	0.42	0.19
MgO	15.88	15.11	14.72	16.13	15.55	14.44	14.71	15.14	16.02
CaO	18.20	18.72	19.43	18.35	19.46	20.31	18.74	18.08	17.30
Na ₂ O	0.40	0.41	0.28	0.28	0.35	0.27	0.24	0.27	0.29
NiO ₂	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.02	---
Cr ₂ O ₃	0.00	0.03	0.16	0.12	0.03	0.04	0.01	0.01	0.18
Total	99.23	98.98	99.49	99.29	99.32	99.32	99.80	100.2	99.92

Number of Ions on the Basis of 6 Oxygen Atoms

Si	1.910	1.938	1.903	1.918	1.924	1.942	1.950	1.957
Al	0.090	0.062	0.097	0.082	0.076	0.058	0.050	0.043
Al	0.005	0.020	0.032	0.023	0.029	0.042	0.036	0.049
Ti ²⁺	0.015	0.016	0.023	0.019	0.022	0.012	0.011	0.009
Fe	0.348	0.334	0.321	0.307	0.282	0.297	0.353	0.345
Mn	0.015	0.013	0.011	0.011	0.008	0.010	0.014	0.013
Mg	0.893	0.850	0.824	0.900	0.867	0.807	0.821	0.838
Ca	0.736	0.757	0.782	0.736	0.779	0.816	0.752	0.720
Na	0.029	0.030	0.020	0.020	0.025	0.019	0.018	0.020
Cr	0.000	0.001	0.005	0.003	0.001	0.001	0.000	0.000
Ni	0.000	0.001	0.005	0.003	0.001	0.001	0.000	0.000
Z	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
XY	2.041	2.022	2.023	2.022	2.014	2.005	2.005	1.994

Atomic Ratios

Ca	37.2	39.0	40.6	37.9	40.4	42.5	39.1	37.9
Mg	45.2	43.8	42.8	46.3	45.0	42.0	42.6	44.0
Fe	17.6	17.2	16.6	15.8	14.6	15.5	18.3	18.1

+ - from The Study of Basaltic Volcanism, 1981.

* - total iron as FeO

Table V-4 Magnetite compositions from Telica.

Sample#	10	10	10	10	328	328	328	329
SiO ₂	0.22	0.13	0.12	0.20	0.23	0.14	0.15	0.20
TiO ₂	7.94	8.86	8.80	9.17	8.27	10.02	10.09	10.32
Al ₂ O ₃	3.71	3.60	3.47	3.43	3.84	3.14	3.30	3.87
FeO*	76.83	76.36	76.72	75.64	75.33	74.21	73.84	72.31
MnO	0.42	0.40	0.38	0.39	0.42	0.43	0.44	0.33
MgO	2.92	3.17	3.15	3.23	2.90	3.18	3.25	4.21
CaO	0.04	0.00	0.01	0.08	0.11	0.01	0.03	0.09
Na ₂ O	0.01	0.02	0.01	0.10	0.11	0.01	0.03	0.09
Cr ₂ O ₃	0.15	0.12	0.12	0.12	0.19	0.08	0.07	0.06
NiO	0.02	0.01	0.04	0.00	0.02	0.00	0.01	0.03
V	1.92	1.93	1.86	1.54	1.25	1.14	1.16	1.23
Total	94.18	94.60	94.69	93.89	92.57	92.35	92.36	92.67

Number of Ions on the Basis of 6 Oxygen Atoms

Si	0.077	0.044	0.043	0.070	0.081	0.051	0.053	0.068
Al	0.042	0.034	0.032	0.032	0.053	0.021	0.021	0.016
Cr	2.092	2.312	2.301	2.410	2.216	2.697	2.687	2.698
Fe ₂	13.789	13.79	13.894	13.488	13.650	13.251	13.239	13.218
Fe	8.723	8.367	8.407	8.63	8.800	8.801	8.634	7.807
Mg	1.526	1.640	1.623	1.686	1.538	1.684	1.717	2.182
Mn	0.123	0.116	0.112	0.114	0.128	0.129	0.133	0.096
Ca	0.016	0.000	0.003	0.028	0.044	0.005	0.013	0.034
Na	0.010	0.016	0.007	0.065	0.006	0.007	0.000	0.034
Ni	0.006	0.004	0.013	0.000	0.005	0.000	0.002	0.022
V	0.446	0.441	0.428	0.356	0.295	0.267	0.272	0.282

* - total iron as FeO

Table V-5. Pyroxene compositions from Telica.

Clinopyroxene

Sample	10 rim	10 core	10 rim	10 core	10 rim	10 core	10 rim	10 core
SiO ₂	50.93	50.97	50.62	50.75	51.40	51.68	51.13	50.81
Al ₂ O ₃	1.71	1.68	1.55	1.46	1.36	1.37	1.28	1.72
TiO ₂	0.41	0.49	0.43	0.44	0.42	0.43	0.48	0.49
FeO*	13.27	12.70	11.20	11.07	11.26	11.17	14.22	11.85
MnO	-	-	-	-	-	-	-	-
MgO	12.28	13.69	14.69	14.33	15.48	15.54	12.12	14.01
CaO	19.18	19.33	19.52	20.97	19.84	19.73	19.24	20.09
Na ₂ O	-	-	-	-	-	-	-	-
NiO ₂	-	-	-	-	-	-	-	-
Cr ₂ O ₃	-	-	-	-	-	-	-	-
Total	97.77	98.86	98.00	99.02	99.76	99.93	98.48	98.98

Number of Ions on the Basis of 6 Oxygen Atoms

Si	1.966	1.943	1.937	1.929	1.932	1.937	1.969	1.933
Al	0.034	0.057	0.063	0.071	0.068	0.063	0.031	0.067
Al	0.044	0.029	0.027	0.006	0.008	0.002	0.027	0.010
Ti	0.012	0.014	0.012	0.007	0.004	0.010	0.014	0.014
Fe ₂	0.428	0.405	0.358	0.352	0.354	0.350	0.458	0.377
Mn	-	-	-	-	-	-	-	-
Mg	0.706	0.778	0.838	0.812	0.867	0.868	0.696	0.795
Ca	0.793	0.790	0.800	0.854	0.799	0.793	0.794	0.819
Na	-	-	-	-	-	-	-	-
4	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
KY	1.983	2.016	2.035	2.025	2.024	2.021	1.989	2.015

Atomic Ratios

Ca	43.6	43.3	44.3	46.5	44.1	43.9	42.8	44.9
Mg	23.6	25.8	28.1	26.8	29.0	29.1	22.8	26.4
Fe	32.8	30.9	27.6	26.7	26.9	27.0	34.4	28.7

* - total iron as FeO

Table V-5 cont. Pyroxene compositions from Telica.

Pyroxene

Sample	10	10	10	10	10	10	10	49
	inter	core	rim	core	core	rim	core	rim
	-----	-----	-----	-----	-----	-----	-----	-----
SiO ₂	51.15	51.17	51.76	51.56	52.83	52.11	51.76	50.58
Al ₂ O ₃	1.12	1.42	1.57	1.63	0.93	0.90	1.05	2.57
TiO ₂	0.40	0.47	0.45	0.45	0.30	0.27	0.30	0.86
FeO*	11.31	12.87	12.10	13.14	21.23	22.48	22.62	8.32
MnO	-	-	-	-	-	-	-	-
MgO	14.76	14.06	14.80	14.08	22.58	21.80	22.05	14.38
CaO	20.23	19.27	18.97	19.30	2.04	2.13	2.09	21.51
Na ₂ O	-	-	-	-	-	-	-	-
NiO	-	-	-	-	-	-	-	-
Cr ₂ O ₃	-	-	-	-	-	-	-	-
Total	98.86	99.66	99.64	100.16	99.91	99.69	99.87	98.23

Number of Ions on the Basis of 6 Oxygen Atoms

Si	1.942	1.949	1.947	1.941	1.964	1.965	1.943	1.915
Al	0.050	0.051	0.053	0.059	0.036	0.035	0.046	0.085
Al	0.008	0.012	0.017	0.023	0.005	0.005	0.003	0.030
Ti	0.003	0.013	0.013	0.013	0.008	0.008	0.008	0.025
Fe2	0.359	0.407	0.381	0.414	0.660	0.706	0.707	0.263
Mn	-	-	-	-	-	-	-	-
Mg	0.835	0.792	0.830	0.791	1.252	1.220	1.234	0.812
Ca	0.823	0.780	0.765	0.779	0.081	0.086	0.084	0.873
Na	-	-	-	-	-	-	-	-
Z	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
XY	2.020	2.004	2.006	2.020	2.006	2.025	2.025	2.003

Atomic Ratios

Ca	45.0	42.7	42.5	42.5	4.6	4.7	4.6	50.4
Mg	27.7	26.3	28.0	26.1	43.1	40.9	41.1	28.4
Fe	27.3	31.0	29.5	31.4	52.3	54.4	54.3	21.2

* - total iron as FeO

Table V-5 cont. Pyroxene compositions from Follet.

Clinopyroxene								
Sample	49	49	49	49	49	49	49	328
	core	rim	core	core	rim	core	rim	inclusion
SiO ₂	50.94	51.20	50.98	50.47	49.67	51.57	52.78	50.58
Al ₂ O ₃	2.51	1.43	1.04	2.09	2.96	1.64	1.82	1.99
TiO ₂	0.55	0.48	0.36	0.77	0.55	0.40	0.44	0.36
FeO*	8.82	10.08	12.14	11.27	9.51	11.26	11.92	12.90
MnO	-	-	-	-	-	-	-	-
MgO	13.81	13.90	13.45	13.01	13.64	14.49	14.60	13.24
CaO	22.69	21.11	20.10	19.65	21.77	20.01	17.11	18.89
Na ₂ O	-	-	-	-	-	-	-	-
NiO ₂	-	-	-	-	-	-	-	-
Cr ₂ O ₃	-	-	-	-	-	-	-	-
Total	99.31	98.20	98.06	97.25	98.09	99.36	98.69	97.95

Number of Ions on the Basis of 6 Oxygen Atoms

Si	1.917	1.952	1.960	1.945	1.898	1.945	1.985	1.946
Al	0.083	0.048	0.040	0.055	0.102	0.055	0.015	0.054
Al	0.028	0.016	0.007	0.040	0.031	0.018	0.066	0.036
Ti	0.016	0.014	0.010	0.022	0.016	0.011	0.012	0.010
Fe ²⁺	0.278	0.321	0.390	0.363	0.304	0.355	0.375	0.415
Mn	-	-	-	-	-	-	-	-
Mg	0.775	0.790	0.771	0.747	0.777	0.814	0.819	0.759
Ca	0.915	0.862	0.828	0.811	0.892	0.809	0.690	0.779
Na	-	-	-	-	-	-	-	-
Z	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
XY	2.012	2.003	2.006	1.983	2.020	2.007	1.902	1.999

Atomic Ratios

Ca	51.7	48.2	45.0	45.8	49.9	45.0	40.4	42.9
Mg	26.5	26.8	25.4	25.6	26.4	27.5	29.1	25.3
Fe	21.8	25.0	29.6	28.6	23.7	27.5	30.5	31.8

& - oxidized rim

@ - clinopyroxene inclusion in plagioclase

* - total iron as FeO

Table V-5 cont. Pyroxene compositions from Telica.

Clinopyroxene

Sample	328	328	328	328	328	328	328	328
	Inclus.	rim	core	rim	core			
SiO ₂	51.18	50.56	50.84	51.05	50.59	51.28	51.16	50.90
Al ₂ O ₃	2.56	2.80	2.10	2.61	2.36	1.80	2.69	2.29
TiO ₂	0.36	0.40	0.33	0.38	0.39	0.34	0.37	0.38
FeO*	10.42	11.08	12.14	11.36	11.93	11.50	10.56	12.88
MnO	-	-	-	-	-	-	-	-
MgO	13.60	14.35	14.70	14.67	14.00	13.81	14.61	13.86
CaO	19.13	19.40	19.35	19.47	19.77	19.72	20.43	18.88
Na ₂ O	-	-	-	-	-	-	-	-
NiO	-	-	-	-	-	-	-	-
Cr ₂ O ₃	-	-	-	-	-	-	-	-
Total	97.24	98.59	99.46	99.54	99.05	98.45	99.83	98.63

Number of Ions on the Basis of 6 Oxygen Atoms

Si	1.957	1.919	1.922	1.920	1.921	1.952	1.917	1.944
Al	0.043	0.081	0.078	0.080	0.079	0.048	0.083	0.056
Al	0.072	0.044	0.016	0.036	0.027	0.033	0.036	0.023
Ti	0.010	0.011	0.009	0.011	0.011	0.010	0.010	0.011
Fe ₂	0.333	0.352	0.384	0.357	0.379	0.366	0.331	0.411
Mn	-	-	-	-	-	-	-	-
Mg	0.775	0.812	0.829	0.822	0.793	0.785	0.816	0.789
Ca	0.784	0.789	0.784	0.785	0.805	0.804	0.820	0.773
Na	-	-	-	-	-	-	-	-
Z	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
XY	1.974	2.008	2.022	2.011	2.015	1.998	2.013	2.007

Atomic Ratios

Ca	45.6	44.6	43.1	44.1	44.4	44.9	46.2	42.4
Mg	27.4	27.8	27.6	28.0	26.5	26.6	27.9	26.2
Fe	27.0	27.6	29.3	27.9	29.1	28.5	25.9	31.4

* - total iron as FeO

Table V-5 cont. Pyroxene compositions from Toluca.

Clinopyroxene

Sample	328	328	328	328	328	328	328	328
	core	rim	core	rim	core	rim	core	rim
SiO ₂	50.99	50.79	51.24	50.82	50.58	51.54	51.79	51.44
Al ₂ O ₃	2.29	2.25	2.95	1.70	1.96	1.71	1.92	1.58
TiO ₂	0.38	0.60	0.73	0.35	0.35	0.38	0.31	0.40
FeO*	12.19	11.38	10.27	12.53	12.35	12.34	11.44	12.63
MnO	-	-	-	-	-	-	-	-
MgO	13.94	14.92	15.50	13.77	13.94	15.21	15.46	15.49
CaO	20.05	19.74	19.70	19.35	19.70	19.96	21.03	19.44
Na ₂ O	-	-	-	-	-	-	-	-
NiO	-	-	-	-	-	-	-	-
Cr ₂ O ₃	-	-	-	-	-	-	-	-
Total	99.84	99.67	100.38	98.53	98.83	101.15	101.96	100.97

Number of Ions on the Basis of 6 Oxygen Atoms

Si	1.923	1.912	1.903	1.943	1.928	1.920	1.911	1.920
Al	0.077	0.088	0.097	0.057	0.072	0.080	0.089	0.080
Al	0.025	0.012	0.032	0.009	0.016	0.000	0.000	0.000
Ti	0.011	0.017	0.020	0.010	0.010	0.006	0.002	0.000
Fe ²⁺	0.385	0.358	0.319	0.401	0.394	0.385	0.353	0.393
Mn	-	-	-	-	-	-	-	-
Mg	0.784	0.837	0.858	0.785	0.792	0.845	0.851	0.862
Ca	0.810	0.796	0.784	0.793	0.805	0.797	0.832	0.777
Na	-	-	-	-	-	-	-	-
Z	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
XY	2.015	2.02	2.013	1.998	2.017	2.033	2.038	2.032

Atomic Ratios

Ca	44.4	44.1	44.8	43.3	43.8	43.1	45.1	42.0
Mg	26.1	28.2	29.8	26.1	26.2	27.8	28.1	28.3
Fe	29.5	27.7	25.4	30.6	30.0	29.1	26.8	29.7

* - total iron as FeO

Table V-5 cont. Pyroxene compositions from Telica.

Sample	Clinopyroxene							
	328 core	328 rim	328 core	328 rim	328 core	328 rim	328 core	328 inclus.
SiO ₂	51.29	50.47	50.94	50.85	50.67	51.53	50.89	51.39
Al ₂ O ₃	1.58	1.97	1.89	2.16	2.06	2.03	2.43	2.41
TiO ₂	0.29	0.48	0.40	0.48	0.45	0.35	0.38	0.40
FeO*	12.24	13.05	12.17	13.18	13.29	11.64	12.00	11.81
MnO	-	-	-	-	-	-	-	-
H ₂ O	15.42	15.34	15.01	15.62	15.16	15.20	16.44	15.90
CaO	19.89	19.29	20.17	19.50	19.70	19.57	20.34	20.03
Na ₂ O	-	-	-	-	-	-	-	-
NiO	-	-	-	-	-	-	-	-
Cr ₂ O ₃	-	-	-	-	-	-	-	-
Total	100.70	100.59	100.59	101.78	101.33	100.32	102.48	101.95

Number of Ions on the Basis of 6 Oxygen Atoms

Si	1.919	1.897	1.910	1.890	1.894	1.926	1.873	1.895
Al	0.081	0.113	0.090	0.110	0.106	0.074	0.127	0.105
Al	0.000	0.000	0.000	0.000	0.000	0.016	0.000	0.000
Ti	0.000	0.000	0.004	0.000	0.000	0.010	0.000	0.011
Fe ²⁺	0.379	0.407	0.382	0.408	0.415	0.364	0.359	0.364
Mn	-	-	-	-	-	-	-	-
Mg	0.860	0.860	0.839	0.865	0.845	0.847	0.902	0.874
Ca	0.798	0.777	0.811	0.777	0.789	0.784	0.802	0.792
Na	-	-	-	-	-	-	-	-
Z	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
XY	1.977	2.044	2.036	2.030	2.049	2.022	2.063	2.041

Atomic Ratios

Ca	43.0	41.5	43.7	41.5	41.9	43.4	43.0	43.2
Mg	28.2	27.9	27.5	28.0	27.3	28.5	29.4	29.0
Fe	28.8	30.6	28.8	30.5	30.8	28.1	27.6	27.8

* - total iron as FeO

Table V-5 cont. Pyroxene compositions from Telica.

Clinopyroxene and Orthopyroxene

Sample	328	328	328	328	328	328	328	328
	rim	core	rim	core	rim	core	rim	core
SiO ₂	50.46	50.97	52.51	52.38	52.67	51.72	52.41	52.50
Al ₂ O ₃	2.69	2.52	1.04	0.98	1.03	1.17	0.98	0.99
TiO ₂	0.78	0.44	0.16	0.17	0.18	0.20	0.24	0.24
FeO*	10.87	9.97	22.70	22.90	22.65	23.18	23.01	23.14
MnO	-	-	-	-	-	-	-	-
MgO	16.32	16.40	22.71	22.42	23.57	23.05	23.46	22.70
CaO	19.16	20.43	1.84	1.77	2.02	1.98	1.99	1.95
Na ₂ O	-	-	-	-	-	-	-	-
NiO	-	-	-	-	-	-	-	-
Cr ₂ O ₃	-	-	-	-	-	-	-	-
Total	100.29	100.54	100.95	100.61	102.14	101.30	102.09	101.54

Number of Ions on the Basis of 6 Oxygen Atoms

Si	1.883	1.888	1.946	1.949	1.931	1.919	1.926	1.940
Al	0.117	0.112	0.054	0.051	0.069	0.081	0.074	0.060
Al	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ti	0.022	0.010	0.000	0.000	0.000	0.000	0.000	0.000
Fe ²⁺	0.339	0.310	0.699	0.701	0.675	0.696	0.682	0.705
Mn	-	-	-	-	-	-	-	-
Mg	0.908	0.909	1.255	1.244	1.288	1.275	1.285	1.250
Ca	0.766	0.814	0.073	0.070	0.079	0.079	0.078	0.077
Na	-	-	-	-	-	-	-	-
Z	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
XY	2.036	2.043	2.027	2.024	2.042	2.050	2.045	2.032

Atomic Ratios

Ca	0.428	0.453	0.040	0.388	0.044	0.043	0.043	0.042
Mg	0.308	0.307	0.420	0.415	0.427	0.417	0.423	0.414
Fe	0.264	0.240	0.540	0.546	0.529	0.540	0.534	0.544

* - total iron as FeO

Table 4-5 (cont). Pyroxene compositions from Telila.

Orthopyroxene and Clinopyroxene

Sample	328	328	329	329	329	329	329	329
	rim	core	rim	core	rim	core	rim	core
SiO ₂	53.10	53.10	51.29	50.17	50.95	51.51	50.28	51.21
Al ₂ O ₃	1.51	1.40	2.50	2.78	2.05	2.11	2.60	2.00
TiO ₂	0.30	0.31	0.43	0.42	0.41	0.37	0.46	0.40
FeO*	19.48	20.16	9.61	9.47	10.86	10.69	9.38	10.98
MnO	-	-	-	-	-	-	-	-
MgO	25.65	25.00	13.35	13.91	13.30	14.24	11.25	14.12
CaO	1.98	1.89	21.16	20.09	20.17	20.04	21.25	19.75
Na ₂ O	-	-	-	-	-	-	-	-
NiO	-	-	-	-	-	-	-	-
Cr ₂ O ₃	-	-	-	-	-	-	-	-
Total	102.31	101.86	98.34	96.85	97.74	98.96	95.23	98.47

Number of Ions on the Basis of 6 Oxygen Atoms

Si	1.917	1.927	1.945	1.929	1.951	1.944	1.969	1.945
Al	0.083	0.073	0.055	0.071	0.049	0.056	0.031	0.055
Al	0.000	0.000	0.057	0.054	0.043	0.038	0.089	0.035
Ti	0.000	0.000	0.012	0.012	0.012	0.011	0.014	0.012
Fe ²⁺	0.586	0.608	0.305	0.305	0.348	0.337	0.307	0.349
Mn	-	-	-	-	-	-	-	-
Mg	1.380	1.353	0.754	0.797	0.759	0.801	0.657	0.799
Ca	0.077	0.073	0.860	0.828	0.828	0.811	0.892	0.804
Na	-	-	-	-	-	-	-	-
Z	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
XY	2.043	2.034	1.988	1.996	1.99	1.998	1.959	1.999

Atomic Ratios

Ca	0.044	0.042	0.494	0.477	0.467	0.459	0.519	0.453
Mg	0.483	0.470	0.263	0.279	0.260	0.275	0.232	0.273
Fe	0.473	0.488	0.243	0.244	0.273	0.266	0.249	0.274

* - total iron as FeO

Table V-3 cont. Pyroxene compositions from Telica.

Orthopyroxene and Clinopyroxene

Sample	328	328	328	328	328	328	328	329
	core	rim	core	rim	core	rim	core	rim
SiO ₂	51.27	52.85	52.93	51.22	51.37	53.86	53.31	50.43
Al ₂ O ₃	2.26	0.90	0.97	1.68	1.79	1.15	1.38	2.66
TiO ₂	0.58	0.21	0.19	0.33	0.36	0.30	0.32	0.41
FeO*	10.90	22.13	22.28	12.13	12.29	18.65	19.20	9.69
MnO	-	-	-	-	-	-	-	-
MgO	13.97	21.52	21.83	13.45	13.56	23.74	25.04	15.88
CaO	20.62	1.97	1.85	20.12	20.18	1.91	1.99	20.47
Na ₂ O								
NiO								
Cr ₂ O ₃								
Total	99.60	99.58	100.04	98.91	99.54	99.62	101.25	99.54

Number of Ions on the Basis of 6 Oxygen Atoms

Si	1.929	1.978	1.972	1.949	1.944	1.980	1.938	1.893
Al	0.071	0.022	0.028	0.051	0.056	0.020	0.054	0.107
Al	0.029	0.018	0.042	0.024	0.024	0.030	0.000	0.011
Ti	0.016	0.006	0.005	0.009	0.010	0.008	0.006	0.012
Fe ²⁺	0.343	0.693	0.694	0.386	0.389	0.573	0.584	0.304
Mn	-	-	-	-	-	-	-	-
Mg	0.784	1.201	1.212	0.763	0.765	1.301	1.357	0.888
Ca	0.832	0.079	0.074	0.820	0.818	0.075	0.078	0.823
Na								
Z	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
XY	2.004	1.997	2.027	2.002	2.006	1.987	2.025	2.038

Atomic Ratios

Ca	0.466	0.045	0.042	0.451	0.449	0.045	0.045	0.461
Mg	0.266	0.411	0.414	0.254	0.254	0.475	0.480	0.302
Fe	0.268	0.544	0.544	0.295	0.297	0.480	0.474	0.227

* - total iron as FeO

Table V-5 Pyroxene compositions from Tullahoma.

Clinopyroxene

Sample#	329	329	329	329	329	329	329
Unit	core	rim	core	rim	core	rim	core
SiO ₂	50.29	51.09	50.55	50.07	49.85	49.11	50.49
Al ₂ O ₃	3.66	2.23	2.59	3.70	2.91	2.04	2.05
TiO ₂	0.51	0.38	0.42	0.64	0.47	0.75	0.39
FeO*	11.04	10.75	11.37	10.64	9.95	9.31	11.26
MnO	-	-	-	-	-	-	-
MgO	15.29	15.49	15.06	15.30	15.55	15.91	15.08
CaO	19.88	20.13	19.66	20.10	20.27	20.03	19.48
Na ₂ O							
NiO ₂							
Cr ₂ O ₃							
Total	100.66	100.07	99.66	100.44	98.99	97.15	98.75

Number of Ions on the Basis of 6 Oxygen Atoms

Si	1.873	1.912	1.904	1.868	1.884	1.890	1.918
Al	0.127	0.088	0.096	0.132	0.116	0.093	0.082
Al	0.034	0.010	0.019	0.030	0.013	0.000	0.011
Ti	0.014	0.011	0.012	0.018	0.013	0.005	0.011
Fe ²⁺	0.344	0.336	0.358	0.332	0.315	0.300	0.358
Mn	-	-	-	-	-	-	-
Mg	0.849	0.864	0.845	0.851	0.876	0.912	0.854
Ca	0.793	0.807	0.793	0.803	0.821	0.826	0.793
Na							
Z	2.000	2.000	2.000	2.000	2.000	2.000	2.000
XY	2.034	2.028	2.027	2.007	2.038	2.043	2.026

Atomic Ratios

Ca	0.444	0.449	0.440	0.451	0.458	0.460	0.438
Mg	0.288	0.291	0.284	0.290	0.297	0.308	0.286
Fe	0.268	0.260	0.277	0.260	0.245	0.233	0.275

* - total iron as FeO

Table V-6 Plagioclase compositions from Telica.

plagioclase

Sample#	10	10	10	10	10	10	10	10
Unit	rim	core	rim	core	rim	core	rim	core
SiO ₂	46.70	46.00	48.66	49.57	53.13	51.48	50.77	49.94
Al ₂ O ₃	34.25	35.48	33.38	33.58	30.83	32.13	31.01	32.49
FeO*	1.12	0.74	0.89	0.85	0.73	0.72	0.73	0.72
MnO								
MgO								
CaO	17.55	17.87	15.61	15.46	12.70	14.28	14.28	15.85
Na ₂ O	2.94	1.58	2.81	2.57	3.96	3.15	3.76	2.50
K ₂ O	0.12	0.09	0.16	0.14	0.36	0.28	0.27	0.17
Cr ₂ O ₃								
Total	102.67	101.77	101.50	102.17	101.17	101.70	102.04	100.82

Number of Ions on the Basis of 32 Oxygen Atoms

Si	8.461	8.359	8.815	8.894	9.495	9.208	9.226	9.807
Al	7.315	7.600	7.128	7.100	6.495	6.774	6.643	6.906
Fe ₂	0.170	0.113	0.135	0.127	0.109	0.107	0.112	0.108
Mn								
Mg								
Ca	3.406	3.480	3.031	2.972	2.433	2.737	2.780	3.063
Na	1.031	0.556	0.986	0.892	1.371	1.092	1.324	0.874
K	0.029	0.021	0.036	0.032	0.082	0.064	0.062	0.040
Z	15.776	15.859	15.943	15.994	15.99	15.982	15.869	15.913
XY	4.636	4.17	4.188	4.023	3.995	4.000	4.278	4.085

Molecular Ratios

Ab	23.1	13.7	24.4	3.0	35.3	28.1	31.8	22.0
An	76.3	85.8	74.7	76.2	62.6	70.3	66.7	77.0
Or	0.6	0.5	0.9	0.8	2.1	1.6	1.5	1.0

* - total iron as FeO

Table 7-6 Plagioclase compositions from Telica.

Plagioclase								
Sample #	10	329	329	329	329	329	329	329
Unit	core	rim	core	rim	core	rim	core	rim
SiO ₂	46.56	50.24	46.63	53.75	52.60	50.07	47.08	48.06
Al ₂ O ₃	35.26	31.26	33.60	29.65	32.37	31.62	33.42	32.67
FeO*	0.65	0.85	0.83	0.55	0.50	0.77	0.83	0.88
MnO								
HgO								
CaO	18.27	14.35	16.86	10.44	12.78	15.09	18.12	17.04
Na ₂ O	1.28	3.19	2.01	4.40	3.18	3.05	1.64	2.95
K ₂ O	0.10	0.17	0.12	0.39	0.41	0.10	0.07	0.16
Cr ₂ O ₃								
Total	102.12	100.07	100.05	99.18	101.84	100.71	101.15	101.76

Number of Ions on the Basis of 32 Oxygen Atoms

Si	8.422	9.186	8.603	9.768	9.357	9.110	8.610	8.747
Al	7.519	6.735	7.306	6.352	6.787	6.781	7.203	7.008
Fe ²⁺	0.099	0.130	0.128	0.083	0.074	0.118	0.128	0.133
Mn								
Mg								
Ca	3.542	2.810	3.332	2.034	2.436	2.943	3.550	3.322
Na	0.450	1.131	0.720	1.550	1.097	1.076	0.580	1.041
K	0.023	0.041	0.28	0.090	0.094	0.023	0.017	0.037
Z	15.941	15.921	15.909	16.12	16.144	15.891	15.813	15.755
XY	4.114	4.112	4.208	3.757	3.701	4.16	4.275	4.533

Molecular Ratios

Ab	11.2	28.4	17.6	42.2	30.9	26.6	14.0	23.7
An	88.2	70.6	81.7	55.3	68.3	72.8	85.6	75.5
Or	0.6	1.0	0.7	2.5	0.6	0.6	0.4	0.8

* - total iron as FeO

Table V-6 Plagioclase compositions from Tellica.

Sample#	Plagioclase		
	329	329	329
Unit	core	rim	core
SiO ₂	46.72	49.77	52.31
Al ₂ O ₃	34.57	31.64	30.75
FeO*	0.81	0.84	0.90
MnO			
MgO			
CaO	18.28	14.56	12.93
Na ₂ O	1.88	3.18	3.63
K ₂ O	0.09	0.22	0.24
Cr ₂ O ₃			
Total	102.63	100.21	100.76

Number of Ions on the Basis of 32 Oxygen Atoms

Si	8.460	9.100	9.443
Al	7.379	6.819	6.544
Fe ²⁺	0.123	0.129	0.136
Mn			
Mg			
Ca	3.548	3.853	2.500
Na	0.661	1.129	1.271
K	0.021	0.050	0.054
Z	15.389	15.919	15.987
XY	4.353	4.161	3.961

Molecular Ratios

Ab	15.6	28.0	33.2
An	83.9	70.7	65.4
Or	0.5	1.3	1.4

* - total iron as FeO

Table V-7 Olivine compositions from Teflon.

Sample#	Olivine						
	10 rim	10 core	10 rim	10 core	10 rim	10 rim	10 core
SiO ₂	38.63	39.24	37.67	37.87	37.44	37.48	37.45
TiO ₂							
Al ₂ O ₃							
FeO*	26.46	27.08	29.46	28.42	30.45	30.14	30.16
MnO	0.48	0.49	0.56	0.52	0.58	0.56	0.58
MgO	34.21	33.79	31.56	32.47	31.18	31.37	31.20
CaO							
Na ₂ O							
K ₂ O							
Cr ₂ O ₃							
Total	99.79	100.60	99.25	99.23	99.64	99.55	99.39

Number of Ions on the Basis of 4 Oxygen Atoms

Si	1.0247	1.0327	1.0217	1.0205	1.0166	1.017	1.018
Al							
Ti							
Fe ²⁺	0.587	0.596	0.668	0.640	0.692	0.684	0.686
Mg	1.353	1.338	1.276	1.306	1.260	1.269	1.264
Mn	0.011	0.011	0.013	0.012	0.013	0.013	0.014
Na							
Ca							
[Y]	1.951	1.945	1.957	1.958	1.965	1.966	1.964

Atomic Ratios

Fe ²⁺	30.3	30.8	34.4	32.9	35.5	35.0	35.2
Mg	69.7	69.2	65.6	67.1	64.5	65.0	64.8

* - total iron as FeO

Table V-7 Olivine compositions from Telica.

Sample#	olivine							
	328 rim	328 core	328 rim	328 rim	328 core	328 core	328 rim	328 core
SiO ₂	37.67	37.97	39.24	39.29	39.57	39.55	37.56	37.42
TiO ₂								
Al ₂ O ₃								
FeO*	28.53	29.14	21.12	17.85	17.27	17.36	30.51	28.64
MnO	0.50	0.47	0.25	0.25	0.22	0.23	0.50	0.52
MgO	33.38	32.88	38.75	39.96	41.37	41.36	32.65	34.16
CaO								
Na ₂ O								
K ₂ O								
Cr ₂ O ₃								
Total	100.08	100.46	99.36	97.35	98.42	98.50	101.21	100.74

Number of Ions on the Basis of 4 Oxygen Atoms

Si	1.009	1.015	1.018	1.025	1.018	1.018	1.003	0.997
Al								
Ti								
Fe ₂	0.639	0.651	0.459	0.390	0.371	0.374	0.682	0.638
Mg	1.333	1.309	1.499	1.554	1.587	1.586	1.300	1.357
Mn	0.011	0.011	0.005	0.006	0.005	0.005	0.011	0.012
Na								
Ca								
[Y]	1.983	1.971	1.963	1.949	1.964	1.965	1.993	1.995

Atomic Ratios

Fe ₂	32.4	33.2	23.4	20.1	18.9	19.1	34.4	32.0
Mg	67.6	66.8	76.6	79.9	81.1	80.9	65.6	68.0

* - total iron as FeO

Table V-7 Olivine compositions from Tellica.

Sample#	olivine							
	328	329	329	329	329	329	329	329
Unit	rim	rim	core	?	rim	core	rim	core
SiO ₂	37.30	37.74	38.02	38.48	38.37	38.30	38.69	38.44
TiO ₂								
Al ₂ O ₃								
FeO*	29.04	27.78	27.78	23.62	24.13	25.35	24.07	25.95
MnO	0.51	0.55	0.60	0.50	0.48	0.49	0.50	0.50
MgO	33.80	33.22	34.30	38.17	37.87	36.66	38.04	36.35
CaO								
Na ₂ O								
K ₂ O								
Cr ₂ O ₃								
Total	100.65	99.29	100.62	100.76	100.85	100.80	101.30	101.25

Number of Ions on the Basis of 4. Oxygen Atoms

Si	0.997	1.015	1.000	0.999	0.998	1.002	1.001	1.003
Al								
Ti								
Fe ₂	0.649	0.625	0.614	0.513	0.525	0.555	0.521	0.567
Mg	1.346	1.332	1.356	1.478	1.468	1.430	1.467	1.415
Mn	0.012	0.013	0.013	0.011	0.010	0.011	0.011	0.011
Na								
Ca								
[Y]	2.007	1.970	1.984	2.002	2.004	1.996	1.998	1.993

Atomic Ratios

Fe ₂	32.5	31.9	31.2	25.8	26.3	28.0	26.2	28.6
Mg	67.5	68.1	68.8	74.2	73.7	72.0	73.8	71.4

* - total iron as FeO

Table V-7 Olivine compositions from Telica.

Olivine

Sample#	329	329
Unit	rim	core
SiO ₂	38.63	38.77
TiO ₂		
Al ₂ O ₃		
FeO*	24.61	22.58
MnO	0.46	0.45
MgO	37.41	39.02
CaO		
Na ₂ O		
K ₂ O		
Cr ₂ O ₃		
Total	101.12	100.83

Number of Ions on the Basis of 32 Oxygen Atoms

Si	1.003	1.001
Al		
Ti		
Fe ²⁺	0.535	0.488
Mg	1.449	1.501
Mn	0.010	0.010
Na		
Ca		
[Y]	1.994	1.999

Atomic Ratios

Fe ²⁺	27.0	24.5
Mg	73.0	75.5

* - total iron as FeO

Appendix VI

Crystal Fractionation Computer Programme and Output

Computer Programme

A Fortran computer programme (see next page) that models crystal fractionation was modified to run on a Digital PDP 11/23 computer. It was originally written by T. Pearce of Queen's University, Kingston, Ontario. The programme takes a parent composition and subtracts or adds minerals to produce a daughter composition. The user specifies the composition and amount of each mineral (up to 13 minerals) and the number of times these minerals are subtracted.

Appendix VI Crystal Fractionation Computer Program and Output

*** CRYSTAL FRACTIONATION PROGRAMME ***

D. Lefebvre Feb. 1984 modified from Pearce, 1973

P is the parent composition

1 is the combined composition of the minerals being fractionated.

C is the composition of the differentiate or cumulate in absolute units

WC or PERC is the wt% of the rock C

MX is the composition (wt %) of the mineral mix formed from the mineral compositions and the array (X)

N = number of stages, less than 10

Array S(P,N) indicates the proportion of each mineral fractionated at each of the N stages.

P = proportion of mineral fractionated; +ve = fractionation
-ve = accumulation

Array X(N) is the weight fraction of the original parent which is added or subtracted at each stage; for example -0.1 means a loss of 10 grams to be subtracted at each stage from a parent of 100grams

$C(I) = P(I) + X(I)MX$ forms the daughter from the parent at each stage

```

*****
C
C
C          SAMPLE DATA SET
C          P2O5, H2O, TOTAL
C          NOT SHOWN
C
C          SI02  TI02  AL2O3  CR2O3  FEO  MnO  MgO  CaO  Na2O  K2O
C P      49.50  1.40  16.00  0      10.22  0.17  6.80  10.40  2.70  0.82
C FO      39.57  0      0      0      17.27  0.22  41.37  0      0      0
C FA      37.44  0      0      0      30.45  0.58  31.18  0      0      0
C DI      51.56  0.45  1.63  0      13.14  0      14.18  19.30  0      0
C H       50.94  0.55  2.51  0      8.82  0      13.81  22.69  0      0
C EN      51.78  0.30  1.05  0      22.62  0      22.05  2.09  0      0
C FS      53.86  0.30  1.15  0      18.65  0      23.74  1.91  0      0
C AN      46.63  0.36  33.60  0      0.83  0      0.0  16.86  2.01  0.12
C AB      53.13  0      30.93  0      0.73  0      0      12.70  3.96  0.36
C MAG     0.10  19.42  1.39  0.07  71.59  0.33  2.29  0      0      0
C ILM     0      52.66  0      0      47.34  0      0      0      0      0
C QZ      100.0  0      0      0      0      0      0      0      0      0
C CR      0.12  0.14  10.28  59.40  17.09  0.14  12.62  0.14  0      0
C
C N      10
C X(I) -0.01-0.01-0.01-0.01-0.01-0.01-0.01-0.01-0.01-0.01

```

C 1	1.0	0.0	0.00	0.00	0.0	0.0	0.00	0.00	0.0	0.0	0.0	0.0
C 2	0.7	0.3	0.000	0.000	0.0	0.0	0.00	0.00	0.0	0.0	0.0	0.0
C 3	0.5	0.5	0.000	0.000	0.0	0.0	0.00	0.00	0.0	0.0	0.0	0.0
C 4	0.3	0.7	0.000	0.000	0.0	0.0	0.00	0.00	0.0	0.0	0.0	0.0
C 5	0.1	0.9	0.000	0.000	0.0	0.0	0.00	0.00	0.0	0.0	0.0	0.0
C 6	1.0	0.0	0.00	0.00	0.0	0.0	0.00	0.00	0.0	0.0	0.0	0.0
C 7	0.7	0.3	0.000	0.000	0.0	0.0	0.00	0.00	0.0	0.0	0.0	0.0
C 8	0.5	0.5	0.000	0.000	0.0	0.0	0.00	0.00	0.0	0.0	0.0	0.0
C 9	0.3	0.7	0.000	0.000	0.0	0.0	0.00	0.00	0.0	0.0	0.0	0.0
C 10	0.1	0.9	0.000	0.000	0.0	0.0	0.00	0.00	0.0	0.0	0.0	0.0
C	FD	FA	DI	HD	EN	FS	AN	AB	MAG	ILM	QZ	LR

```

      READ (M(13), MAG(13), ILM(13), KF(13),
     & DIMENSION N(20)
     & DIMENSION S(12,20)
     & DIMENSION P(13), C(13), FFS(13), FD(13), FA(13), DI(13), HD(13),
     & EN(13), FS(13), AN(13), AB(13), QTZ(13), PERM(13)

```

```

      CALL ASSIGN(1, IY1:DIFF.DAT)
      CALL ASSIGN(2, IY1:DIFF.QUIT)

```

```

      READ(1,6010) P,FD,FA,DI,HD,EN,FS,AN,AB,MAG,ILM,QTZ,KF
      FORMAT(12,13F7.3)

```

```

      E(6,6015) P,FD,FA,DI,HD,EN,FS,AN,AB,MAG,ILM,QTZ,KF

```

```

      6015 FORMAT(1X, PARENT MAGMA, 12,13F7.3)
      READ(1,6020) N

```

```

      6020 FORMAT(I2)

```

```

      WRITE(6,6025) N

```

```

      6025 FORMAT(1X,I2)

```

```

      READ(1,6030) (X(I), I=1,N)

```

```

      6030 FORMAT(10F5.2)

```

```

      WRITE(6,6035) (X(I), I=1,N)

```

```

      6035 FORMAT(1X,10F5.2)

```

```

      READ(1,6040) ((S(I,J), I=1,12), J=1,N)

```

```

      6040 FORMAT(10(12F6.3))

```

```

      WRITE(6,6045) S(I,J)

```

```

      6045 FORMAT(12(1X,F6.3))

```

```

      CONTINUE

```

```

      DO 7 L=1,N

```

```

      DO 5 I=1,12

```

```

      M(I) = X(L)*S(1,L)*FD(I)+S(2,L)*FA(I)+S(3,L)*DI(I)+

```

```

      *S(4,L)*HD(I)+S(5,L)*EN(I)+S(6,L)*FS(I)+S(7,L)*AN(I)

```

```

      *S(8,L)*AB(I)+S(9,L)*MAG(I)+S(10,L)*ILM(I)+S(11,L)*ILM(I)

```

```

      *S(11,L)*QTZ(I)+S(12,L)*KF(I)

```

```

      WRITE(6,6050) M(I)

```

```

      6050 FORMAT(1X,F5.2)

```

```

      CONTINUE

```

```

      SUM = 0

```

```

      DO 3 I=1,12

```

```

      SUMM = SUMM + M(I)

```

```

      3 CONTINUE

```

```

      DO 4 I=1,13

```



```
*T118, H2O, T128, TOTAL  
WRITE(6,7050)F,M,D,PERC,PERM  
7050 FORMAT(1X, F,13F10.3,1X, M,13F10.3,1X, D,13F10.3,1X, PERC,  
13F10.3,1X, PERM,13F10.3,1X,  
WRITE(2,2000) PERC  
2000 FORMAT(A8,13F5.2)  
DO 30 I=1,13  
30 CONTINUE  
CALL CLOSE (2)  
STOP  
END
```

THE GEOLOGY OF NORTHWESTERN NICARAGUA

MAP 1

from Catastro and National Resources
Inventory 1972a

LEGEND

VOLCANIC ROCKS

Qa Pyroclastic deposits

Qb Lava flows

Qc Undifferentiated pyroclastic
deposits and lava flows

SEDIMENTARY ROCKS

To Undifferentiated sediments

INTRUSIVE ROCKS

To Felsic intrusives

Intermediate intrusives

Basic intrusives

Agglomerate deposits
and lava flows

67°45'

87°30'

1 OF/DE

Fault

Major fracture

Calders, craters and maars

Anticline

Syncline

Contact

Sample

Pacific Ocean

QUATERNARY

Qa Pyroclastic deposits

Qb Lava flows

Qc Undifferentiated pyroclastic deposits and lava flows

QUATERNARY

Qc Undifferentiated sediments

INTRUSIVE ROCKS

Ta Felsic intrusives

Ti Intermediate intrusives

Tb Basic intrusives

Fault

Major fracture

Calders, craters and mounds

Anticline

Syncline

Contract

Sample

Analysis

Pacific Ocean

TERTIARY

PLIOCENE

T1 Agglomerate deposits and lava flows

T2 Ash flows (andesitic to rhyolitic)

T3 Basalt flows and agglomerate deposits

MIOCENE

T6 Ash flows (andesitic and dacitic) and tuffs

T7 Andesite flows and pyroclastic deposits

PRE-MIOCENE

Matagalpa Group

T4 Ash flows (andesitic and dacitic) and tuffs

T5 Andesite flows, agglomerates and sediments

Undifferentiated Lower Coyol Group and Matagalpa Group

2 OF/DE

Pacific Ocean

INDEX MAP

Scale 1:50,000

Kilometres

D. Lefebvre 27.2.83

3 OF/DE

HONDURAS
NICARAGUA

4 OF/DE

1400

86°45'

86°30'

86°15'

5 OF/DE

5 OF/DE 5

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010A
(ANSI and ISO TEST CHART No. 2)

525

Rio Tecomapa

10F/DE

Cerro
Blandon

Cerro
Las Palmeras

Cerro
El Penasco

MAP 2 GEOLOGY OF THE MINA EL LIMON AREA

LEGEND

QUATERNARY PLEISTOCENE and RECENT

Alluvium, soil, tuff

TERTIARY MIOCENE?

- 6** Basalt and andesite dikes
- 5** Dacite dikes and stocks
- 4** Andesite and dacite flows, 4a) intrusion
- 3** Dacite domes, flows and volcanoclastics, 3a) domes
- Two-pyroxene andesite flows
- Plagioclase clinopyroxene basalt and andesite volcanoclastics and flows

Geological boundaries (defined approximate, assumed)

Bedding

Flow banding (inclined, vertical)

Fault (defined, approximate, assumed)

Quartz vein (many along faults)

Quartz vein with dacite dike

Joint (inclined, vertical)

Laminar jointing

Columnar jointing

Outcrop, area of outcrop

Spring, well

Pit

Gravel road

Dirt road

Volcanic breccia

Volcanic conglomerate

Volcanic sandstone

Silicification

Diamond drill hole

Geology by D. Lefebvre 1976, 1977

Geological cartography by D. Lefebvre 1983

Some data taken from Geyne (1952)

The base map was drafted from photographic enlargements of 1964 government topographic maps at 1:50,000 scale.

30F/DE

topographic maps at 1:50,000 scale.

Ocean

Managua

Scale

0 1 1.5 2 km

1 16,250

0 1 1.5 2 mi

Approximate magnetic declination in 1960 was $6^{\circ} 15'$ E and is decreasing $3'$ annually.

(4 4 83 92 83)

4
OF/D

5
OF/DE

6 OF/DE

Note

The Footwall, Hanging Wall and Southern Extension veins belong to the Panteon Vein System and the Limon North, Main Limon and Pozo Bono veins make up the Limon Vein System.

S
410

7
OF/DE

86° 47' 20"

525

45'

Colonla Agricola
Cristo Rey

Cerro Montosa
600

La Colba

Tellica Est

San Jacinto

El Guanbo Flow

La Guatuzza Flow

El Arenal Flow

Volcan Santa Clara

El Guanbo Flow

Los Canales Flow

Los Cedros Flow

3 OF/DE

Montaña El Pegón

MAP 3

GEOLOGY OF THE TELICA COMPLEX

60F/DE

LEGEND

QUATERNARY RECENT

- 9 Alluvium and colluvium, 9a) Lahar, 9b) alluvium
- 8 Telica Formation, pyroxene plagioclase basalt porphyry
 - 8c Upper Tephra Member
 - 8bt Terminal Lava Member
 - 8br Los Ranchos Lava Member
 - El Azucenal Flow
 - Santa Elena Flow
 - 8bm La Martinez Lava Member
 - Telica Este Flow
 - El Arenal Flow
 - 8bp El Pegon Lava Member
 - La Guatuzá Flow
 - Los Cedros Flow
 - 8bpx El Porvenir Lava Member
 - El Guánabo Flow
 - Los Canales Flow
 - San Rafael Flow
 - Basal Tephra Member

RECENT or PLEISTOGENE

- 7 Corral Falso andesite, plagioclase andesite porphyry lavas
- 6 San Jacinto Formation, altered basalt lapillistone and tuff
- 5 Santa Clara Formation, olivine plagioclase basalt porphyry lavas and tephra
- Cerro de Aguero Formation, olivine

Geological boundary (defined, approximate, gradational)

Possible flow borders covered with later tephra, interpreted from airphotos

Fault (assumed)

Fumarole

Outcrop

Crater

Escarpment

Topographic contour in metres

Dirt road

Building

0 500 1000 2000 m

1:25000

Geology, by D. Lefebure 1976 and 1977
Geological cartography by D. Lefebure 1980 and 1983

The base map was drafted from a photographically enlarged 1:50,000 topographic map published in 1973 by the Instituto Geografico Nacional, Managua, Nicaragua

Approximate magnetic declination in 1970 was 4°49' and is decreasing 2' annually.

Flow
Pegón
Los Cedros Flow
Los Cedros
8bp
1385
1350
1300
1250
1200
1150
1100
1050
1000
950
900
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0

Geology by
Geological
and 1983

The base m
photograph
map publis
Geographic

Approxima
was 4 49

7 OF / DE

Geology by D. Lefebure 1976 and 1977
Geological cartography by D. Lefebure 1980
and 1983

The base map was drafted from a
photographically enlarged 1:50,000 topographic
map published in 1973 by the Instituto
Geografica Nacional, Managua, Nicaragua

Approximate magnetic declination in 1970
was $4^{\circ} 49'$ and is decreasing $2'$ annually.

- 8bp El Pegon Lava Member
- La Gualuza Flow
- Los Cedros Flow
- 8bpv El Porvenir Lava Member
- El Guanabo Flow
- Los Canales Flow
- San Rafael Flow
- Basal Tephra Member

RECENT or PLEISTOCENE

- 7 Corral Falso andesite, plagioclase
andesite porphyry lavas
- 6 San Jacinto Formation, altered basalt
lapillistone and tuff
- 5 Santa Clara Formation, olivine
plagioclase basalt porphyry lavas
and tephra
- 4 Cerro de Aguero Formation, olivine
plagioclase andesite porphyry
lavas and tephra
- 3 El Najo Formation, olivine pyroxene
plagioclase basalt porphyry lavas
- 2 La Ceiba Formation, andesite lavas

TERTIARY or QUATERNARY

PLIOCENE or PLEISTOCENE

- 1 Cerro Los Portillos Formation, olivine
plagioclase basalt porphyry lavas

8 OF DE 8

10F/DE

20F/DE

86°45'

12°40'

COLONIA AGRICOLA
CRISTO REY

Tellico M

La Ceiba

EL DESMONTE

Santa Clara

EL GUANABO

LA GUATUZA M

PALO DE AGUA

La Martinez

EL ARENAL

Montaña La Cueva del Leon

Los Canales

Montaña El Pegón

LOS CEDROS

30F/DE

4 OF DE

GEOLOGICAL HAZARDS OF THE TELICA COMPLEX

5 OF/DE

GEOLOGICAL HAZARDS OF THE TELICA COMPLEX

LEGEND

Paved road

Unpaved road

Relative Degree of Risk

TEPHERO

ANDERSON VOLCANIC CASE

H
M
L

High

Moderate

Low

High

M

Moderate

L

Low

L

Low

Only volcanic activity associated with Telica and Santa Clara has been considered in drafting this map. Consult Map 3 for location and source for base map.

D. Telipure 1983

Scale

MAP 4

TELICA

6
OF/DE
6

516 517 518 519 520 521 522 523 524 525 526 527

96°45'

12°30'

END / FIN

7 04 87