

GEOLOGY OF LOWER CANYON SANTA CLARA,  
CHIHUAHUA, MEXICO

by

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THE GEOLOGY OF LOWER CANYON SANTA CLARA,  
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ABSTRACT

Basalt flows and subalkaline to peralkaline ash-flow tuffs of mid-Tertiary age crop out in lower Canyon Santa Clara, 91 km north of Chihuahua City, Chihuahua, Mexico. The rocks are cut by two, east-west trending, normal faults (south blocks down). Between the faults, there is a north-south trending vent containing vertically foliated tuff. North-south trending Basin and Range-style normal faults cut the eastern portion of the area.

A mildly alkaline (?) basalt, subalkaline Acantilado tuff, comenditic Cryptic tuff, and strongly comenditic Campana tuff compose a genetically related sequence. These rocks are stratigraphically equivalent to the Bellavista Volcanics (Mauger, 1979). At least 400 m of basalt, with a few interbedded rhyolite tuffs, are exposed. Near the top of the section there is a glassy andesite which resulted from mixing of basaltic and rhyolitic magmas. The Acantilado ash-flow rhyolite overlies the basalt. This unit forms prominent columnar-jointed cliffs averaging 25 m in height. Above the Acantilado tuff is a thick section of peralkaline Cryptic tuff. It contains a basal vitrophyre overlain

by a red and white flowed zone. A highly porous zone containing vapor-phase minerals overlies this, and continuing upward there is a thick section of micropoikilitic rhyolite with Na-pyroxenes and Na-amphiboles in the groundmass. Breccias are seen at the top and bottom of each cooling unit. The uppermost unit is the Campana tuff. It forms massive, columnar-jointed cliffs which become 200 m thick atop Sierra La Campana, south of the field area. Typically the Campana is strongly eutaxitic and blue from groundmass riebeckite, but brown to pink varieties such as the Chocolate tuff, contain groundmass aegirine.

Low initial  $\text{Sr}^{87}/\text{Sr}^{86}$  ratios indicate that the rocks in this area were probably differentiated by fractional crystallization at shallow depths to produce rhyolite magmas that became progressively Na-enriched and Al-depleted. These liquids could have become peralkaline during later phases of differentiation. The magmas probably formed in a tensional back-arc environment that may have had a genetic relationship to early stages of the Rio Grande rift.

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•

## INTRODUCTION

### Problem/Purpose

No detailed geological investigations have ever been made on the Sierra de la Calera, Sierra Cumbres de Majalca, Sierra de la Campana, and Sierra del Nido extending northward from Chihuahua City, Chihuahua. With support of the Mexican government, Mauger (1974) began a detailed geologic mapping and petrographic study of rocks found in the region. Potential economic occurrences are to be noted. Subsequently Mauger (1975), Spruill (1976), Gall (1977), and Mauger 1978 and 1979) have expanded on this work. This study is a continuation of the project; it presently represents the northernmost extension of the investigation.

### Physiography

The study area is located 91 km north of Chihuahua City, Chihuahua, Mexico (Figure 1) and may be reached by taking a dirt road west from Mexican highway 45 for 2 km. The area extends from the mouth of Canyon Santa Clara westward for 7 km and includes an area approximately 4.5 km north and south of the canyon. Santa Clara Canyon is a major east-west drainage that divides Sierra de la Campana to the south from the Sierra del Nido to the north. Two large tributary canyons, Las Norias and El Obscuro, flow from the south and enter Canyon Santa Clara near its mouth. Canyon Las Tapias is the largest tributary valley in the northern half of the area.

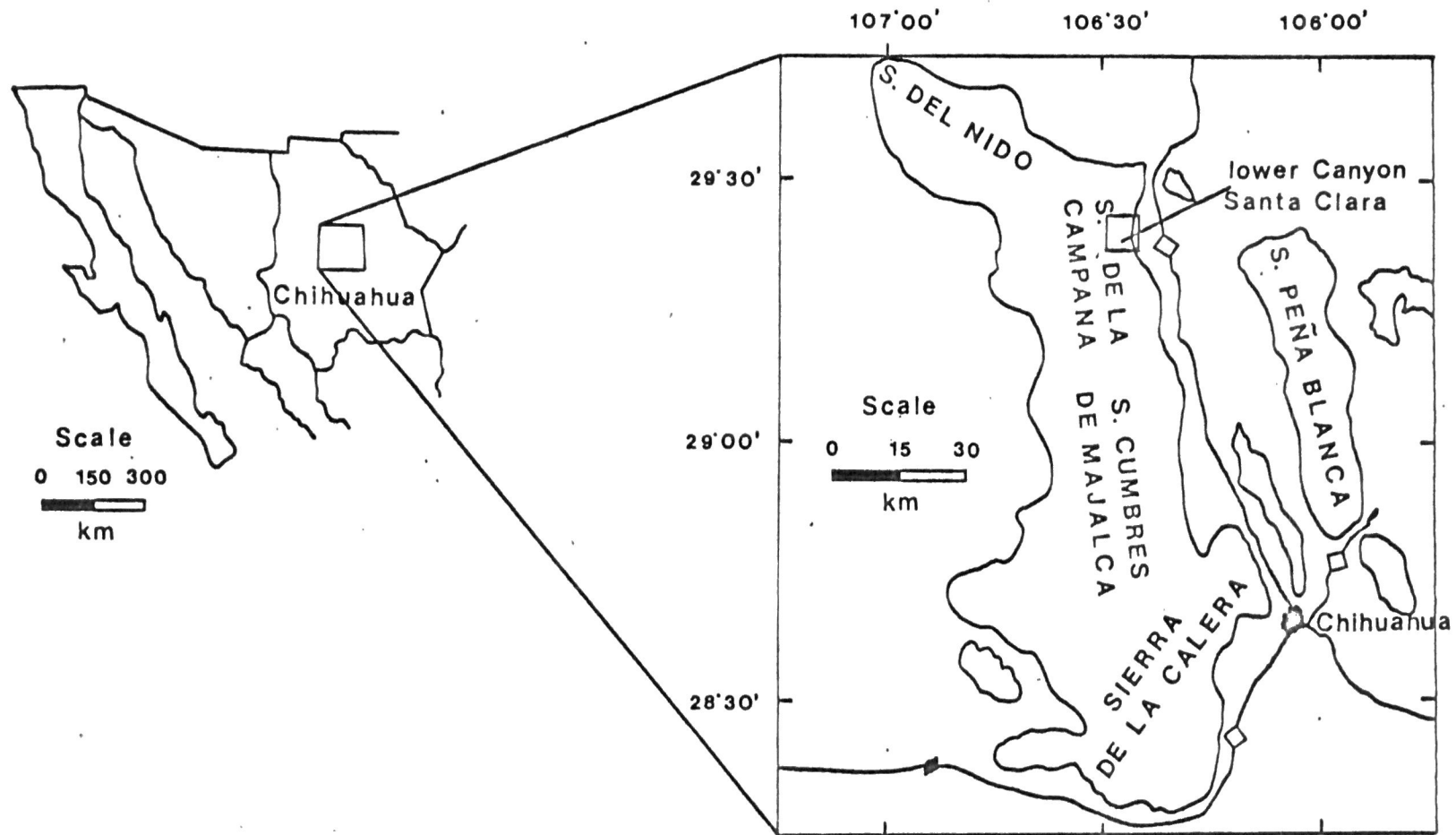


Figure 1. Index map of northern Mexico showing the area of investigation (modified from Spruill, 1976).

Streams are intermittent but often flow during the summer rainy season. Rainfall averages 30-35 cm/yr and the mean temperature is 16°C (Hawley, 1969). Cacti, various species of agave, thick-bladed grasses, and low scrubs are common in the lowlands, but higher regions contain ocotillo, juniper, pinon pine, and ponderosa pine. The area is generally rugged with a maximum relief of 800 m. Valley floors have elevations of 1600 to 1700 m; the highest peaks and ridges attain elevations slightly above 2400 m (Figure 2).

This area is part of the Mexican Basin and Range. It is situated between the Sierra Madre Occidental to the west and the Chihuahua desert region to the east. The Sierra Madre Occidental is a large, high plateau that is cut by narrow NNE-SSW trending basins. The Basin and Range contains fault-block mountain chains separated by large inter-mountain basins or bolsons (Brand, 1937; Hawley, 1969). Farther east, the Chihuahua desert region is composed of narrow, steep, N-S trending mountains and broad valleys. Elevations are lower than in the western regions.

### Geologic Setting

The Sierra Madre Occidental consists of volcanic rocks that have been divided into two groups (McDowell and Keizer, 1977):

- 1) A "lower volcanic complex" of granitic batholiths (102-45 m.y. old) is associated with altered extrusive rocks and is undoubtedly a part of the West Coast Mesozoic igneous complex; and

- 2) an "upper volcanic supergroup" of calc-alkaline ignimbrites, mostly 34-27 m.y. old, that is comparable to the Tertiary ignimbrites of the western United States.

The Chihuahua Basin and Range is mainly composed of Tertiary volcanic rocks in the western section, but Mesozoic marine carbonates and terrigenous rocks are exposed toward the east. Throughout the Chihuahua desert region Cretaceous marine carbonates are the dominant rock type. The field area is located in the transition zone between the Tertiary volcanic and marine carbonate terranes. The Sierra de la Campana and Sierra del Nido contain no limestones; however, the next range to the east, the Sierra Peña Blanca, contains limestones and volcanic rocks.

Regionally the Sierra de la Campana and Sierra del Nido blocks dip gently to the west; however, near the mouth of Canyon Santa Clara rocks dip east-southeast from  $1^{\circ}$  to  $3^{\circ}$ . This can be seen in cross section B-B' (Plate 2) of the geologic map (Plate 1).

The stratigraphic section in Canyon Santa Clara (Plate 3) is nearly identical to the section seen in Canyon Bellavista, 40 km to the south (Mauger, personal communication, 1978). No age dates have been completed for rocks in this study area but a  $29.5 \pm 1.0$  m.y. date for "Acantilado" tuff in Canyon Bellavista is reported (Mauger, 1978). The stratigraphic sequence in Canyon Santa Clara is at least 960 m thick.

#### Nomenclature

The rhyolitic rocks in this study area exhibit characteristics of welded ash and lapilli deposits and of liquid rhyolite flows. It was



finally concluded that the felsic rocks are ash-flow tuffs. "Ash-flow" is defined by Ross and Smith (1961, p. 3) as an adjective and "tuff" as a size indicator. It should be noted that some particles included in the ash-flow tuffs from the field area are larger than 4 mm. The degree of welding may range from non-welded to highly welded.

Ash-flow tuffs are named using Cook's (1965) classification which is modified from an earlier classification of Wentworth and Williams (1932). The igneous flow-rock classification used in this text is one proposed by the IUGS Commission (Hyndman, 1972, p. 35).

#### Analytical Data and Procedures

Orthoclase (Or) content for sanidine was measured using the procedure given by Orville (1963) and by Jones and others (1969). Measurements were made on the GE model XRD-6 X-ray diffractometer utilizing copper radiation. Samples were heated to 910°C for 24 hours to homogenize the sanidine. Quartz is usually present in the samples and serves as an internal standard: potassium bromate is added to samples that don't contain quartz. The d 201 values for sanidine are from Smith (1974).

Chemical analyses for  $\text{Al}_2\text{O}_3$ ,  $\text{SiO}_2$ ,  $\text{K}_2\text{O}$ ,  $\text{CaO}$ ,  $\text{TiO}_2$ , and  $\text{Fe}_2\text{O}$  (+) were done by X-ray fluorescence. The samples were pulverized and then ground in a McCrone micronizing mill for 30 minutes in acetone. Methyl cellulose (15 wt %) was added to increase the cohesion of the powder.

Calibration curves for the major elements in rhyolitic rocks were determined using nine standards (Table 1a). Background, counting factor, and dead-time correlations were performed on all data.

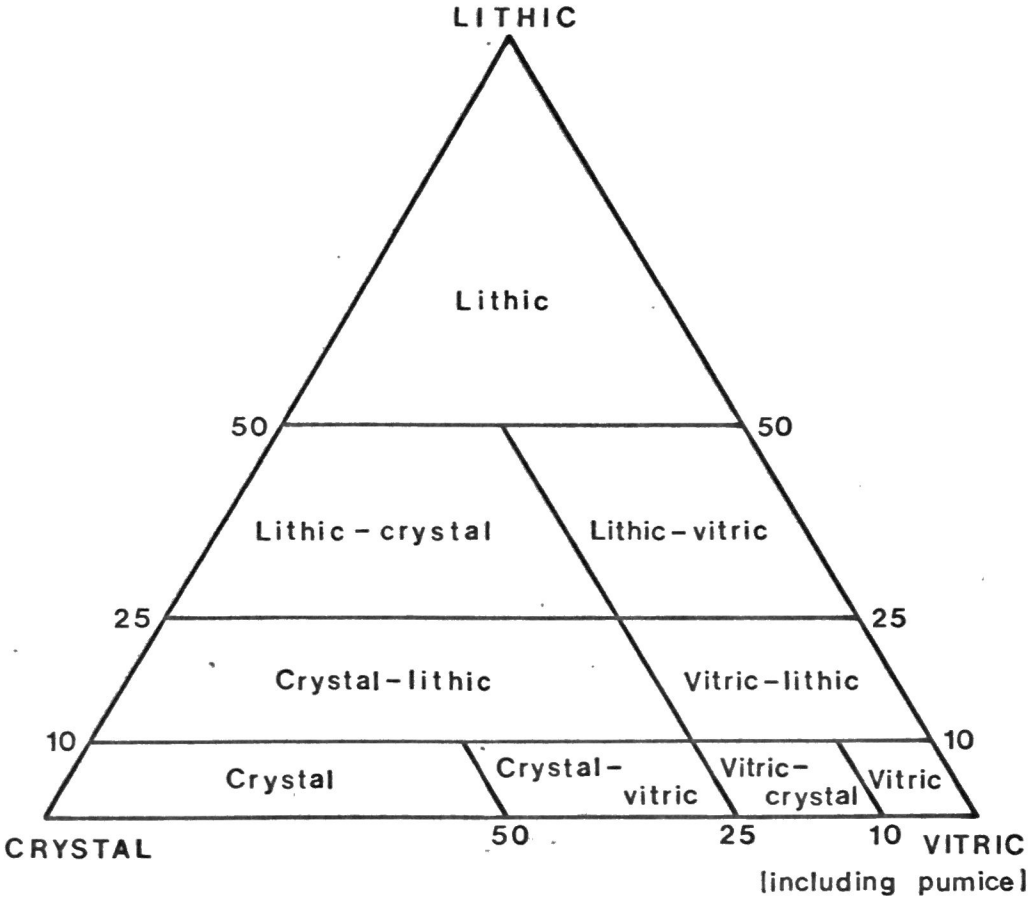


Figure 3.  
Classification of ash-flow tuffs.

|       |         |          |
|-------|---------|----------|
| NIM-G | CM-108  | Sunny II |
| G-2   | CM-182  | Nancy Gh |
| GSP-1 | Sunny-I | Nancy Ga |

Table 1a. Standards used for XRF analyses.

Slopes and correlation coefficients for the standards are listed in Table 1b.

| <u>Oxide</u>                       | <u>Slope</u> | <u>Correlation<br/>Coefficient</u> |
|------------------------------------|--------------|------------------------------------|
| Al <sub>2</sub> O <sub>3</sub>     | 59.42        | 0.992                              |
| SiO <sub>2</sub>                   | 127.5        | 0.992                              |
| K O                                | 5389         | 0.990                              |
| CaO                                | 5515         | 0.999                              |
| TiO <sub>2</sub>                   | 9390         | 0.998                              |
| Fe <sub>2</sub> O <sub>3</sub> (T) | 2284         | 0.997                              |

Table 1b. Slope expressed as cps/wt % and correlation coefficients for runs.

Field work was carried out during the summers of 1977 and 1978. Mapping was done on aerial photographs, scale 1:50,000, and the final geologic map is based on CETENAL's Los Sauces HI3C35 topographic map of the same scale. Over 120 hand specimens were collected and 150 thin sections were prepared for petrographic study. Rock names are based on thin section point counts (1,000 counts).

## GENERAL GEOLOGY

### East-West Faults

There are two prominent east-west faults. The northern fault passes through Canyon Las Tapias (Figure 4) and bifurcates near the mouth of the canyon. The southern segment is covered by alluvium in lower Canyon Santa Clara and is terminated by the north-south Basin and Range fault. The northern segment extends through the first valley north of Canyon Santa Clara. The southern block is down dropped by about 120 m in Canyon Las Tapias and by at least 200 m farther east.

The other east-west fault is exposed in Canyon Las Norias, 2.5 km south of Canyon Santa Clara. It intersects Canyon Las Norias at a 90° angle and here, the fault has been differentially eroded to form the mouth of Canyon El Rosal. The fault is exposed in Canyon El Obscuro, farther east; it cannot be recognized with certainty in the southeast front range. In canyon El Rosal, the displacement is 80 to 100 m and Cryptic tuffs are juxtaposed against basalts (6 m thick). Tuffs, laharic breccias, and sedimentary deposits are present at the fault contact (Figure 5). Rocks younger than those in the basaltic section do not occur as clasts. Thus the fault scarp was present before the eruption of the Acantilado and Cryptic tuffs. Faulting continued; however, after they were deposited.

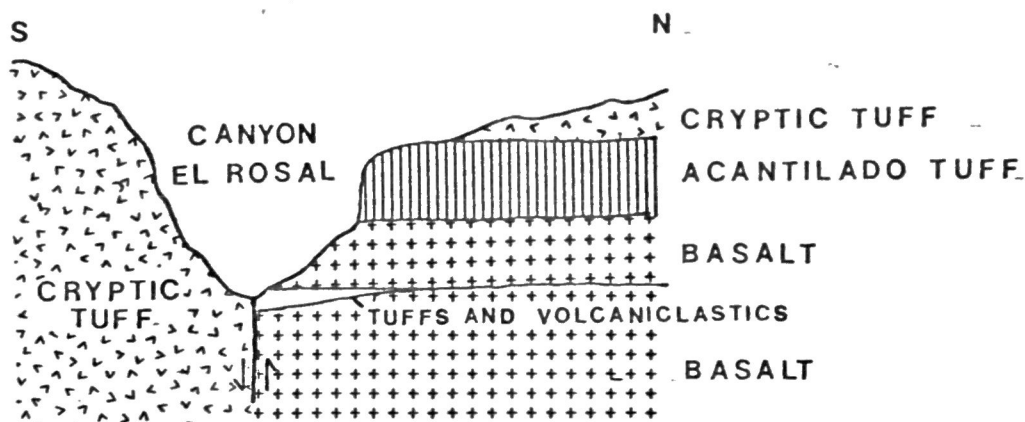


Figure 6. Generalized cross section across Canyon El Rosal at the intersection of Canyon Las Norias. A wedge of volcanoclastic sediments thickens toward the fault. Clastics in the volcanoclastic rocks predate the Acantilado tuff. Presumably the fault trace was a topographic low where sediments and tuffs could accumulate. A thicker wedge of volcanoclastic strata might be located on the downthrown block.

Both large east-west faults have vertical dips and both southern blocks are downthrown. The faults extend beyond the field area to the west and are truncated by a north-south Basin and Range fault to the east. Other smaller east-west normal faults occur and all but one are downfaulted to the south.

#### North-South Faults

A large range-front Basin and Range fault cuts the eastern third of the field area. The low-lying hills (Figure 7) in the southeastern section of the study area are en echelon fault slivers that are progressively dropped down to the east. Displacement along the principal fault is estimated to be 500 m but smaller, parallel faults show displacements of 10 to 35 m. These faults strike from N. 5 W. to N. 15 W.

and dip vertically or steeply to the east. North of Canyon Santa Clara the main range-front fault is displaced eastward and buried under alluvium. This easterly displacement may be explained as an adjustment along the younger fault where it intercepted the older east-west faults that trend through the Canyon Santa Clara area.

The major Basin and Range fault system extends well beyond the field area. It displaces the youngest ash flows and truncates all east-west faults. On a regional scale it belongs to the Basin and Range structures of central Chihuahua. These structures probably did not become important until the Miocene (Christiansen and Lipman, 1972, Part I) but they may have been active in this area more recently (McDowell and Claybaugh, 1978).

## BASALT SECTION

### General Statement

Slightly alkaline (?) basalts are the lowermost rocks in the study area. Some intercalated rhyolitic tuffs and andesitic flows occur near the top of the section, especially toward the west. Minimum relief on the upper contact is estimated to be 100 m, indicating that erosion had occurred prior to the eruption of the Acantilado tuff. The base of the basaltic section is not exposed, thus the observed thickness of 400 m is a minimum value. The best exposures of these rocks are in their northwest part of the area.

In Canyon Bellavista, 40 km to the south, similar basalts lie below a 30 m.y. old ash-flow tuff that is the same unit as the Acantilado tuff of this field area (Mauger, 1979, personal communication).

### Main Basalts

The main rock type is an olivine augite basalt containing labradorite (An<sub>59</sub>). There are three major varieties; massive flows, scoriaceous/amygdaloidal flows, and flow breccias. These varieties change within a few meters and they represent variations in single or different flows (Figure 8).

The massive basalts are charcoal gray when fresh but typically oxidize to some shade of rusty red. They contain a few small amygdules and vesicles and columnar joints (2 to 10 cm wide) are common but poorly formed.

Groundmass plagioclase laths (An<sub>58</sub>) are euhedral to subhedral and exhibit a pilotaxitic texture. Albite twinning is common; Carlsbad twinning is less common. Mafic minerals include augite ( $Zc = 45^\circ$ ), magnetite, and hematite (?). Small olivine phenocrysts have rims of iron oxide and are cut by irregular cracks lined with iron oxide. Augite grains are considerably larger than the plagioclase laths and often surround the laths to produce a crude ophitic texture (Figure 9). Tiny apatite needles are common as inclusions in plagioclase phenocrysts. Zircons occur with magnetite phenocrysts. A brown, clayey material occurs interstitially and along cracks. Labradorite (An<sub>59</sub>) phenocrysts may be up to 2 mm in diameter. Additional thin section information is provided in Table 2.

Amygdules have spherical to irregular shapes and range up to 11 mm in diameter. They are filled with chalcedony, calcite, clinoptilolite, and one or more other tabular zeolites.

The vesicular/amygdaloidal basalts are gradational with their massive counterparts. Vesicles are about 3 mm long and typically have a preferred orientation. Colors are similar to those of massive units; however, more reddish hues are seen. Amygdules are most common in the upper parts of flows.

| Sample No. | Plag. | Mafic<br>(Oliv., Mag.) | Pyrox. | Amyg. |
|------------|-------|------------------------|--------|-------|
| 73A        | 66    | 15                     | 10     | 7     |
| 26         | 53    | 28                     | 13     | 0.5   |
| 21         | 56    | 31                     | 15     | 0.5   |
| 10         | 53    | 33                     | 10     | 5     |
| 4          | 50    | 30                     | 15     | 5     |
| Average    | 55    | 27                     | 13     | 4     |

Table 2. Point count information for Basalt. Numbers expressed as percents.

Amygdules are twice as abundant compared to the massive basalt, but they still constitute less than 10% of the rock. Secondary minerals are often arranged in concentric layers. From the rim to the center, typical layers would be a clay, calcite, quartz, and a zeolite. Fluorite is infrequently found associated with the zeolites.

Flow breccias are associated with the other two varieties of basalt. These contain fragments up to 2 m in diameter and occur in units 5 to 10 m thick. They are dark gray, brown, or red and are poorly lithified.

#### Upper Rhyolitic Tuffs

Rhyolitic ash-flow, air-fall, and lapilli tuffs, and laharic breccias occur toward the top of the basaltic section. In the field



area these are quite thin (about 3 m), but they thicken substantially to the west.

They rhyolites are poorly welded, vitric tuffs have 1 to 2% phenocrysts. Quartz phenocrysts are less abundant than in either the Acantilado or Campana tuffs and overgrowths are common. The ground-masses generally show granophyric textures. Accessory minerals include magnetite, zircon, altered pyroxene, and iron oxides. The rocks are typically altered and contain tiny tabular heulandite crystals (?) which replace sanidine (Or<sub>80</sub>) phenocrysts. Fluorite is present in a few cavities.

The laharic rocks are heterolithologic. Many lithic fragments are altered to an olive-green mineral that has a fibrous texture and high, second or third order birefringence. X-ray diffraction indicates that it is clinoptilolite. Tabular crystals of heulandite (?) are also common. Calcite, chalcedony, fluorite, and a clayey material are common replacement minerals in many lithic fragments and phenocrysts (Figure 10).

### "Andesite"

At the head of Canyon Las Tapias, a glassy, spherulitic, crystal-rich andesite crops out about 35 m below the base of the Acantilado tuff. A lower glassy unit is 1 to 5 m thick and weathers to light brown, rounded boulders (Figure 11). It grades upward into a glassy rock with rusty-red spherulites that average 8 mm in diameter. They occur in clumps and are apparently concentrated along flowage foliations (Figure 12). This andesite weathers into spheroidal boulders

and the surrounding ground is littered with pebble-sized spherulites. An upper rusty-red, devitrified, spherulitic andesite is 2 to 5 m thick.

In thin section the rock displays good perlitic cracking. Lath-shaped plagioclase microlites, averaging 3  $\mu$  in diameter, produce a pilotaxitic texture. Spherulite fibers have extremely small diameters and radial textures are difficult to see even with high magnification. However, crude concentric bands can be seen under low magnification (Figure 13).

A petrological problem is encountered when considering the glass composition (Table 3). The glass has a rhyolitic composition but the rock is classified as an andesite on the basis of its phenocryst (Xenocryst) content.

| <u>Metal Oxide</u>             | <u>Spherulite 1a</u> | <u>Spherulite 1b</u> | <u>Glass</u> |
|--------------------------------|----------------------|----------------------|--------------|
| Na <sub>2</sub> O              | 4.60                 | 0.36                 | 1.80         |
| MgO                            | 0.07                 | 0.02                 | 0.11         |
| Al <sub>2</sub> O <sub>3</sub> | 19.70                | 2.62                 | 13.60        |
| SiO <sub>2</sub>               | 66.50                | 94.61                | 70.10        |
| K <sub>2</sub> O               | 9.40                 | 0.60                 | 2.57         |
| CaO                            | 0.51                 | 0.04                 | 0.39         |
| TiO <sub>2</sub>               | 0.00                 | 0.01                 | 0.30         |
| MnO                            | 0.00                 | 0.00                 | 0.00         |
| FeO(t)                         | 0.21                 | 0.22                 | 1.87         |
|                                | 100.98               | 98.85                | 92.53        |

Table 3. Microprobe analyses of spherulitic andesite.

Analysis of spherulite 1a (Table 3) indicates sanidine (Or<sub>56</sub>) plus minor amounts of a silica phase. Spherulite 1b is mainly cristobalite with minor amounts of sanidine. Fe and Ca can be incorporated into the sanidine in small amounts. These elements plus Mn and Ti represent impurities and would be expelled or concentrated along the

rim of the spherulite. Obviously, enough Fe remains in the spherulite to produce a red color. Kesler and Weiblen (1968) studied a spherulite, andesite glass from Haiti. They found Na and Mg to be more abundant in the spherulite. At the spherulite/glass border Ca, Ti, and Si were concentrated; Al and K were depleted relative to the glass. It was tentatively concluded that Al and K were incorporated into the sanidine structure producing the higher concentrations of these elements in the spherulite. Ca, Ti, and excess Si were extraneous to the crystallizing sanidine fibers and formed an impurity layer around the spherulite.

The upper red, massive spherulitic zone has fine-grained granophyric matrix. Feldspars show severe alteration and pyroxenes are completely altered to a brown clayey material. Small, 1-5  $\mu$  diameter, dark brown acicular crystals of amphibole (?) occur throughout the matrix. These may have formed when the pyroxenes altered or more likely, they are primary, altered amphiboles.

The fresh glassy phase contains about 30% xenocrysts. Feldspars are often glomeroporphyritic and groups can be 1 cm across (Figure 14). Feldspars also account for most of the xenocrysts; pyroxenes, magnetite, zircons, and quartz constitute the remainder. Apatite needles are present in many plagioclase crystals. The rock is composed of about 2% lithic fragments.

Feldspar xenocrysts (Figure 15) can be divided into at least 5 different types. Some phenocrysts show reaction rims indicating disequilibrium with the magma. Others have internal resorption features indicating an earlier period of disequilibrium. The latter

crystals have clear, euhedral, outer zones that suggest equilibrium crystallization within the groundmass liquid.

Type I feldspars (Figure 16) are euhedral sanidines (1 to 2 mm in width) that often show prominent rhombic forms. Exterior portions are clear and untwinned. Cores, although clear, have slight undulatory extinctions and may have faint, finely spaced twin lamellae. The internal composition boundary is usually irregular (Figure 17). Internal and external compositions are very similar (Figure 17). These crystals are thought to result from resorption and/or conversion

1.



Figure 17. Type I feldspars, may be completely clear (a) may have an irregular core that shows undulatory extinction; (b) or may have finely spaced twin lamellae within an irregular core (c). Core compositions average  $Ab_{51.9} Or_{42.6} An_{5.5}$  and rims  $An_{5.1}$ .

of Type II anorthoclase cores to sanidine followed by crystallization of additional sanidine. The cores may have been xenocrysts.

Type II feldspars (Figure 18) have several different textural habits that are evidently dependent upon the original composition of the core. Rims or exteriors are clear; cores are irregularly shaped, and usually show twin lamellae, undulatory extinction, and some degree or resorption. The resorbed zone is often cloudy, and riddled with

lenticular holes that sometimes intersect at right angles. Other crystals have albite twinning through the entire crystal. This type of crystal was not analyzed by microprobe but may represent an original calcic feldspar xenocryst. Type II crystals may be euhedral to subhedral, are often glomeroporphyritic, and average 3 to 4 mm in length. Microprobe analyses (Figure 18) show that cores are anorthoclase or calcian anorthoclase; rims are sanidine. These crystals are considered xenocrysts.

11.



Figure 18. Type II feldspars have euhedral outlines with irregularly shaped cores that contain finely spaced twin lamellae and show undulatory extinctions (a); may have an altered core riddled with sinuous holes (b); or may have slightly altered cores with a clear, albite-twinned exterior. Average interior composition  $\text{Ab}_{63.3} \text{Or}_{19.0} \text{An}_{17.8}$ ; average exterior compositions  $\text{Ab}_{50.9} \text{Or}_{43.2} \text{An}_{5.9}$ .

Type III feldspars are plagioclase. Crystals may be euhedral to anhedral but are most commonly subhedral. They average 5 mm in length and are usually glomerophyritic with Type I and Type II feldspars, clinopyroxenes, titanomagnetite, and zircons. Cores have straight to irregular boundaries and show albite twinning, Carlsbad twins are less common. The degree of resorption in the cores is variable (Fig. 19).

Typically, the core is cloudy, splotchy and contains wavy, lenticular or cuniform holes, and has an undulatory extinction. A colorless, clayey material can be seen to rim the holes under high magnification. Pyroxene, titanomagnetite, and apatite may occur as inclusions. Alteration rims of variable thickness are always present and often appear as tiny, wavy parallel lines that are perpendicular to the edge of the crystal. Very thin, clear, outer rims may envelope all of this (Figure 20). These outermost rims were not analyzed but they are assumed to be sanidine.

III.



Figure 20. Type III feldspars usually show albite twinning, some internal resorption and an alteration rim (a); may have clear sanidine rims around an otherwise partially resorped rim (b); or may be fragmental with cuniform resorption features. Average interior composition  $\text{Ab}_{52.6} \text{Or}_{7.2} \text{An}_{40.2}$ ; average exterior composition  $\text{Ab}_{57.5} \text{Or}_{10.0} \text{An}_{32.2}$ .

Microprobe data show crystal interiors to be andesine and exteriors to be potassic oligoclase. These crystals follow a normal compositional zoning trend for plagioclase in a magma where the temperature is decreasing and  $\text{K}_2\text{O}$  is increasing. The original phenocrysts were incorporated into a more siliceous melt and underwent partial resorption. Thus, they should be considered as xenocrysts.

Type IV feldspars are usually anhedral, average 4 mm in diameter, and are not glomeroporphyritic (Figure 21). Interiors of crystals are clear, with no twinning or undulatory extinction and rims are always altered. The alteration produces a graphic or cuniform network composed of two feldspars; one is in optical continuity with the core (Figure 16). Indices of refraction for the two feldspars are also different. Microprobe analyses show the interiors to be a potassic sanidine, the two exterior feldspars are calcian anorthoclase and potassic oligoclase. The ragged graphic feldspar intergrowths (Figure 22c) are considered to have formed by the reaction of a potassic sanidine from a rhyolite with a basaltic magma. Thus type IV sanidines are also thought to be xenocrysts.

IV.



Figure 21. Type IV feldspars usually have clear, untwinned interiors without undulatory extinctions. They may show a slight reaction rim (a), may have a strong reaction rim consisting of two feldspars (b), or be completely reacted (c) without a clear portion. Microprobe analyses show that clear interiors average  $\text{Ab}_{37.7} \text{Or}_{61.0} \text{An}_{1.4}$  and exterior feldspars average  $\text{Ab}_{54.8} \text{Or}_{28.3} \text{An}_{14.8}$  and  $\text{Ab}_{65.2} \text{Or}_{9.7} \text{An}_{25.3}$ .

Textures similar to those of type IV feldspars have been reported by Bantor (1951). He considered them to have formed by autoresorption of an earlier phaneritic phase.

Type IV feldspars are anomalous. They have interior compositions of sanidine instead of plagioclase. These are probably "xenocrysts" from mixing with rhyolite magma; however, the sanidine in exposed rhyolite from this area have much lower Or values.

Type V feldspar crystals are the smallest and are associated with orthopyroxenes in rounded xenoliths (Figure 21a). These feldspars may show alterations but usually appear to be fresh and have good albite twinning. They have a calcic andesine,  $Ab_{39.5} Or_{5.1} An_{54.0}$ , composition, and are the most calcic plagioclases in the rock. The relatively coarse grain size and composition of the xenoliths suggest that they were removed from a gabbro that had crystallized or partly crystallized at depth.

Three different pyroxenes have been identified by microprobe analyses (Figure 23). Augite ( $En_{40}Wo_{35}Fs_{25}$ ) is the most common of the pyroxenes. The grains average about 0.8 mm in diameter, are light green to colorless, and exhibit a  $Z_{Ac}$  of  $47^\circ$ . Crystals are euhedral to subhedral and sometimes twin with a 001 twin plane. Many display cloudy cores; more severely altered crystals contain cores of biotite(?) (see Figure 24).

The second type of clinopyroxene is ferropigeonite ( $En_{43}Wo_8Fs_{49}$ ). These crystals are smaller and more poorly formed than the augites. The optical properties are quite similar to those of



augite but ferropigeonite has a smaller 2V. A third pyroxene (orthopyroxene;  $\text{En}_{65}\text{Wo}_2\text{Fs}_{33}$ ) is associated with calcic plagioclases in the gabbro xenoliths. The orthopyroxenes are subhedral to anhedral and average 0.1 mm in diameter. Their birefringence is low and they are nearly colorless.

Other phenocrysts include titanomagnetite, with an average of 21.1%  $\text{TiO}_2$ , zircons, and a small percentage of badly altered olivine. There are also a few quartz xenocrysts which are highly rounded and often show conchoidal fractures. Lithic fragments from the main basaltic section are common. There are several unusual grains consisting of rounded quartz grains surrounded by acicular and granular pyroxene (Figure 25).

### Petrogenesis

Although the basalt was not analyzed chemically, the petrography is similar to that of alkalic basalts found on east and west flanks of the Rio Grande Depression (Lipman, 1969). These basalts typically have a fine-grained, pilotaxitic groundmass of plagioclase, olivine, and augite. Small olivine phenocrysts and occasional xenocrysts of quartz and quartz rimmed with granular augite are present. Lipman (1969) alludes to experimental, high-pressure studies indicating that magmas of these compositions would be expected to differentiate at depths of 35 to 70 km. Thus a portion of the basaltic section in the field area may have evolved at relatively great depths.

Tuttle and Bowen (1958) show that two feldspars crystallizing in equilibrium will cease to follow converging trends toward Ab (in the

An-Ab-Or system) and instead will begin to follow resorption curves of similar trends. The point at which precipitation reverts to resorption depends upon the original composition of the liquid (Rahman and McKensize, 1969). The five varieties of feldspars in the andesite were not precipitated in equilibrium. The various resorption trends were initiated when the crystals became incorporated into magmas and encountered disequilibrium conditions. The groundmass for the spherulitic andesite is highly siliceous and existed as a liquid at a low temperature and pressures. Many of its phenocrysts (xenocrysts) are stable in less silicic magmas and at higher temperatures and/or pressures. Therefore, the glassy, spherulitic andesite is thought to have formed by near-surface mixing of a rhyolitic and basaltic magma.

#### Basalt

|           |   | Ab   | Or   | An   |                     |   | Ab   | Or   | An   |
|-----------|---|------|------|------|---------------------|---|------|------|------|
| Type I    | I | 51.9 | 42.6 | 5.5  | Type IV             | I | 36.6 | 62.4 | 1.0  |
|           | R | 50.0 | 44.9 | 5.1  |                     | I | 35.6 | 63.2 | 1.2  |
| Type II   | I | 62.9 | 22.9 | 14.2 |                     | I | 40.8 | 57.4 | 1.9  |
|           | I | 62.5 | 20.8 | 16.7 |                     | R | 55.9 | 28.9 | 15.1 |
|           | I | 64.1 | 15.5 | 20.4 |                     | R | 64.0 | 11.0 | 25.0 |
|           | I | 63.5 | 16.8 | 19.7 |                     | R | 66.3 | 8.3  | 25.5 |
|           | R | 52.0 | 42.0 | 6.0  | I Avg.              |   | 37.7 | 61.0 | 1.4  |
|           | R | 47.1 | 48.1 | 4.8  | R <sub>1</sub> Avg. |   | 55.9 | 28.9 | 15.1 |
|           | R | 52.0 | 41.3 | 6.7  | R <sub>2</sub> Avg. |   | 65.2 | 9.7  | 25.5 |
|           | R | 54.6 | 38.5 | 6.9  | Type V              |   | 47.9 | 3.0  | 49.0 |
|           | R | 48.7 | 46.1 | 5.3  |                     |   | 59.1 | 6.1  | 34.8 |
| I Average |   | 63.3 | 19.0 | 17.8 |                     |   | 59.1 | 6.2  | 34.7 |
| R Average |   | 50.9 | 43.2 | 5.9  | Average             |   | 55.4 | 5.1  | 39.5 |
| Type III  | I | 54.5 | 6.75 | 38.8 |                     |   |      |      |      |
|           | I | 55.2 | 9.3  | 35.4 |                     |   |      |      |      |
|           | R | 56.0 | 7.6  | 28.0 |                     |   |      |      |      |
|           | R | 59.0 | 12.4 | 28.0 |                     |   |      |      |      |
| I Average |   | 52.6 | 7.2  | 40.2 |                     |   |      |      |      |
| R Average |   | 57.5 | 10.0 | 32.2 |                     |   |      |      |      |

Table 4. Microprobe analyses of feldspar crystals in spherulitic andesite. I = interior areas, R = exterior areas (rims).

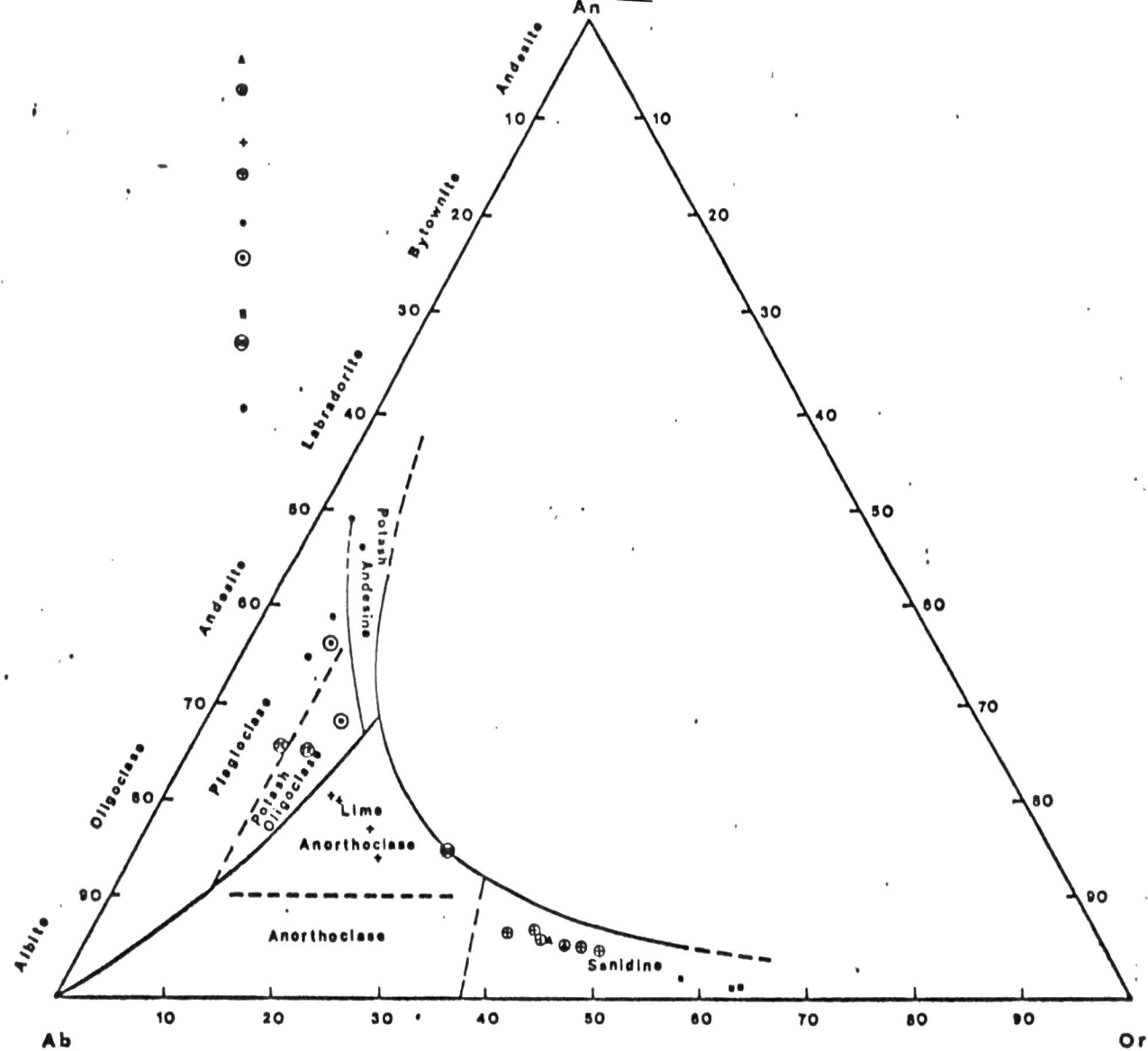


Figure 15. Ternary phase diagram of the system Albite-Orthoclase-Anorthite. The boundary between the fields of crystallization and no crystallization are from Tuttle and Bowen (1958). The boundaries between the fields of sanidine, anorthoclase and plagioclase are from Smith and MacKenzie (1958). The subfields and nomenclature of calcic anorthoclase, potassic oligoclase, and potassic andesine are from Muir (1962) and Smith (1967). Analyses by microprobe.

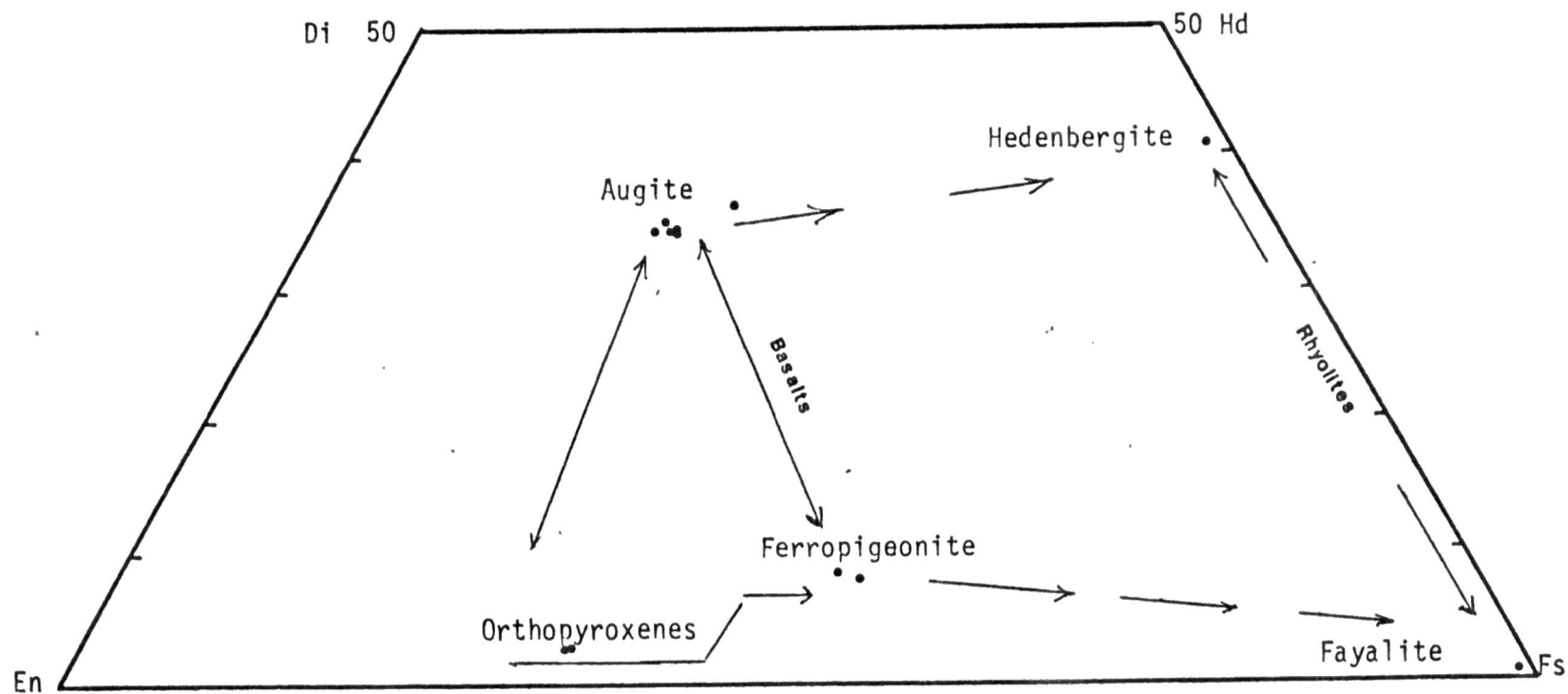


Figure 23. Composition diagram of the system enstatite-wollastonite-ferrosilite (from Carmichael, 1976b). Analyses by microprobe.

| Basalt              |         |      |      |
|---------------------|---------|------|------|
|                     | En      | Wo   | FeS  |
| Augite              | 35.1    | 36.9 | 28.1 |
|                     | 41.2    | 35.2 | 23.6 |
|                     | 42.0    | 34.6 | 23.5 |
|                     | 41.2    | 35.0 | 23.8 |
|                     | 40.7    | 34.5 | 24.8 |
| Average             | 40.0    | 35.2 | 24.8 |
|                     |         |      |      |
| Ferro-<br>pigeonite | 43.5    | 8.5  | 48.5 |
|                     | 41.9    | 7.7  | 50.4 |
|                     | Average | 8.1  | 49.5 |
|                     |         |      |      |
| Ortho-<br>pyroxene  | 64.5    | 2.2  | 33.3 |
|                     | 64.6    | 2.2  | 33.2 |
|                     | Average | 2.2  | 33.3 |

Table 5. Microprobe analyses of pyroxene crystals in spherulitic andesite.

#### ACANTILADO TUFF

##### General Statement

The Acantilado tuff is a cliff-forming ash-flow tuff that lies disconformably on rocks of the basalt section. It is a distinctive unit that allowed displacement to be observed along the east-west faults (Figure 26). This ash flow represents one cooling unit. It contains the following units:

- 1) A two-part lower zone consisting of
  - a) a basal, highly welded, relatively crystal-rich, spherulitic unit, and
  - b) a slightly less welded upper unit with fewer phenocrysts;
- 2) A middle zone that is moderately welded, relatively crystal-rich, and shows a lesser degree of welding upward in the section; and
- 3) A poorly welded, crystal-poor upper zone.

The Acantilado tuff is a moderately welded, crystal vitric tuff that has a poor to moderately well developed eutaxitic texture. The flattened pumice lumps can be 6 cm in diameter, but average 1 to 2 cm in diameter. The tuff is 25 to 30 m thick, except toward the west where thicknesses reach 40 m. Columnar joints are common and range from 0.3 to 3.5 m in diameter. Columns often show secondary wavy cracks parallel to bedding. This produces a vertical stack of plates, each from 1 to 10 cm thick.

Phenocryst percentages (Table 6a) are highest in the lowermost spherulitic and middle zones. Sanidine/quartz ratios are highest (3.3) in the lowermost spherulitic and upper zones. Phenocrysts are generally smaller in the upper and lower zones but multiple phenocrysts are more numerous in the middle zone. This suggests that the magma chamber was richer in phenocrysts toward the top, and that sanidine phenocrysts were more common near the top and bottom of the chamber. Sanidines twinned by the Carlsbad rule are more common in the lower zone. Rock samples X-rayed for orthoclase content (Table 7a) do not indicate a vertical trend in alkali magma content. Relatively fresh, lower zone spherulite (#1B) and middle zone (#74A) samples contain similar Or values. Microprobe analyses (Table 7b) of sanidine phenocrysts in the basal, spherulitic section agree favorably with these compositions. This demonstrates an equilibrium condition between the phenocrysts and liquid. The subsolidus formation of spherulites in this basal section; however, demonstrates a distinct loss of equilibrium. The average spherulitic sanidine composition is Or<sub>78.4</sub> (Table 7c) and the silica component for the spherulite is

| Spherulitic unit in lower zone |          |        |       |              |         |          |          |                    |                          |                   |                      |
|--------------------------------|----------|--------|-------|--------------|---------|----------|----------|--------------------|--------------------------|-------------------|----------------------|
| Sample No.                     | Matrix % | Sani % | Qtz % | Open Space % | Mafic % | Lithic % | Sani/Qtz | Twinned Crystals % | Spherulites %            | Multiple Grains % | Average Phenos in mm |
| 1 B "A"                        | 89.8     | 6.2    | 2.0   | 1.4          | 0.7     | -        | 3.1      | 3.2                | 55                       | 4.9               | 0.4                  |
| 1 B "B"                        | 90.5     | 7.2    | 1.5   | 0.4          | 0.3     | 0.1      | 4.8      | 1.4                | 40                       | 5.7               | 0.5                  |
| 13 A                           | 85.7     | 9.5    | 3.5   | 0.6          | 0.7     | -        | 2.4      | 7.4                | 52                       | 7.1               | 0.4                  |
| 13 B                           | 84.0     | 10.7   | 4.1   | 0.6          | 0.7     |          | 2.8      | 6.1                | $\frac{40}{48}$          | 6.1               | 0.7                  |
| Average                        | 88.0     | 8.4    | 2.8   | 0.8          | 0.6     | trace    | 3.3      | 3.7                | Granophytic dia. Average | 6.0               | 0.5                  |
| 1 C                            | 84.1     | 7.1    | 1.8   | 5.9          | 1.0     | 0.2      | 3.9      | 3.4                | 0.01                     | 6.8               | 0.8                  |
| 1 D                            | 83.9     | 5.5    | 3.2   | 6.6          | 0.8     | -        | 1.7      | 4.6                | 0.04                     | 4.6               | 0.8                  |
| 8                              | 81.0     | 6.2    | 3.5   | 8.6          | 0.8     | -        | 1.8      | 8.2                | 0.1                      | 1.0               | 0.9                  |
| 12                             | 86.7     | 6.1    | 3.0   | 3.8          | 0.4     | -        | 2.0      | 9.9                | -                        | 8.9               | 0.8                  |
| 24                             | 88.5     | 6.2    | 2.2   | 2.3          | 0.8     | -        | 2.8      | 3.6                | v.f.                     | 8.3               | 0.7                  |
| Lower Zone                     | 84.8     | 6.2    | 2.7   | 5.4          | 0.8     | trace    | 2.4      | 5.9                | v.f.                     | 5.9               | 0.8                  |
| Total Average                  | 85.3     | 6.6    | 2.8   | 4.7          | 0.7     | trace    | 2.6      | 5.6                | v.f.                     | 5.9               | 0.8                  |

Table 6a. Petrographic Characteristics of the Acantilado Tuff

Lower: spherulitic unit and highly Acantilado Tuff (Continued)

| Sample No.         | Matrix % | Sani % | Qtz % | Open Space % | Mafic % | Lithic % | Sani/Qtz | Twinned Crystals % | Spherulites % | Multiple Grains % | Average Phenos in mm |
|--------------------|----------|--------|-------|--------------|---------|----------|----------|--------------------|---------------|-------------------|----------------------|
| <u>Middle Zone</u> |          |        |       |              |         |          |          |                    |               |                   |                      |
| 3 A                | 76.8     | 10.6   | 4.2   | 7.7          | 0.7     | -        | 2.4      | 3.3                | 0.3           | 4.7               | 0.9                  |
| 3 B                | 75.9     | 12.8   | 4.1   | 6.2          | 1.1     | -        | 3.1      | 3.5                | 0.3           | 7.7               | 0.9                  |
| 14                 | 79.0     | 8.0    | 5.4   | 7.2          | 0.5     | -        | 1.5      | 3.7                |               | 2.9               | 1.0                  |
| 15                 | 72.0     | 14.8   | 7.0   | 5.3          | 1.0     | -        | 2.1      | 5.5                | 0.1           | 10.1              | 1.0                  |
| 22                 | 77.9     | 12.0   | 6.3   | 2.7          | 1.1     | -        | 1.9      | 2.2                | 0.2           | 6.7               | 0.6                  |
| 23                 | 86.0     | 6.9    | 2.5   | 2.7          | 0.6     | 1.2      | 2.7      | 4.2                | -             | 4.2               |                      |
| 74A                | 78.2     | 10.6   | 4.2   | 5.5          | 1.3     | 0.2      | 2.5      | 3.4                |               | 4.7               | 1.0                  |
| CF                 | 78.4     | 12.4   | 6.3   | 1.5          | 1.2     | 0.2      | 2.0      | 8.5                |               | 10.1              |                      |
| Average for Middle | 78.0     | 11.0   | 5.0   | 4.9          | 0.9     | Trace    | 2.2      | 4.3                | 0.2           | 7.9               | 0.9                  |
| <u>Upper Zone</u>  |          |        |       |              |         |          |          |                    |               |                   |                      |
| 38                 | 93.9     | 3.4    | 1.6   | 1.0          | 0.1     | -        | 2.1      | 6.0                | 0.7           | -                 | 0.75                 |
| 39                 | 92.8     | 2.4    | 0.7   | 2.8          | 0.4     | -        | 3.4      | -                  | -             |                   | 0.5                  |
| 68                 | 82.9     | 3.8    | 0.0   | 12.0         | 0.1     | 1.2      |          | -                  | -             | 5.5               | 0.1                  |
| 71                 | 91.2     | 4.5    | 1.0   | 2.9          | 0.4     | -        | 4.5      | -                  | -             | 3.6               | 0.5                  |
| Average for Upper  | 90.2     | 3.5    | 0.8   | 4.7          | 0.3     | Trace    | 3.3      | -                  | -             | -                 | 0.5                  |
| Overall Ave.       | 79.9     | 9.8    | 4.4   | 4.8          | .8      | Trace    | 2.3      | 4.0                | .16           | 6.1               | .83                  |

Table 6b. Thin section information Acantilado Tuff (Continued)



lacking. Perhaps the low temperature of formation,  $<500^{\circ}\text{C}$ , (Table 9) as indicated by the sanidine fiber diameter could produce abnormal subsolidus conditions conducive to partitioning potassium into the lattice. Secondary leaching of  $\text{Na}_2\text{O}$  by groundwater may have produced this condition.

Hydrothermal or deuteritic activity in the tuff as evidenced by altered phenocrysts and groundmass is apparent in all rocks except those of the northwestern section. This decomposition can probably be attributed to solutions associated with large east-west faults and hydrothermal activity associated with the vent system.

#### Lower Zone

A basal spherulite unit is 20 to 25 cm thick and consists of a rusty-red, highly welded, crystal vitric tuff. Small red spherulites averaging 0.8 mm in diameter occupy nearly 50% of the rock. Sanidine and quartz phenocrysts are euhedral to subhedral. Quartz phenocrysts are moderately to severely embayed (see Figure 29) and some show overgrowths. Sanidine ( $\text{Or}_{54}$ ), quartz and mafic phenocrysts compose about 12% of the rock; the average phenocryst diameter is 0.5 mm. Pyroxene, fayalite, and magnetite phenocrysts are all altered. Zircons are sparse and are associated with mafic minerals. A few basaltic lithic fragments are seen. Cracks are filled with quartz and a yellowish, Fe-montmorillonite is seen in the more altered specimens.

The groundmass has an obvious shaly texture and shows considerable compaction. Pumice lumps show great compaction; pumice lumps and shards wrap around phenocrysts. Flattened pumice lumps show good axialitic textures and the groundmass has a uniform, fine-grained,

|    | <u>Sample #</u> | <u>Or + 1 Std. dev.</u> | <u>Comments</u>                                            |
|----|-----------------|-------------------------|------------------------------------------------------------|
| 1. | 1B              | 54.9+ 1.1               | Spherulitic, basal, fresh                                  |
| 2. | 1C              | 58.7+ 1.0               | Lower unit, moderately fresh                               |
| 3. | 1D              | 74.3+ 1.9               | Lower unit, altered                                        |
| 4. | 13              | 80.6+ 3.9               | Spherulitic, basal, altered                                |
| 5. | 22              | 87.8+ 3.2               | Middle unit, altered                                       |
| 6. | 23              | 87.9+ 3.5               | Middle unit, altered                                       |
| 7. | 24              | 82.6+ 0.7               | Lower unit, altered                                        |
| 8. | 74A             | 54.3+ 1.5               | Fresh, NW corner, middle unit                              |
| 9. | CF              | 48.0+ .4                | Freshest, age date sample, w<br>of field area, middle unit |

Note: no upper units were fresh  
enough to obtain results

Table 7a. Or content of Acantilado tuff alkali feldspar  
determined by X-ray diffraction.

|    | <u>Or</u>    | <u>FeO</u> | <u>CaO</u> |                                |
|----|--------------|------------|------------|--------------------------------|
|    | <u>mole%</u> | <u>Wt%</u> | <u>Wt%</u> |                                |
| 1. | 13           | 54.3       | 0.15       | 0.60 Basal, spherulitic, fresh |
| 2. | 13           | 52.7       | 0.17       | 0.10 Basal, spherulitic, fresh |
| 3. | 13           | 55.0       | 0.24       | 0.07 Basal, spherulitic, fresh |
| 4. | 13           | 53.3       | 0.30       | 0.02 Basal, spherulitic, fresh |
| 5. | 13           | 56.4       | 0.15       | 0.04 Basal, spherulitic, fresh |

Table 7b. Or Content of Sanidine Phenocrysts determined by  
Microprobe.

|    | <u>Or</u> | <u>FeO</u> | <u>CaO</u> |
|----|-----------|------------|------------|
| 1. | 13        | 83.0       | 1.27       |
| 2. | 13        | 78.8       | 4.57       |
| 3. | 13        | 85.4       | 0.81       |
| 4. | 13        | 66.3       | 1.19       |
|    |           | 78.4       | 0.11       |

Table 7c. Or Content of Basal Section Spherulites determined  
by Microprobe.

granophyric texture. Small, incomplete spherulites occupy nearly 50% of the groundmass. Under x-nicols the radial and concentric structure of the spherulites is easily seen (Figures 28a and 28b). Many phenocrysts served as nuclei for spherulitic development. Fiber widths of the spherulites average  $0.9\ \mu$  indicating a relatively low ( $\sim 500^{\circ}\text{C}$ ) temperature of formation (Lofgren, 1971b). A vague foliation is imparted by the parallel alignment of shards, squashed pumice lumps, and the subparallel alignment of tabular, sanidine phenocrysts.

This thin unit could have been a basal vitrophyre. In Canyon Bellavista, 40 km to the south, Mauger (personal comm., 1978) has seen a basal vitrophyre in a tuff that is equivalent to the Acantilado tuff.

A splotchy section 25 cm thick occurs directly above the basal spherulitic unit. It consists of irregularly shaped, light-colored, devitrification orbs, 1 to 2 cm in diameter, that occupy about 35% of the tuff. The orbs have a granophyric texture, coarser than the matrix and their lighter color results from the coalescence of microscopic mafic blebs into larger specks.

Above the splotchy section lies a dark violet to grayish-violet, moderately to highly welded crystal vitric tuff (Table 6a). Shards and pumice lumps do not show as much compaction in this section as in the spherulitic unit. The rock is very hard to break, a quality that is probably attributable to its fine-grained, granophyric groundmass.

The upper portion of the lower zone differs from the middle zone by its greater degree of welding and darker color, its lower

concentration of phenocrysts, and its finer-grained granophyric texture. It varies from 1.5 to 3 m thick and has a gradational contact with the middle zone.

### Middle Zone

The middle zone is a crystal vitric tuff containing about 17% phenocrysts. It is grayish-violet to pink and has a eutaxitic texture. Flattened pumice lumps are 2 to 6 cm in diameter. Outcrops normally show well developed columnar joints that form vertical walls averaging about 25 m in height. In a few places there is a definite break in the weathering pattern, the lower portion is less pitted and slightly less altered (Figure 29). Upper portions of the middle zone may be pink or even red. Thin section studies do not indicate a visible difference in the degree of welding; therefore, these colors may have resulted from more intensive deuteric activity. Fresh Acantilado tuff is found in the northwestern corner of the area. It is generally buff with lilac stringers parallel to bedding. Fresh Acantilado tuff is also found west of the study area.

The middle zone is the richest in phenocrysts and in large, flattened pumice lumps (Table 6b). Sanidine (Or54) and quartz phenocrysts are euhedral to subhedral, and average nearly 1 mm in diameter. Quartz phenocrysts are often strongly embayed and occasionally have overgrowths. Four percent of the sanidine phenocrysts are twinned by the Carlsbad rule. Sanidine phenocrysts are usually altered to orthoclase and montmorillonite. Severely altered sanidine crystals remain as a chalky looking shell with several plates of harder mineral matter

(quartz?) perpendicular to the long axis of the crystal. Olivine (fayalite) phenocrysts are completely altered. A few magnetite and zircon crystals are present.

Most shards and all pumice lumps are flattened perpendicular to the plane of bedding; however, many tricusate and Y-shaped shards are seen, especially in places where phenocrysts are abundant. Under x-nicols the shards are masked by the granophyric groundmass. In some rocks the groundmass is micropoikilitic; polygonal quartz grains enclose small sanidine crystals. Near the bottom of the middle zone an incipient spherulitic texture has developed in the micropoikilitic groundmass. Axiolitic structures are often well developed and have central cavities that are open or filled with quartz and small amounts of fluorite. Fluorite is also seen in small cracks, altered phenocrysts, and in small lithophysae (Figure 30).

#### Upper Zone

The upper zone is poorly welded, light-violet to lilac, vitric tuff. This zone rarely obtains thicknesses over 3 m and is quite friable. Phenocrysts are small (0.5 mm) and the sanidine/quartz ratio is high (3.3). The groundmass is granophyric and fine-grained. Sanidine is severely altered.

### CRYPTIC TUFF

#### General Statement

The peralkaline Cryptic tuff is the thickest ash-flow tuff in this study area. Rocks are moderately to highly welded. These vitric

tuffs may have well developed eutaxitic textures, but more commonly they exhibit massive, fine-to medium-grained crystalline textures. The groundmass has a micropoikilitic texture containing irregular patches of quartz that are interspersed with smaller sanidine laths. Glassy and granophyric phases of the Cryptic tuff may show laminar flowage features that resemble rhyolite lava flows. The lower contact with the upper Acantilado tuff shows slight relief, but the upper contact with the Campana tuff shows topographic undulations of up to 10 m. A maximum thickness of 480 m was measured 2 km south of Canyon Santa Clara in Canyon El Oscuro. However, greater thicknesses occur in the down faulted block to the south. In the field area, the Cryptic tuff has a volume of at least 14 km<sup>3</sup>.

The Cryptic tuff is made up of at least three cooling units, south of Canyon Santa Clara. Table 8 lists and describes these in chronologic order. The main textural varieties from bottom to top include: 1) a basal section composed of glassy and spherulitic pods set in greenish, devitrified, densely welded matrix, 2) a red and white, thinly laminated, laminarly flowed and folded zone, 3) a miarolitic zone containing highly elongated lenses of vapor-phase minerals, 4) a thick zone having virtually no porosity, that has undergone micropoikilitic devitrification and contains Na-rich mafic minerals (mostly riebeckite and aegirine) and, 5) an upper breccia (some or much of which may be related to the succeeding flow) or a thin, frothy, poorly welded upper zone. Generally, except for the breccia, the Cryptic tuff is densely welded from top to bottom.

## Campana (Chocolate) Tuff

### Campana Tuff

#### Minor unconformity

Minor, riebeckitic section similar to other cooling units  
Large blocks of glass and spherulites occur near top

### Third Cryptic Tuff

Less brecciation at top of flow than in other cooling units  
Disruption and incorporation of upper No. 2 cooling unit

#### Minor break

Minor weathering at upper surface  
Development of micropoikilitic texture  
Devitrification-formation of spherulites, axiolites, vapor-phase minerals  
Miarolitic section forms above base of laminarly flowed section and near bottom of section  
Intense compression and flowage throughout most of cooling unit

### Second Cryptic Tuff

Stretching of pumice lumps  
Compaction of pumice lumps, glass from along base  
Hot ash flow fuses regolith on Acantilado tuff and upper meter of Acantilado tuff north of Canyon Santa Clara  
Disruption of No. 1 cooling unit as ash flow moves over surface

#### Minor break

Development of micropoikilitic texture  
Miarolitic section and vapor phase minerals form near base and at top of section

### First Cryptic Tuff

Frothy layer forms near top of section  
Brecciation at top of section  
Disruption of upper Acantilado and/or Basalt sections

#### Minor unconformity

### Acantilado Tuff

One cooling unit

Table (cont.)

### Minor Unconformity

#### Basalt Section

Multiple flows with upper tuffs and ash flows

Table 8. Stratigraphic sequence and approximate chronologic history of the Cryptic tuffs (No. 2 cooling unit observed more than others)

In most Cryptic tuff stratigraphic sections, breccias occupy the stratigraphic position where the green, glassy and red Cryptic tuff sequence lie. These are autobreccias since they contain lithic fragments of Cryptic tuff. Autobreccias usually form at the top and especially the bottom of liquid rhyolite flows because outer portions of the flow solidify, break up as the flow continues to move, and become incorporated in a matrix of the same composition (Christiansen and Lipman, 1966). Part of the lithic component in the Cryptic tuff breccia is crystallized (micropoikilitic) Cryptic tuff which could not have been formed during the brief emplacement of an ash flow. This component had to have been torn out of the vent area or ripped up from the ground surface during the eruption. Therefore, breccia sequences found between (they are part of the top of one unit and the base of the next unit) the thick cooling units result in part from autobrecciation, similar to that found in liquid rhyolite flows. In addition, crystallized lithic fragments from the preceeding ash flow would be incorporated into the new ash flow. The breccia units are 20 to 30 m thick and weather into rugged columnar joints. Lateral extent of the breccia was apparently influenced by paleotopography; thicker sequences correspond to paleovalleys.



Cryptic tuffs contain vertical foliations in the eastern-most ridge, south of Canyon Santa Clara (see Plate 1). Foliations strike north, the same trend as the ridge, and rapidly approach horizontal attitudes away from the ridge. A domal structure like this is good evidence for a vent. The vent's northern terminus is against the northern, east trending fault; the southern terminus is not precisely known but the structure extends at least 3.5 km south of Canyon Santa Clara. The southern terminus may correspond to the southern, east trending fault.

North of the vent, the Cryptic tuff is usually less than 50 m thick; however, south of this point the tuff is five to six times this thickness. This may simply indicate less erosion on the down-thrown block, but another factor is also important. The southern east-west fault was active before the Cryptic tuff was erupted (see p. 13) and the northern, east trending fault may also have been active. Pre and synvolcanic movements along the east-trending faults caused damming of the Cryptic tuff ash flows. This conclusion is consistent with evidence from other caldera-related faults or collapse features that were active prior to and (or) during ash-flow eruptions (Cook, 1965; Lipman and others, 1966; Christiansen and Lipman, 1966).

It is interesting that complete vertical sections of Cryptic tuff (glass, red zone, miarolitic zone, micropoikilolitic zone, breccia) are only found along fault contacts. These contacts would represent fault scarps or topographic lows during the eruption. Secondary flowage would have little effect on tuffs at these points. Figures 21 a, b, and c are diagrammatic cross sections along the fault that

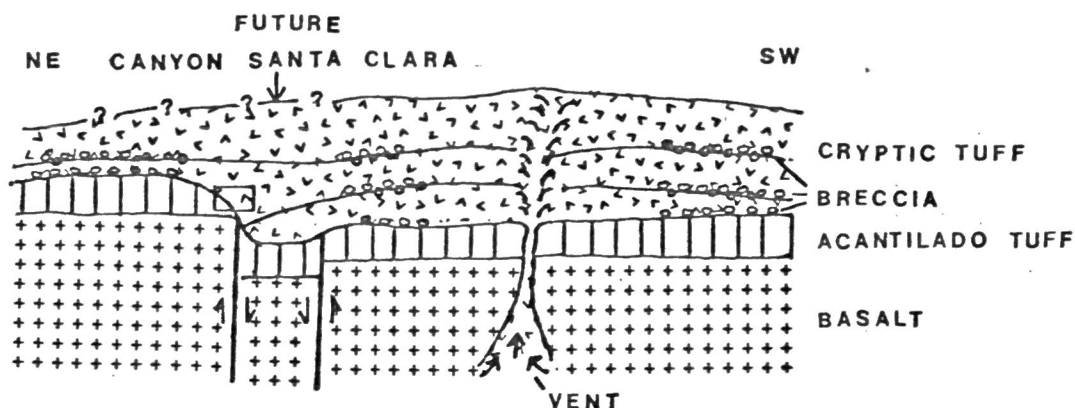


Figure 31a. Paleorelationship of the Cryptic tuff with the east-trending fault. The cross section is drawn across the north-trending vent structure. Today the graben has been downfaulted and broken into several pieces. Canyon Santa Clara eventually eroded a valley through the graben. Figure 31b is located by the rectangle.

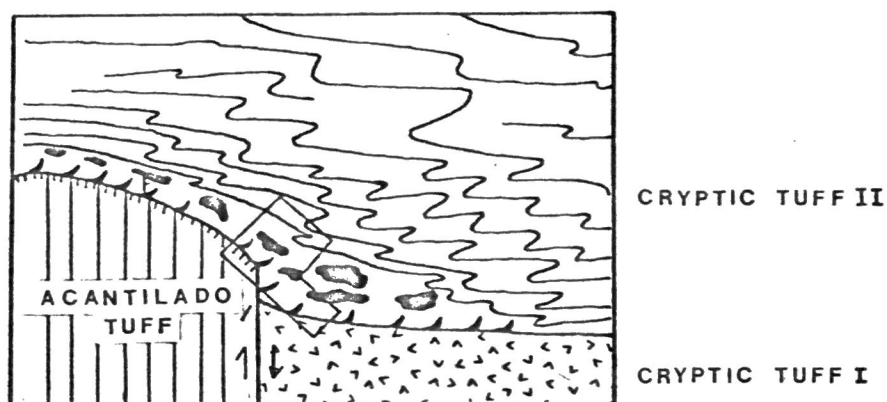


Figure 31b. General relationship of the basal sequence in the Cryptic tuff. Complete stratigraphic textural sections were only found along contacts. The box represents Figure 31c.

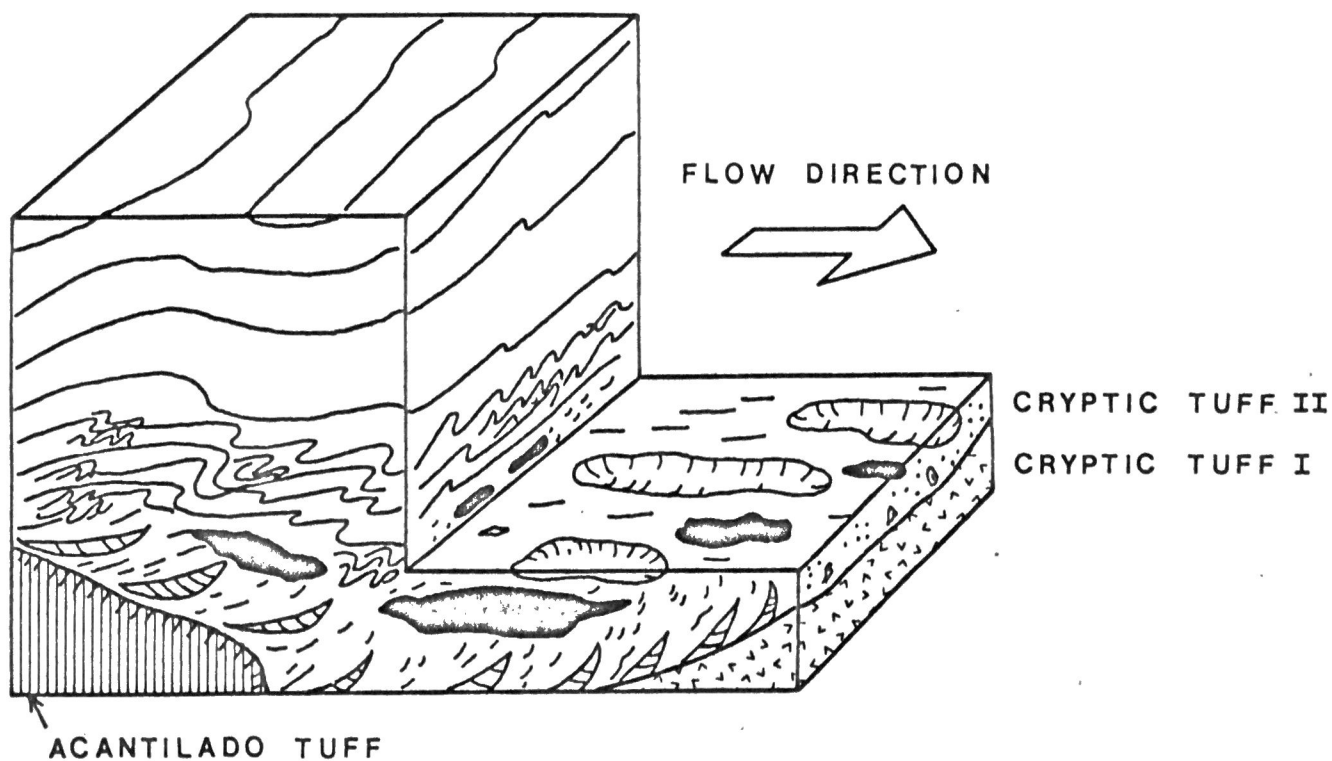


Figure 31c. Close view above the fault contact. Imbricated and compressed pumice lapilli dip into the direction of flowage. Shards show similar orientations. Lapilli are elongated, parallel to the direction of flowage and contain tension cracks which dip in the direction of flowage. Black masses are glassy and spherulitic pods. Laminar flowage is initiated above the glassy pods and shear folding becomes prominent. Detached antiforms and synforms can be seen. Higher in the section, folds become broader. Acantilado tuff is fused at its upper contact. Drawing is not to scale. (adapted from Schmincke and Swanson, 1967).

provide progressively closer views of the rock textures. Schmincke and Swanson (1967) discuss similar features found in peralkaline ash-flow tuffs on Gran Canaria, Canary Islands. Today a large valley has been eroded along the fault trace.

North of Canyon Santa Clara, a few centimeters of regolith and a meter of Acantilado tuff are fused by the Cryptic tuff. Thin section studies reveal incipient compaction in the regolith. Although the Acantilado tuff does not show increased compaction, it is highly welded into a dense rock that is different from normal, upper-zone, Acantilado tuff. Christiansen and Lipman (1966) describe a thick section of tuff that has been fused by a rhyolite flow. They recognize the importance of water content to the degree of fusion. Enlows (1955) describes the fusion of underlying rocks by ash flow sheets in southern Arizona. Cryptic tuff was hot enough to fuse the Acantilado tuff; this may be a factor in the pervasive alteration of the Acantilado tuff throughout the study area.

### Spherulites

Attention will be given to the origin, growth, and habits of spherulites because of their extent and variety in the Cryptic tuffs. Spherulites are rounded or spherical masses of acicular crystals, commonly feldspar, radiating from a central point (Macdonald, 1972). X-ray diffraction indicates that the spherulites from this study area are composed of sanidine and cristobalite or quartz.

Spherulite zones in the red Cryptic tuff are always associated with glassy phases. In one outcrop a 1 m thick zone of spherulites

averaging 2 mm in diameter is overlain by another 0.5 m thick zone of spherulites that average 5 to 8 mm in diameter. However, most spherulites do not display size layering and average about 4 mm in diameter (Table 1). Radial and concentric growth textures are well developed (Figure 36). Spherulites are usually orange-red; however, yellow, brown, gray and grayish green colors are observed. In thin section the matrix is usually devitrified to a fine-grained granophyric texture with relict perlitic cracks. Phenocryst compositions and percentages are similar to those of the glassy phases; however, alterations of mafic phenocrysts are more severe in the spherulitic rocks. Like the glassy sequences, spherulitic rocks rarely form layers more than 1 m thick and 20 m long. Outcrops occur as elongate pods associated with glassy Cryptic tuff or with red to green crystalline Cryptic tuffs.

The temperature of crystallization is important to the growth history of spherulites. Lofgren (1971a) showed that the embryonic sheaves quickly approach sphericity at temperatures less than 400°C. At temperatures from 400°C to 650°C the sheaf texture is preserved because the impingement of numerous sheaves prevents spherical maturity, and at temperatures of 650°C to 700°C crystal fibers in the spherulites become larger (10 $\mu$  to 20 $\mu$  in diameter) and widely spaced. Crystal fiber diameters at temperatures below 500°C were in the 1 $\mu$  to 3 $\mu$  range. Table 9 shows the average spherulite fiber diameters for various rocks in the field area and the inferred temperatures of formation. This data provides an estimate of minimum temperature (750°C) for the thick micropoikilitic, riebeckitic, Cryptic tuffs.

| <u>Rock Type</u>                      | <u>Needle Average<br/>in Microns</u> | <u>Comments</u>                   | <u>Temp. of Forma-<br/>tion in °C</u> |
|---------------------------------------|--------------------------------------|-----------------------------------|---------------------------------------|
| Massive, riebeckite<br>Cryptic tuff   | 24.4                                 | Widely spaced<br>fibers           | 600-750 +                             |
| Mariolitic<br>Cryptic tuff            | 8.6                                  | Impingment of<br>sheaf structures | 400-650                               |
| Red flowed<br>red Cryptic             | 11.7                                 | Good spherical<br>shape           | 600-750                               |
| Glassy red Cryptic                    | 1-3                                  | Good spherical<br>shape           | <500                                  |
| Basal spherulitic<br>Acanitilado tuff | 0.9                                  | Poorly developed                  | <500                                  |

Table 9. Average spherulite fiber diameters for various tuff units. According to Lofgren (1971b): sheaf structures assume nearly spherical outline,  $T < 400^{\circ}\text{C}$ ; fiber diameters  $1\mu - 3\mu$ ,  $T < 500^{\circ}\text{C}$ ; growth of sheaf arrested by impingment of neighboring sheaves, therefore sheaves preserved,  $T = 400^{\circ}\text{C}$  to  $650^{\circ}\text{C}$ ; coarse fiber diameters,  $10\mu$  to  $20\mu$  and more, widely spaced,  $600^{\circ}\text{C} - 750^{\circ}\text{C}$ ; spherulite diameter greater than  $20\mu$ ,  $T$  usually greater than  $700^{\circ}\text{C}$ .

During cooling of a melt, preferential stress or a slight movement in the lava may allow high temperature components better access to certain parts of an enlarging spherulite. The impurity layer will not be evenly maintained around the spherulite and fibrulation may advance in a lopsided fashion (Figure 35).

Lofgren (1970) has also shown that excessive aqueous Na- and K-silicate solutions increase hydration and devitrification (including spherulite formation) rates from one to five orders of magnitude. Sodium silicate was probably present in residual peralkaline solutions of the Cryptic tuff. Growth rates of spherulites and other devitrification textures may have progressed at rapid rates.

Close-packed spherulites in thin section frequently form triangular junctions with the three intersections approaching  $120^{\circ}$ . This geometry is related to the free energy of the grain boundaries. As the system approaches the lowest possible equilibrium energy, boundaries become planar and all angles approach  $120^{\circ}$  (Stanton, 1972). This phenomenon has been studied using bubbles which show the same relationship and for which the textural term "foam structure" has been coined (Smith, 1964). Figures 35 and 36 demonstrate the tendency for spherulites to form triple junctions.

#### Cryptic Tuff, Glassy Zone

A vitrophyre occurs at the base of Cryptic tuff cooling units. It occurs about 1 m above the lower contact (inside the green zone) or is seen directly above the lower contact when the green zone is missing. The glass is discontinuous and forms outcrops with maximum dimensions of 20 m in length and 2 m in thickness. The glass alters to a yellowish-green to brownish-green material composed of quartz and clinoptilolite.

Textures in the glass are extremely variable and depend on the extent of post-emplacement flowage. Figures 38, 39, and 40 show a glass that was deposited in a topographic low area at a fault. Glassy fragments have not undergone secondary flowage; however, a eutaxitic texture is imparted by compressed lenticular, glassy lapilli.

Figures 41 and 42 are photomicrographs of a different Cryptic tuff glass. This glass occurs in an outcrop near a fault. The area of deposition is interpreted to have been protected in a topographic low and

the glass has undergone limited movement after deposition. This glass shows incipient flowage by a series of shears.

Figure 43 illustrates a vitrophyric lithic fragment collected from a breccia unit. Lithic fragments found in breccias are interpreted as having been deposited on more open flat terrain, not in topographic lows. Ash-flow tuffs deposited on flat terrain would be more susceptible to secondary flowage since there were no barriers to impede it. Smith (1960a) and Ross and Smith (1961) state that pumice lapilli (in rhyolitic ash flows) are occasionally drawn out to produce flowage-looking laminae; however shards are not known to lose their identity. In rocks from this area pumice lapilli and shards are completely obliterated and a laminar flowage texture is produced. Thin, peralkaline ash-flow tuffs, with extensive post eruptive flowage have been reported from other parts of the world (Vallari, 1975; Gibson, 1975; and Barberi and others, 1975). Figure 44 shows the lower left corner of Figure 43 and demonstrates the shear folding associated with flowage. Folding in the ash-flow tuff may have been initiated where obstructions were over ridden or where the flow was confined to a narrower channel.

Phenocrysts in the glassy Cryptic tuff account for about one percent of the rock and average about 0.5 mm in diameter (Table 10). Sanidine ( $Or_{44.1}$ ) phenocrysts are usually fresh, subhedral, rounded, phenocrysts. Quartz phenocrysts are also rounded. Pyroxene phenocrysts are green, euhedral to subhedral, and average about 0.8 mm in diameter, but may be as long as 2 mm. The  $Z_{Ac}$  is about  $48^\circ$  and the  $2V$  is  $50^\circ$  to  $60^\circ$ . Microprobe analyses (Table 14) show that the pyroxene



| No.              | M    | S   | Q   | OS   | H   | S/Q   | Mg                     | Mp  | Ma   | Mul.p | Tw. xl | p.mm |
|------------------|------|-----|-----|------|-----|-------|------------------------|-----|------|-------|--------|------|
| 37 (riebeckitic) | 79.5 | 3.3 | 0.1 | 3.2  | 0.3 | (33)* | 4.3                    | 8.0 | 1.6  | 4     | 12     | 0.8  |
| 32 (riebeckitic) | 78.4 | 1.4 | 0.3 | 7.7  | 0.1 | 4.7   | 6.6                    | 3.5 | 2.1  | 1     | 4      | 0.4  |
| 30 (riebeckitic) | 72.2 | 2.0 | 0.1 | 0.1  | 0.4 | 20*   | 6.4                    | 7.9 | 11.2 | 3     | 4      | 1.5  |
| 1 (riebeckitic)  | 82.3 | 0.8 | 0.5 | 0.1  | 0.2 | 1.6   | 7.2                    | 3.6 | 5.6  | -     | -      | 1    |
| 56A (frothy)     | 77.2 | 1.4 | 0.5 | 20.7 | -   | 2.8   | (0.3 hematite needles) |     |      | 9     | 9      | 0.5  |
| 43A (red)        | 96.5 | 0.6 | 0.4 | 2.5  | 0.1 | 1.5   | (0.3 aigerine needles) |     |      | 2     | 3      | 0.5  |
| Average %        | 81.0 | 1.6 | 0.3 | 2.4  | 0.2 | 2.7   | 6.1                    | 5.8 | 5.1  | 3.8   | 6.4    | 0.8  |

Table 10. Cryptic tuffs point count information. Symbol key: M = matrix %, S = sanidine %, Q = quartz %, OS = open space %, H = hedenbergite %, Mf = matrix fayalite %, Mp = matrix pyroxene %, Ma = matrix amphibole %, s/q = sanidine/quartz, mul.p = multiple phenocrysts 0/00, Tw xl = twinned (by Carlsbad) sanidine 0/00, p = diameter of phenocrysts in mm, No. = author's number.

\*Omitted from average

Table 11. Cryptic tuffs; physical characteristics. Symbol key:  
 p = diameter of average phenocryst in mm, max p = diameter of maximum  
 phenocryst in mm, D spher. = diameter of average spherulite in mm,  
 % pheno = percentage of phenocrysts, No = author's number.

| No.           | p    | max p | D spher | % pheno |
|---------------|------|-------|---------|---------|
| (Vitrophyre)  | 0.5  | 2     | 0.5     | 1       |
| 73            | 0.7  | 4     | 0.5     | 1       |
| 59            | 0.7  | 4     | 0.5     | 1       |
| 56A           | 0.5  | 3     | -       | 2       |
| 41            | 0.5  | 2.2   | -       | 0.5     |
| <hr/>         |      |       |         |         |
| Average       | 0.6  | 2.8   | ?       | 1.1     |
| (Spherulites) |      |       |         |         |
| 91            | 0.5  | 1     | 3       |         |
| 90            | 0.9  | 1.5   | 1.5     |         |
| 87            | 0.5  | 4     | 2.5     | 0.5     |
| 74            | 0.1  | 4     | 3       | 0.5     |
| 58            | 0.75 | 6     | ?       |         |
| 57            | 0.5  | 3     | ?       |         |
| 56            | 0.5  | 1     | ?       |         |
| 56            | 0.5  | 1.2   | ?       |         |
| <hr/>         |      |       |         |         |
| Average       | 0.6  | 2.8   | 2.5     | ?       |

Table 11 . (continued)

| No.                   | p    | max p | D spher | % pheno |
|-----------------------|------|-------|---------|---------|
| (Red and Green Tuffs) |      |       |         |         |
| 69                    | 0.1  | 0.3   | -       | 0.5     |
| 43a                   | 1.1  | 1.5   | 0.08    | 0.5     |
| 43c                   | 0.5  | 2.5   | 0.14    | -       |
| 43d                   | 0.4  | 1.5   | -       | -       |
| 42a                   | 0.3  | 2     | 0.20    | -       |
| 42                    | 0.4  | 1.7   | -       | 0.5     |
| 27a                   | 0.5  | 2     | 0.09    | 0.5     |
| 27b                   | 0.6  | 5     | 0.11    | -       |
| 7                     | 0.6  | 3.4   | -       | 0.5     |
| <hr/>                 |      |       |         |         |
| Average               | 0.5  | 2.2   | 0.12    | 0.5     |
| (Breccia)             |      |       |         |         |
| 86                    | 0.1  | 3.0   | -       | 0.5     |
| 79                    | 0.5  | 1.5   | -       | -       |
| 78                    | 0.5  | 4.0   | -       | 0.5     |
| 72                    | 0.1  | 0.6   | -       | -       |
| 52                    | 0.2  | 1.5   | -       | -       |
| <hr/>                 |      |       |         |         |
| Average               | 0.28 | 3.2   | -       | 0.5     |

Table 11. (Continued)

| No.                  | p    | Max.p | mp   | max.mp | spher | spher.n | pheno. |
|----------------------|------|-------|------|--------|-------|---------|--------|
| 30                   | 1.5  | 4.0   | 0.08 | 0.4    | -     | 0.026   | -      |
| 29                   | 0.4  | 2.0   | 0.16 | 1.4    | -     | -       | -      |
| 28                   | 0.3  | 2.5   | -    | -      | -     | -       | -      |
| 18                   | 0.5  | 1.5   | 0.14 | -      | 0.21  | 0.017   | -      |
| 17                   | 0.8  | 3.0   | 0.11 | -      | -     | -       | -      |
| 1                    | 1.0  | 4.5   | 0.10 | -      | -     | -       | -      |
| <hr/>                |      |       |      |        |       |         |        |
| Average              | 0.61 | 2.54  | 0.34 | -      | 0.37  | 0.024   | 0.5-10 |
| (Miarolitic section) |      |       |      |        |       |         |        |
| 32A                  | 0.4  | 1.5   | -    | -      | 0.4   | 0.030   | 0.5    |
| 64                   | 0.2  | 1.0   | -    | -      | -     | -       | -      |
| 45A                  | 1.6  | 3.2   | -    | -      | 0.3   | 0.041   | -      |
| 72A                  | 1.0  | 4.0   | -    | -      | 1.0   | -       | 0.5    |
| <hr/>                |      |       |      |        |       |         |        |
| Average              | 0.8  | 2.4   | -    | -      | 0.6   | 0.035   | -      |

| No. 59<br>Oxide                | Clear<br>Glass | Yellow<br>Glass | Brown<br>Glass | Yellow Devitri-<br>fied Material | Low Birefrigent<br>Material in Veinlet |       |
|--------------------------------|----------------|-----------------|----------------|----------------------------------|----------------------------------------|-------|
| MgO                            | 0.00           | 0.00            | 0.00           | 0.00                             | 0.00                                   | 0.00  |
| SiO <sub>2</sub>               | 74.15          | 74.03           | 73.32          | 74.37                            | 78.29                                  | 86.18 |
| FeO(t)                         | 2.34           | 2.39            | 2.53           | 2.52                             | 0.56                                   | 0.18  |
| Na <sub>2</sub> O              | 2.28           | 1.80            | 1.62           | 1.04                             | 1.63                                   | 1.04  |
| Al <sub>2</sub> O <sub>3</sub> | 10.71          | 10.60           | 10.15          | 10.82                            | 11.34                                  | 4.43  |
| K <sub>2</sub> O               | 2.08           | 1.52            | 3.40           | 1.54                             | 3.22                                   | 0.40  |
| CaO                            | 0.25           | 0.28            | 0.25           | 0.29                             | 0.02                                   | 0.00  |
| TiO <sub>2</sub>               | 0.20           | 0.20            | 0.22           | 0.23                             | 0.06                                   | 0.03  |
| MnO                            | 0.10           | 0.21            | 0.10           | 0.07                             | 0.00                                   | 0.00  |
| Total                          | 92.61          | 90.88           | 91.60          | 91.78                            | 95.10                                  | 92.27 |

| No. 41                         | Clear<br>Glass | Dark<br>Glass | Average | No. 73 | Clear<br>Glass | Dark<br>Glass | Average |
|--------------------------------|----------------|---------------|---------|--------|----------------|---------------|---------|
| MgO                            | 0.01           | 0.00          | 0.00    |        | 0.00           | 0.00          | 0.00    |
| SiO <sub>2</sub>               | 73.22          | 72.06         | 73.61   |        | 73.42          | 73.96         | 73.69   |
| FeO(t)                         | 2.31           | 2.50          | 2.41    |        | 2.20           | 1.93          | 2.07    |
| Na <sub>2</sub> O              | 2.82           | 2.28          | 2.55    |        | 2.28           | 2.55          | 2.41    |
| Al <sub>2</sub> O <sub>3</sub> | 10.77          | 10.79         | 10.78   |        | 10.20          | 11.02         | 10.61   |
| K <sub>2</sub> O               | 2.32           | 2.54          | 2.43    |        | 3.18           | 3.22          | 3.20    |
| CaO                            | 0.40           | 0.01          | 0.21    |        | 0.31           | 0.09          | 1.20    |
| TiO <sub>2</sub>               | 0.21           | 0.23          | 0.22    |        | 0.20           | 0.15          | 0.18    |
| MnO                            | 0.15           | 0.03          | 0.09    |        | 0.13           | 0.04          | 0.08    |
| Total                          | 92.21          | 92.43         |         | Total  | 91.92          | 92.95         |         |

Table 12. Microprobe Analyses of various glass and materials in Cryptic tuff. Sample contains about 5.5% water.

| Sample No.      | Or   | FeO(t) | CaO  | Remarks                                           |
|-----------------|------|--------|------|---------------------------------------------------|
| 41 "A"          | 44.5 | 0.20   | 0.22 | In fragmental glass north of Canyon Santa Clara   |
| 41 "A"          | 43.1 | 0.19   | 0.15 |                                                   |
| 41 "B"          | 43.1 | 0.25   | 0.14 | Inner part of crystal                             |
| 41 "B"          | 40.1 | 0.24   | 0.20 | Outer part of crystal                             |
| Average         | 42.7 | 0.22   | 0.18 |                                                   |
| 73              | 43.9 | 0.22   | 0.19 | From northwest corner                             |
| 73              | 43.8 | 0.25   | 0.18 |                                                   |
| 73              | 44.8 | 0.29   | 0.15 |                                                   |
| Average         | 44.8 | 0.25   | 0.17 |                                                   |
| 59              | 46.4 | 0.46   | 0.35 | Frothy flow sequence, south of Canyon Santa Clara |
| 59              | 45.2 | 0.21   | 0.16 |                                                   |
| 59              | 45.1 | 0.21   | 0.17 |                                                   |
| 59              | 43.9 | 0.21   | 0.16 |                                                   |
| 59              | 43.5 | 0.26   | 0.18 |                                                   |
| Average         | 44.8 | 0.27   | 0.21 |                                                   |
| Overall Average | 44.1 | 0.25   | 0.18 |                                                   |

Table 13. Microprobe analyses of sanidine phenocrysts in Cryptic tuff glasses.

Table 14. Microprobe analyses of pyroxene phenocrysts from Cryptic tuff glasses.

| Sample No.         | Wo    | En   | Fs    | Rh   |
|--------------------|-------|------|-------|------|
| 59                 | 40.47 | 1.01 | 54.48 | 4.04 |
| 59                 | 41.39 | 1.05 | 54.44 | 3.11 |
| 59                 | 41.53 | 0.87 | 54.03 | 3.56 |
| Average            | 41.13 | 0.98 | 54.32 | 3.57 |
| 41                 | 49.94 | 0.80 | 54.68 | 3.58 |
| 41                 | 41.14 | 0.93 | 54.49 | 3.42 |
| Average            | 41.05 | 0.87 | 54.59 | 3.50 |
| 73                 | 41.01 | 1.06 | 54.31 | 3.62 |
| 73                 | 41.49 | 0.98 | 53.73 | 3.79 |
| Average            | 41.25 | 0.97 | 54.02 | 3.71 |
| Overall<br>Average | 41.14 | 0.94 | 54.31 | 3.59 |

is Mn-hedenbergite. Some Ti-rich magnetite and, less commonly, zircons are associated with hedenbergite. Rounded lithic fragments of riebeckitic, micropoikilitic Cryptic tuff account for a maximum ten percent of the rock.

Glasses occur in various shades and diaphaneity ranging from clear-colorless to opaque-black. Table 12 summarizes glass compositions analysed by microprobe. Sample No. 59, seen in Figure 45, contains well defined color zones that range inward from clear to brown and yellow. Along central cracks, spherulites or a narrow band of dark devitrified products (probably sanidine, quartz, plus zeolites and hematite blebs) often form. Microprobe data indicate  $\text{SiO}_2$ ,  $\text{Na}_2\text{O}$ ,  $\text{Al}_2\text{O}_3$ , and probably  $\text{CaO}$  are depleted inward. Sodium is highly mobile in hydrated glassy rocks and  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{K}_2\text{O}$  concentrations vary in the low birefringent areas probably in response to feldspar and quartz formation. The brown glass contains slightly more  $\text{FeO}(\pm)$  which may account for its darker hue; however, the color may also be a function of water content. The water content for all three glasses was estimated by weighing samples that were heated at  $1000^\circ\text{C}$  for 24 hours. Samples Nos. RD-41 and RD-73 (Table 12) show varying compositional differences between clear and dark glasses, however  $\text{CaO}$  and  $\text{MnO}$  concentrations are consistently greater in clear phases.

#### Cryptic tuff; Green Zone

Two outcrops of green Cryptic tuff were observed. One is on the upper southeastern flank (above the Acantilado tuff cliffs) of the



hills 1 km north of the entrance to Canyon Santa Clara and the second outcrop is on the lower west side of Canyon Las Tapias about 200 m north of Canyon Santa Clara.

The lowest part of most Cryptic tuff cooling units is a 1 to 5 m thick zone of green to grayish-green, waxy to dull, highly welded, eutaxitic, vitric tuff. Pumice lumps exhibit various degrees of compaction; fragments that settled in the topographic lows were not severely compressed or stretched but pumice lumps higher in the section or those deposited away from depressions have length to height ratios greater than 60:1. This high ratio represents flattening beyond simple loss of pore space and indicates stretching (Ross and Smith, 1961). Stretched pumice lapilli are 20 to 30 cm and more in length and only 1 to 2 mm in height. In addition, pumice lumps display preferred orientations (Figure 46). Length to width ratios average about 5:1. Smith (1960b) cites this as evidence of mass flowage in ash-flow tuffs. Lapilli are elongated in the direction of flowage.

The green zone contains several textural varieties. Lowest in the sequence is a layer of parallel lapilli with ellipsoidal cross sections and a slight curvature or bulge in the middle (Figure 31c). They range up to 7 cm long by 1 cm thick and form an imbricated series of lapilli with the concave side up (Figure 47). Smaller vitric fragments are similarly imbricated. Schmincke and Swanson (1967) observe that imbricated pumice lumps dip sourceward at angles of  $10^{\circ}$  to  $30^{\circ}$ . They suggest that the imbrication may result from ramping or up-thrusting during flowage. As the compacted lower portion of the ash flow begins to cool, it becomes more viscous, and adheres to underlying rocks.

During this period pumice lapilli and shards ramp upward along newly developing shear surfaces.

Above the imbricated unit, the rocks are often extremely brecciated. Breccia zones are from 1 to 3 m thick, and exhibit matrix support. The matrix has been completely rewelded. The breccias may have been produced by autobrecciation during flowage of overlying tuff. Rocks in this lower horizon would have cooled sufficiently to fail by brittle fracture while, upper material was still hot enough to flow laminarly. Above the brecciated section, laminar flowage features predominate. Shards and lapilli are extremely elongated and folded. Subsequently, the retained heat would be sufficient to reweld the matrix of the brecciated rock.

The green zone contains about 0.5 percent phenocrysts. Altered sanidine is most common followed by moderately embayed quartz and minor mafics (altered pyroxene, magnetite, and a few zircons). The sanidine to quartz ratio is about 1:5. Rounded lithic fragments of riebeckitic micropoikilitic Cryptic tuff account for 1 to 2% of the rock. Lithics of Acantilado tuff often show flattening. Groundmass and compressed lapilli exhibit extremely fine-grained granophyric textures.

Pumice lumps and the groundmass frequently contain tension cracks which are best seen in thin section (Figures 48 and 49). The tension cracks dip slightly in the direction of flowage because of differential movement from shearing (Schmincke and Swanson, 1967). The lapillae typically show greater stretching and cracking than does the matrix. However, in rocks that contain large pumice lumps, the differential

stretching between pumice and matrix is minimal. In areas where pumice lumps and matrix are stretched, the matrix may have been tightly welded to the pumice fragments and stretched preferentially during final movement (Schmincke and Swanson, 1967). Some tension cracks are highly crenulated (resemble an ammonitic suture pattern). This may indicate a later period of compaction or simply reflect differential stretching.

Rounded vesicles are common in lenticular, stretched pumice lapilli of the upper green unit (Figure 49). These bubbles probably represent postdepositional vesiculation of the pumice lapilli (Schmincke, 1975). This texture is seen in peralkaline rocks from the green ash flows of Pantelleria (Schmincke, 1975), from the ash flows on Fantale (Gibson, 1975), and from ash-flow material of Mt. Mason in the Phillipines (Moore and Melson, 1969). Schmincke (1975, p. 618) points out that rounded bubbles in pumice lapilli do not necessarily indicate a loss of volatiles during deposition. Bubbles may have formed in pumice lapilli and survived compaction because the lapilli were too cold to be compressed, or the gas pressure may have equalled load pressure preventing collapse.

However, in the green Cryptic tuff, pumice lumps are compressed and stretched indicating the bubbles did not survive compaction. Thus, the bubbles are post-depositional vesicles. Almost all of the round vesicles are now filled with quartz. Vapor-phase aegirine needles (Figure 50) and a few stubby, green pyroxene crystals project into the cavities.

Bubble trains are common in the lower green, imbricated section (Figure 51). These are parallel tubular structures that cut across

the entire pumice lapilli. They are not concentrated in the centers of the lapilli as are the postdepositional vesicles. These tubes terminate at the lapilli borders suggesting an abrupt increase in viscosity at lapilli boundary.

The green zone becomes increasingly oxidized upward. Pumice lapilli show reddening near the edges and become progressively red toward the center. Elongation of pumice lapilli and laminar flowage features increase upward until shard and lapilli textures are obliterated and the rock appears to be a lava flow. At this level the rock is completely red and white.

#### Cryptic Tuff, "Frothy" Zone

At one outcrop (N.29°22', W.106°28') a violet to tan, very poorly welded vitric tuff overlies glassy and spherulitic zones. The unit is about 2 m thick and the rock is "frothy" with about 21 percent open space (Table 11). In thin section shards are tricusate and U-shaped and many contain open spaces indicating incomplete collapse (Figure 54). Phenocrysts account for two percent of the rock and sanidine is about three times more abundant than quartz. Sanidine phenocrysts are usually fresh and subhedral; quartz phenocrysts show moderate embayment. Mafic phenocrysts of pyroxene(?), magnetite and zircons are sparse and altered. The groundmass is partly devitrified in porous areas but shows more advanced devitrified where porosity is lower. Poorly developed spherulites are common in devitrified areas and the groundmass exhibits a fine-grained granophyric texture. Tiny, red, hexagonal, plates of hematite adhere to partially collapsed shards. The plates are

associated with small needles of aegirine. Hematite crystals are infrequently impaled by the aegirine needles.

This patch of frothy material may have formed at the top of a cooling unit and become more incorporated in a breccia sequence (the rocks around it are coarsely brecciated). If it formed near the bottom of a Cryptic tuff sequence, it must have been extremely gassy.

#### Cryptic Tuff, Red Zone

At least 50 percent of the lower Cryptic tuff cooling units is composed of a red and white, densely welded, laminarly flowed, folded and sheared, vitric tuff. Closely spaced joints are usually perpendicular to the base of the flow (Figure 52). Joints are usually columnar and form 0.2 to 1 m long columns that average 10 cm wide by 6 cm deep. Shear folds are common and amplitudes may be greater than one meter. Folds are usually asymmetric; however, symmetric, mushroom-shaped, and chevron folds are also present. Sometimes limbs of folds are sheared off (see Figure 31C). The compacted ash-flow mass was evidently liquid and flowed laterally for several meters or more after compaction. The degree of contortion diminishes in lower sections and increases upward where folds become distinct. Higher in the section folds are broader (see Figure 31C).

Lamellae are extremely elongate and may be traced for several meters. Reddish layers are interpreted as the compacted vitric part of an ash-flow sheet which is now iron stained. White laminae were probably pumice lumps. They appear thinner and less abundant in hand specimen. Lamellae often contain tiny, parallel, tension cracks (now

filled with silica) that are oblique or orthogonal to the plane of bedding. Small folds contain cracks that can extend across the fold axis (Figure 53). These tension cracks formed during final stages of movement when the liquid was extremely viscous. Postdepositional vesiculation bubbles are also present. Quartz with altered aegirine needles fills almost all voids that were present. Phenocrysts are similar to those found in the green zone except here, crystals are usually more altered (Table 11).

#### Cryptic Tuff, Mirolitic Zones

Above the red Cryptic tuff is a flow-banded, densely welded, buff to lilac, colored vitric tuff zone. In thin section phenocrysts are scarce (about 1%) and altered; lithic fragments of red or micropoikilitic Cryptic tuff or of Acantilado tuff average about 0.5 cm in diameter.

Alternating light and dark bands of pumice and shardy layers (respectively) become dominant. Higher in the section the light colored layers become more porous and contain lensoidal to elongate crystal lined cavities; dark colored layers remain nonporous (Figure 55). The laminae display varying degrees of contortion; undulating bands are common and open folds are less common. This is considered to be a mirolitic zone. Its maximum thickness is 10 m but the average thickness is nearer 3 m.

In thin section cavities are lined with elongate sprays of sanidine crystals. Terminations are flat and crystals project into hollow or quartz-filled central areas. Fluorite is also common in central

cavities (Figures 56a and 56b). Minute aegirine(?) blebs form concentric layers farther away from the cavities. Concentrations of femic minerals are greatest near the base of final, vapor-phase sanidine sprays. Golden aegirine needles project into central cavities and larger, euhedral, golded to brown, aegirine prisms cap sanidine sprays (Figure 57). Most tabular aegirines are terminated by basal pinicoids; however, some crystals have wedge-shaped terminations. The crystals display second order birefringence, are length fast and have parallel extinction. Most contain internal cloudy, brownish areas surrounded by unaltered, highly birefrigent mineral. Under high magnification individual needles of aegirine lie parallel to striated surfaces of larger aegirine crystals. Aegirine needles often alter to a chocolate-brown color.

The nonporous dark-colored laminae may have a coarse granophyric or micropoikiolite groundmass but, more frequently, contain plumes, sprays, sheaves or spherulitic aggregates of sanidine plus cristobalite or quartz (Figure 57). Spherulite fiber diameters become coarser near cavities. Orb textures (Lofgren, 1971a) are sometimes well developed. These textures are rounded polyhedrons produced by the simultaneous growth and impingement of neighboring spherulites or areas of quartz. Crystallizing fibers or quartz swept aside microlites or other tiny impurities that are deposited as rims or septa between growing units. The resultant pattern, best seen in plane light, is a splotchy series of irregular orb shapes, defined by discontinuous lines of dark blebs (Figure 58).

Lensoidal cavities occur in other peralkaline ash flows (Schmincke, 1975 and Noble, 1968c). Although these usually occur near the top of a cooling unit, cavities are also known to occur lower in the flow sheets (Schmincke and Frisch, 1972; and Vallari, 1975). Cavities may have formed from post-depositional vesiculation of glass low in the ash-flow sheet. Trapped volatiles may have become concentrated beneath a highly welded, impermeable cap rock. In this field area ash-flow tuff that overlies the miarolitic zone is over 50 m thick, extremely dense, and would have prevented the loss of volatiles. An upper miarolitic zone (also seen in this section) would be a normal vesicular upper zone of the ash flow.

Above the lower miarolitic zone, open space decreases but layering remains distinct (Figure 59). The rock contains scattered lithophysae up to 3 cm in diameter. The lighter colored, pumice-rich layers contain rounded vesicles that average 0.1 mm in diameter. Vapor-phase quartz, sanidine, aegirine, and tridymite(?) occur in the cavities. Dark stringers 3 to 4 mm long and 0.5 mm wide cut across 1 or 2 flow laminae at approximately right angles. They are more common in thicker pumice-rich layers and may represent trains of rising gas bubbles (Figure 59). There are a few phenocrysts of sanidine, altered mafics, and embayed quartz. Rounded lithics of micropoikilitic riebeckitic Cryptic tuff occur. In thin section the rock is crudely spherulitic in non-porous laminae and granophyric in more porous layers.

#### Cryptic Tuff, Micropoikilitic Riebeckitic Zone

Near the bottom and top of this zone, pumice-rich lamillae are compressed and crystallized as quartz-rich layers. These stringers



weather out in relief which is helpful in discerning flowage foliations in outcrops. This textural zone varies greatly in thickness from 3 to 30 m and is replaced gradually by the dominant, nearly structureless main body of the micropoikilolitic riebeckitic Cryptic tuff (Figure 60). The rock may be buff, tan, gray, or pink or it may exhibit these colors in a mottled or variagated motif. Outcrops sometimes exhibit irregular, closely spaced joints near fault contacts (Figure 64). Most joints have 4 or 5 sides and average 8 cm thickness, 10 cm in width and 0.3 in length.

In hand specimen the rock is evenly textured and speckled with small mafic aggregates which can produce a slightly greenish hue. When freshly broken, the rock shows numerous cleavage reflections from the coarse-crystalline sanidine groundmass.

Thin section studies reveal a densely welded micropoikilolitic vitric tuff (Figure 58). The matrix is composed of irregular polygonal patches of quartz up to 8 mm across but rarely exceeding 2 mm across (Figure 61). These patches represent single crystals and are optically continuous. Groups of sanidine laths are optically continuous over smaller regions within the quartz (Figures 62a and 62b). Coarse-fiber spherulites up to 1 cm across are composed of sanidine and mafic minerals with interfibular quartz (Figures 63a and 63b). Spherulites are usually composed of 4 to 8 sections of micropoikilitic quartz. Groups of optically continuous sanidine fibers extend across quartz polygon boundaries indicating that the quartz crystallized after the spherulitic development.

Several groundmass mafic minerals have been identified by microprobe analyses. Most grains are very small and dendritic and therefore do not show reliable optical properties. Aenigmatite, fayalite, aegirine, a green Na-amphibole (arfvedsonite?), and riebeckite are represented in the groundmass. Collectively they occupy about 17% of the rock (Table 10).

Femic groundmass minerals occur as clusters of blebs or as dendritic patches up to 2 mm across and frequently as spherulite fibers. Spherulite cores are commonly mixtures of aenigmatite and fayalite which are dendritic in the center and become fibrous outward. In thin section aenigmatite is opaque with transmitted light and silvery with reflected light. Fayalite is translucent in transmitted light and is usually altered to a reddish color. Yellow-green aegirine usually forms patches and blebs that are smaller than other mafic minerals but it is easily identified by its second order birefringence under cross-polarized light. A bright green amphibole (arfvedsonite?) is a common constituent of many spherulites and forms alternating fibers with sanidine (Figure 63a). Diagnostic physical properties are its bright green, olive-green, and brownish pleochroic colors and nearly parallel extinction. Riebeckite occurs as solid crystalline masses up to 1 mm across but usually occurs as spherulitic fibers or dendritic aggregates. Its pleochroic colors are bright blue, gray, and bluish green to brownish green; the  $2\lambda_c = 50^\circ$ .

Phenocrysts of sanidine, quartz, and mafic minerals constitute 1 to 2% of the rock (Table 10). Sanidine phenocrysts are rounded and partly altered; quartz phenocrysts are rounded but not embayed.

Hedenbergite phenocrysts are always altered to clayey material; however, relic birefringence is seen. Ti-magnetite and another Ti mineral, probably ilmenite, were identified by microprobe analysis. Mafic crystals are small and associated with hedenbergite and zircon phenocrysts. For other information see Table 15.

### Cryptic Tuff, Breccia Zone

A moderately welded, matrix support, lithic tuff or breccia usually crops out between successive units of micropoikilitic, riebeckitic Cryptic tuff (Figure 65). The breccia is an orange to red cliff-forming unit that averages 20 m in thickness. Crude columns 1 to 5 m wide erode, forming spires and associated deep indentations. Lithics in order of decreasing abundance are:

1. red, flow-banded Cryptic tuff;
2. subequal amounts of microlitic Cryptic tuff and red, spherulitic Cryptic tuffs;
3. micropoikilitic riebeckitic Cryptic tuff; and
4. rarely, basalt and Acanalado tuff.

The lithic fragments are angular to rounded and have a matrix support (Figure 66). Lithic fragments may represent 20 to 60% of the rock but average about 40%; however, in thin section smaller lapilli sized lithic fragments account for about 75% of the rock.

Crystal fragments from other rocks in the area are present but they usually make up less than 1% of the breccia. Sanidine phenocrysts are broken and altered to a white clay; quartz are usually embayed and original mafic phenocrysts are represented by brown, iron oxide.

| No. | p   | Max.p | mp   | max.mp | spher. | spher.n | pheno. |
|-----|-----|-------|------|--------|--------|---------|--------|
| 85  | 0.1 | 1.5   | -    | -      | -      | -       | -      |
| 80B | 0.5 | 2.5   | -    | -      | -      | -       | -      |
| 75A | 0.6 | 2.5   | -    | -      | -      | -       | 2-3    |
| 72  | 0.4 | 1.5   | -    | -      | -      | -       | -      |
| 63  | 0.5 | 3.0   | -    | -      | -      | -       | 1      |
| 62  | 0.5 | 2.2   | -    | -      | -      | -       | -      |
| 61  | 0.6 | 2.4   | -    | -      | -      | -       | 0.5    |
| 55  | 0.5 | 2.5   | -    | -      | -      | -       | -      |
| 51  | 1.0 | 2.5   | -    | -      | -      | -       | -      |
| 50  | 0.5 | 2.3   | -    | 4.8    | -      | 0.019   | -      |
| 49  | 0.1 | 2.8   | 0.25 | 0.5    | -      | -       | -      |
| 46  | 1.5 | 4.0   | 0.11 | 1.2    | -      | 0.015   | -      |
| 45B | 0.5 | 2.0   | 0.07 | -      | -      | 0.041   | t      |
| 44  | 1.0 | 4.4   | 0.06 | -      | 0.2    | -       | -      |
| 37  | 0.7 | 3.5   | 0.28 | -      | 0.4    | 0.022   | -      |
| 35  | 0.6 | 4.0   | 0.48 | -      | 0,4    | 0.022   | 0      |
| 34  | 0.4 | 1.0   | 2.4  | 8.0    | 0.5    | -       | t      |
| 32  | 0.4 | 2.0   | 0.32 | 0      | 0.5    | 0.020   | -      |
| 31  | 0.3 | 2.0   | 0.14 | -      | 0.4    | 0.026   | -      |

Table 15. Massive, riebeckitic tuffs; physical characteristics.  
 Symbol key: p = diameter of average phenocrysts in mm, max.p = diameter of maximum phenocrysts in mm, mp = diameter of average micropoikilitic area in mm, max. mp = diameter of maximum micropoikilitic area in mm, spher = diameter of average spherulite in mm, spher.n = diameter of average spherulitic needle in mm, % pheno = percentage of phenocrysts, No. = author's number, t = trace; measurements in mm.

Occasionally fresh mineral fragments can be seen. The matrix is crystallized to a fine-grained granophyric texture. Chalcedony and calcite are common as secondary minerals infilling pore space; clinoptilolite is less common. Original porosity varies from 5% to 25% but is difficult to estimate. Most lithic fragments and phenocrysts show alteration and are often stained red, brown or black by iron and/or manganese oxide. The origin of these breccias is complex. Undoubtedly some of the lithic components were incorporated into the ash flow at the vent. However, the large percentage of lower, red, Cryptic-tuff fragments in the breccia suggests that there was a close genetic relationship between the two. The lithic tuff breccia is considered to represent an initial pulse of the eruption that formed the micropoikilitic riebeckitic tuff. The densest part of the moving ash flow dismantled and incorporated fragments of older rock.

On the north side of Canyon Santa Clara, north of the east trending fault, breccia is less common and is confined to a narrow strip which projects northeast from the west side of the field area. This may represent a former valley along which the densest part of an ash flow advanced. Lacroix (1930a) and others witnessed how the densest parts of ash flows move down low areas.

A Cryptic tuff cooling unit contains a lower and upper(?) breccia (with a preponderance of quickly cooled constituents), a basal vitrophyre with flow structures and a core of crystalline tuff. This entire sequence was originally interpreted to be a rhyolite dome or series of liquid flows. Liquid flows often have chilled, glassy margins enclosing slowly cooled rocks and usually have thick lower and thinner upper

breccias (Christiansen and Lipman, 1966). The sequences of red and glassy Cryptic tuffs, usually seen as breccias, could be the quickly cooled upper and lower margins of a flow and the thick riebeckitic Cryptic tuff sequences could be interpreted as the main bodies of the flows.

If a peralkaline ash-flow tuff underwent considerable flowage during the final phase of emplacement, it might become autobrecciated. This process could account for the upper and lower breccias and lithic fragments found in the breccia. However, the author thinks that most of the breccia sequence resulted from the initial erosive force of the ash flow.

#### CAMPANA TUFF

##### General Statement

The Campana tuff is the youngest unit in the study area. It overlies the Cryptic tuff, usually resting on Cryptic tuff No. 3. Relief on the Campana-Cryptic contact is 10 to 20 m. Glassy fragments of Cryptic tuff No. 3 show more alteration (zeolitization) than do glasses in the lower Cryptic tuffs. Evidence to suggest baking is seen in the upper Cryptic tuff; fissile, bleached, poorly indurated rocks are coated with iron manganese oxides. The top of the Campana tuff has not been observed.

The Campana tuff section outcrops south of the large, southern, east trending fault (Plate 1). It attains a total thickness of 80 m in the field area; however, it becomes 300 m thick on Sierra de La Campana, several kilometers to the south. Campana tuff crops out

slightly north of the east-west fault in the low hills, downfaulted by the younger, north trending fault. This indicates either a lateral (northward) displacement in the downthrown fault block or a previously wider aerial extent for the tuff. It is believed that the major east-trending normal faults dammed the northern flow of the Campana tuff. If the Campana ash flow extended farther north across the faults, it must have been much thinner.

The Campana tuff is a dense, moderately to highly welded, blue to grayish-blue, vitric tuff. A striking eutaxitic texture is imparted by white or light-colored, flattened pumice lumps which can be 20 cm and more in diameter (Figure 67). Well developed columnar joints form columns that range from 1.0 to 3 m in diameter.

In the study area only one cooling unit is recognized. The unit contains the following:

- 1) a lower lithic zone that is highly welded near the base; it contains a decreasing amount of lithic fragments upward;
- 2) a middle zone that is mainly blue, dense, moderately to highly welded, and strongly eutaxitic; and
- 3) an upper zone that is moderately to poorly welded, porous, crystal-rich and is referred to as the Chocolate tuff.

Phenocrysts (Table 16) account to 9.7% of the rock in the thick, middle, blue zone and the sanidine/quartz ratio is 1.7. The upper Chocolate tuff zone has considerably more phenocrysts, proportionally more sanidine, and more multiple grains. The Idaho Canyon tuff (Noble, 1965) in southern Nevada, has upper units that are richer in crystals

| No.      | MATRIX | SANI | QTZ  | OS   | MAFICS | LITHIC | SANIDINE/<br>QUARTZ | %<br>Tw<br>Xl | %<br>Graph<br>Text. | %<br>Mul.<br>Grain | Dia.<br>Pheno<br>mm |
|----------|--------|------|------|------|--------|--------|---------------------|---------------|---------------------|--------------------|---------------------|
| 84A      | 50.5   | 19.7 | 11.8 | 16.5 | 0.7    | 1.0    | 1.7                 | 19.8          | 4.4                 | 20.3               | 0.5                 |
| 84B      | 46.2   | 19.3 | 11.3 | 18.4 | 0.8    | 4.2    | 1.7                 | 20.7          | 3.9                 | 13.4               | 0.5                 |
| 83       | 71.3   | 3.7  | 2.4  | 22.3 | 0.3    | -      | 1.5                 | 21.6          | 9.8                 | 14.8               | 0.5                 |
| 82       | 75.3   | 3.4  | 2.2  | 18.7 | -      | 0.4    | 1.6                 | 26.5          | 5.4                 | 9.9                | 0.6                 |
| 81       | 71.0   | 2.6  | 1.8  | 24.5 | 0.2    | -      | 1.4                 | 26.9          | 9.1                 | 18.2               | 0.5                 |
| 80A      | 37.1   | 5.6  | 2.1  | 0.4  | 3.1    | 57.9   | 2.7                 | 12.5          | 2.6                 | 6.5                | 0.5                 |
| Ave. 84  | 49.4   | 19.5 | 11.6 | 17.5 | 0.8    | 2.6    | 1.7                 | 20.3          | 3.3                 | 16.9               | 0.5                 |
| Ave. 3-5 | 72.5   | 3.2  | 2.1  | 21.8 | 1.7    | 0.1    | 1.5                 | 25.0          | 8.1                 | 13.9               | 0.5                 |

Table 16 a. Petrographic Data for the Campana Tuff

| No. | Or $\pm$ std. dev. | comments                     |
|-----|--------------------|------------------------------|
| 84  | 46.8 $\pm$ 1.6     | Chocolate tuff, fresh        |
| 80A | 74.7 $\pm$ 2.9     | Lower lithic zone, altered   |
| 81  | 55.8 $\pm$ 0.6     | Brown Campana - fairly fresh |
| 83  | 48.4 $\pm$ 0.4     | Brown Campana - fresh        |
| 82  | 52.6 $\pm$ 0.9     | Blue Campana - fairly fresh  |

Table 16 b. Rock powder X-rayed for sanidine composition.



than the rest of the sequence. Other examples of ash-flow tuffs with crystal-rich upper zones are common. These ash flows are thought to have been erupted from magma chambers in which fractional crystallization by crystal settling has occurred.

The Chocolate tuff contains fiamme that are similar in texture to zone two of the Campana tuff (Figure 72). This situation may be similar to one described by Vlodaretz (1963) at Kamchatka where fiamme of rhyodacite occur in a matrix of dacite. The rhyodacite is believed to be a differentiated cap of plastic material on the dacite magma chamber. Eruption of the dacite subsequently incorporated fragments of the rhyodacite. The zone 2 fiamme may represent a partly solidified residual magma resting on the crystal-rich magma chamber. Zone two fragments would then maintain their integrity during eruption and emplacement. However, since these fiamme are more crystal-rich than zone 2 Campana tuff, they may represent pumice lumps that have undergone compression, lost porosity, and crystallized differently than the Chocolate tuff matrix. A third possibility exists. Neither upper nor lower contacts of the Chocolate tuff were verified because of erosion and faulting and the stratigraphic location of this ash-flow tuff is not completely resolved. The Chocolate tuff may represent an entirely different eruption, probably from the same magma source but not necessarily from the same vent. This may explain the lithic fragments of Cryptic tuff.

Sanidine analyses in whole-rocks and sanidine phenocrysts analysed by microprobe are the same (Tables 16b and 17). Microprobe data show that Chocolate tuff phenocrysts (no. 84) differ from typical Campana

| No.  | Or | FeO <sub>(t)</sub> % | CaO %                                | No.  | Or | FeO <sub>(t)</sub> | CaO% |
|------|----|----------------------|--------------------------------------|------|----|--------------------|------|
| 82a  | 48 | 0.67                 | 0.03                                 | 84a  | 49 | 0.68               | 0.00 |
| 82b  | 45 | 0.63                 | 0.01                                 | 84b  | 48 | 0.61               | 0.00 |
| 82c  | 45 | 0.62                 | 0.00 - inner part of crystal         | 84c  | 47 | 0.81               | 0.00 |
| 82d  | 45 | 0.61                 | 0.01 - outer part of 82c             | 84d  | 46 | 0.65               | 0.00 |
| 82e  | 48 | 0.76                 | 0.03                                 | 84e  | 49 | 0.61               | 0.00 |
| 82f  | 44 | 0.56                 | 0.01                                 | 84f  | 47 | 0.67               | 0.00 |
| 82g  | 49 | 0.60                 | 0.01 - sanidine in symplectic grain. | Ave. | 48 | 0.67               | 0.00 |
| Ave. | 47 | 0.64                 | 0.02                                 |      |    |                    |      |

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Other Phenocrysts by Microprobe Analyses

|             |         |                            |                    |           |
|-------------|---------|----------------------------|--------------------|-----------|
| Olivine; Fa | MnO wt% |                            | FeO <sub>(t)</sub> | 74.31 wt% |
| 82          | 98.3    | 4.4 - center of crystal    | Titanomagnetite?   |           |
| 82          | 98.5    | 4.8 - edge of same crystal | TiO <sub>2</sub> = | 19.16 wt% |

Table 17. Sanidine Phenocrysts Compositions in Campana Tuff by Microprobe Analyses

phenocrysts (no. 82, Table 17). The upper Chocolate tuff sanidines contain more sodium and iron and less calcium suggesting a higher degree of peralkalinity.

#### Lower Lithic Zone

The lower lithic zone usually rests on a red Cryptic tuff No. 3 breccia. The Campana unit is 1.5 to 2.5 m thick, and contains about 52% lithic fragments and 11% phenocrysts (Figure 68). The lower half is highly welded and the upper half is moderately to poorly welded. Lithic fragments listed in order of decreasing abundance include: glass, micropoikilitic and flow-banded Cryptic tuff, spherulites, and basalt. The lithic fragments are up to 2.5 cm in diameter; however, most are only a few millimeters in diameter. Many fragments show rounding and alteration to a greenish silica (especially the glassy fragments). Some lithic fragments in the basal section show compaction which produces a eutaxitic texture. Phenocrysts are more common in the less welded, upper half.

In thin section the matrix consists of poorly to highly compacted, devitrified, shards in an extremely fine-grained granophyric groundmass. Pore space is nearly obliterated in the lower part. Crystals are euhedral to anhedral, angular to rounded and average 0.5 mm in diameter. Both sanidine and quartz phenocrysts are moderately to severely embayed. Olivine phenocrysts are altered to an iron oxide or clays but pyroxenes are fresh. Zircon, magnetite(?), and a few plagioclase phenocrysts are present. Glassy, olive-green lithic fragments show alteration to a fibrous material, probably chalcedony. The  $Or_{75}$  content for sanidine suggests a considerable loss of sodium.

At the southern end of the southeast ridge, a 1 to 1.5 m thick, discontinuous, dense, olive-green, highly welded lithic tuff is exposed. The green tuff crops out at the same stratigraphic level as the lithic tuff and is probably equivalent to it. Hand specimen and thin section observations reveal a close-packed, compressed network of yellow-green to olive-green, tapered, elliptical lapilli from 0.5 to 2.0 cm long. Rounded, massive Cryptic tuff lithics averaging 0.6 cm occur in the rock. The green material was glass that has devitrified to extremely fine-grained quartz. Porosity is nearly zero and Cryptic tuff lithic fragments, which occupy 10% to 15% of the rock, show little alteration except for minor silicification. Sparse phenocrysts of quartz and sanidine show rounding; sanidine shows some alteration.

#### Middle Zone

The lowest part of the middle zone is a tan to pinkish, moderately welded, vitric tuff which has a well developed eutaxitic texture. This grades upward into the dominant blue middle zone in 3 to 5 m or it alternates with light bluish zones for 10 to 15 m before the blue color dominates. The main blue Campana tuff is about 75 to 80 m thick in the field area and has well developed columnar joints. It is moderately to densely welded with a well-developed eutaxitic texture.

Phenocrysts in the tan and blue portions of the middle zone are similar in abundances and compositions (Table 16). The phenocrysts are euhedral to subhedral, and average about 0.5mm in diameter. Quartz phenocrysts are moderately to highly embayed especially near the

the base of the unit. Phenocrysts may show overgrowths in optical continuity and may occur in multiples of 2 or more crystals. Some, large, densely crystalline clumps of crystals are seen in the upper part of the middle zone (Figure 69). These clumps are usually many centimeters in diameter and may be over 1 m in diameter. Such crystal clumps must represent crystal-rich blocks that were ejected from the vent. Lithic fragments of Cryptic tuff are also common in these crystal-rich clumps.

The average sanidine to quartz ratio is 1.5, indicating relatively more quartz than in the Acantilado or Cryptic tuffs. The total phenocryst content is 7% to 8%. Sanidine phenocrysts form Carlsbad twins about 22% of the time and symplectic intergrowths of sanidine and quartz occur with 8% frequency. Quartz and sanidine were in equilibrium in order to crystallize together. Some of the symplectic grains display two, well developed directions of growth at  $45^{\circ}$  to each other (Figure 70a and b) and some sanidine and quartz grains only show a partial micrographic texture.

Sanidine phenocrysts may be so altered that only a layered skeletal shell is left. These shells may be partially or completely filled with white, chalky microcline and/or by small amounts of deep-violet fluorite. Fresh rock samples yield an Or content of  $48.4\% \pm 0.4$  for the sanidines while the average Or content for sanidine phenocrysts in the blue tuff is Or 46.5 (Talbes 16b and 17). All the phenocrysts contain over 0.5% FeO and very sparse CaO. These bulk chemical composition (Tables 20a and 20b) indicates the Campana tuff is more highly peralkaline than the Cryptic tuff.

| Sample No. | Al <sub>2</sub> O <sub>3</sub> | SiO <sub>2</sub> | K <sub>2</sub> O | *Na <sub>2</sub> O | CaO  | TiO <sub>2</sub> | Fe <sub>2</sub> O <sub>3</sub> (t) | Agpiatic Index |
|------------|--------------------------------|------------------|------------------|--------------------|------|------------------|------------------------------------|----------------|
| 41         | 10.84                          | 76.79            | 3.88             | 3.99               | 0.72 | 0.27             | 3.48                               | 0.99           |
| 74A        | 12.65                          | 75.63            | 5.09             | 3.90               | 0.16 | 0.22             | 2.36                               | 0.94           |
| 42         | 10.87                          | 77.13            | 5.55             | 3.10               | 0.08 | 0.25             | 3.04                               | 1.02           |
| 43         | 10.84                          | 77.44            | 6.11             | 1.98               | 0.48 | 0.25             | 2.92                               | 0.91           |
| 1          | 11.70                          | 75.41            | 5.17             | 3.78               | 0.20 | 0.22             | 2.49                               | 1.04           |
| 82         | 10.32                          | 75.52            | 4.80             | 3.72               | 0.05 | 0.24             | 5.35                               | 1.10           |
| 84         | 10.14                          | 76.40            | 4.82             | 3.69               | 0.02 | 0.23             | 4.70                               | 1.11           |

Table 20a. Chemical analyses by X-ray fluorescence. Cryptic tuffs; 41 = glass, 42 = green tuff, 43 = red tuff, 1 = riebeckitic tuff; Campana tuffs: 82 = blue tuff, 84 = Chocolate tuff; Acantilado tuff = 74A.

\*Analyses from Skyline Labs, Inc.

|        | SiO <sub>2</sub><br>% | Al <sub>2</sub> O <sub>3</sub><br>% | TiO <sub>2</sub><br>%  | Fe <sub>2</sub> O <sub>3</sub><br>% | FeO<br>%                           | MnO<br>%               | Agpiatic Index |
|--------|-----------------------|-------------------------------------|------------------------|-------------------------------------|------------------------------------|------------------------|----------------|
| CM 108 | 75.5                  | 11.7                                | 0.35                   | 3.0                                 | 0.41                               | 0.041                  | 1.11           |
| CM 182 | 75.9                  | 10.4                                | 0.33                   | 4.6                                 | 1.9                                | 0.132                  | 1.31           |
|        | MgO<br>%              | CaO<br>%                            | Na <sub>2</sub> O<br>% | K <sub>2</sub> O<br>%               | P <sub>2</sub> O <sub>5</sub><br>% | H <sub>2</sub> O+<br>% | F<br>%         |
| CM 108 | 1.018                 | 0.12                                | 3.8                    | 5.3                                 | 0.02                               | 0.5                    | 0.15           |
| CM 182 | 0.027                 | 0.14                                | 4.6                    | 4.8                                 | 0.02                               | 0.3                    | 0.33           |

Table 20b. Chemical of CM-108 (Micropokiolitic Cryptic Tuff) and CM 182B (Campana Tuff). Analyses by Skyline Lab, Inc. Boulder, Colorado (Total iron as Fe<sub>2</sub>O<sub>3</sub>)

Olivine (Fa 98.4 with about 4.5% MnO<sub>2</sub>) is more common in the blue than in the tan tuff. A titanium-bearing (19.15% TiO<sub>2</sub>) magnetite occurs along with a few zircons. An amphibole is also present.

In the lowest part of the middle zone pumice fragments are moderately compacted. The pumice rims are dark; centers are buff to white and contain miarolitic cavities (Figure 71). The largest fiamme are 8 cm wide and 3 cm thick but average 1 cm to 1.5 cm long and 1 cm to 2 cm in thickness.

Thin sections reveal a matrix of flattened, moderately welded shards which are often molded around phenocrysts. The groundmass has a poorly developed granophyric texture. There are acicular (3  $\mu$  long) matted aegirine needles throughout the shardy matrix. The needles appear brown to golden in plane light, have second to third order birefringence, and exhibit nearly parallel extinction. These tiny aegirine crystals are thought to produce the tannish color; they are absent or only sparingly present in the blue tuff.

Higher in the zone collapsed pumice lapilli show well-developed, axiolite structures. Sanidine cristobalite and brown, acicular aegirine, are oriented perpendicular to the border of the lapilli. Layers of chocolate-colored aegirine blebs occur near the outer rim and may form one to three concentric zones (Figures 70a and 70b). Between the aegirine layers are zones of sanidine and quartz. Some pumice fragments have a dark rim of nearly equidimensional aegirine blebs which have no apparent orientation. Coarse, elongate, vapor phase, sanidine, tridymite, and acicular aegirine project into the voids of partly compressed lapilli. Central areas are open or filled

with a polygonal network of quartz. Frequently, they contain small amounts of fluorite. In many pumice lapilli, tabular, euhedral, golden, vapor-phase crystals of a pyroxene, up to 1 mm long, were the last phase to develop. These crystals display blue, gray, golden brown, and greenish pleochoric colors and have nearly parallel extinction. The best crystals are striated parallel to their long axis and have simple wedge-shaped terminations (Figure 70a). Occasionally on the pyroxene there are tiny aegirine needles which are oriented parallel to the pyroxene striations.

The edges of the compressed pumice lapilli and shards usually taper into single sinuous tails but many have a ragged appearance with two or more wispy tails (Figure 71).

In the blue Campana tuff, pumice fragments and shards are slightly more compacted than in the tan tuff and devitrification textures are better developed. The blue tuff matrix also has less porosity due to more advanced granophyric crystallization and more vapor-phase crystallization in the pumice fragments. There are very few aegirine needles in the groundmass and the blue coloration stems from the high concentration of very small riebeckite blebs.

Dendritic, vapor phase riebeckite crystals are present in some of the pumice fragments along with smaller, yellow-green pyroxene crystals.

#### Upper Zone (Chocolate Tuff)

A chocolate-colored, moderately to poorly welded, crystal, vitric tuff crops out in several of the southeastern, downfaulted hills. The



position of the lower contact was not absolutely determined. The maximum observed thickness for this unit is 40 to 45 m. This Chocolate tuff appears to be equivalent to a unit found on top of the blue Campana tuff in the low hills 2 km to the south (Spruill, personal communication, 1978).

In outcrop, the Chocolate tuff is a dark brown, porous, crystal-rich tuff with numerous lighter brown, less porous lenses of similar-looking material. The less porous zones average 2 to 3 cm in length, 0.5 cm in width, and they weather more slowly than the groundmass. This differential weathering produces an obvious eutaxitic texture (Figure 72).

The tuff is poorly to moderately welded. A granophyric texture in the groundmass and axiolitic textures in the pumice fragments are poorly developed. Open space accounts for 18% of the rock. Golden to brown needles of aegirine occur profusely in the groundmass as do some brown blebs of altered riebeckite(?). Aegirine needles average 4.5  $\mu$  in length and are partly oxidized to limonite(?). The dark brown color of the tuff is derived from these oxidized aegirines. The denser lenticular areas have a better developed granophyric texture and fewer aegirine needles and thus a lighter color. Discrete blebs of riebeckite(?) similar to those in the blue Campana are present in the lenticular areas. There are a few Cryptic tuff, lithic fragments and a few, tiny, green, vapor-phase pyroxenes in the groundmass.

Phenocrysts account for 31% of the rock and the sanidine/quartz ratio is 1.7. Both values are higher in the Chocolate tuff than in the main, blue, Campana tuff. Phenocrysts are anhedral to euhedral, and average 0.5mm in diameter. Carlsbad twinning in sanidine phenocrysts

and clumps of two or more phenocrysts occur about as frequently as in the blue Campana tuff. Mafic phenocrysts are altered, but fayalite pyroxene, and magnetite associated with sparse zircons are present. Apatite needles occur as inclusions in some sanidines.

Quartz phenocrysts contain striking overgrowths of quartz. Old phenocrysts boundaries are clearly marked by randomly oriented aegirine needles (Figures 73a and 73b). Overgrowth development must have been contemporaneous with early granophyric crystallization.

### ECONOMIC GEOLOGY

#### Manganese

Manganese mineralization occurs in three locations (3 points) along the northern, east trending fault (Plate 1). Points 1 and 2 are located where the fault changes direction. Rocks are more extensively fractured at these locations and mineralization is more extensive than at point 3. Calcite, siderite, rhodochrosite(?) and chalcedony form layered pods and vein-fillings in highly fractured zones. Pyrolusite is the main manganese mineral. Pyrolusite forms coatings on carbonate crystal terminations (Figure 24); occurs as metasomatic(?) replacements of wallrock breccia; and occasionally occurs as acicular, crystalline sprays and matted masses. The concentration of Tl, Ba, Co, Pb, Zn, and U are directly correlated to Mn concentration (Table 18). Additional Mn mineralization might be located by finding areas where the east trending faults show changes in strike.

|          | <u>Tl</u> | <u>Ba</u> | <u>Co</u> | <u>Pb</u> | <u>Zn</u> | <u>U</u> |
|----------|-----------|-----------|-----------|-----------|-----------|----------|
| Mn No. 1 | 5         | 250       | <5        | 15        | 30        | 2        |
| Mn No. 2 | 170       | 11,000    | 10        | 5         | 220       | 4        |
| Mn No. 3 | 11        | 300       | <5        | 15        | 35        | 1        |

Table 18. Analyses of Mn ores for trace elements. Sequence of increasing Mn concentrations: No. 3 pyrolusite vein in carbonates, No. 1 - breccia with associated pyrolusite, No. 2 - massive pyrolusite. Values in ppm (Skyline Labs, Inc.)

### Uranium

Peralkaline magmas are known to contain anomalously high concentrations of U, Th, and heavy REE (Carmichael and others, 1974). Studies by Zielinski (1978) and Rosholt and Noble (1969), Rosholt and others (1971) show that U is evenly dispersed in nonhydrated and hydrated glass. Their studies also reveal that 20% to 80% of the U is lost by groundwater leaching following crystallization. U loss is associated with halogen losses (especially F) and  $UF_6$  may be an important transporting medium for U. Assays show fluorine concentrations of 1,500 ppm for micropoikilitic riebeckitic Cryptic ruff and 3,300 ppm for Campana tuff (Table 20b). Glassy and spherulite Cryptic tuffs (Table 19) average about 14 ppm U; however, micropoikilitic, riebeckitic Cryptic tuffs average about 6 ppm U; indicating that about 60% of the U has been lost. Large percentages of U are lost from rocks with coarser grained devitrified or granophyric textures (Figure 75; Table 17-1).

### Hematite

A small concentration of fine-grained, bright-red hematite with stringers of metallic hematite occurs near the fault contact at the

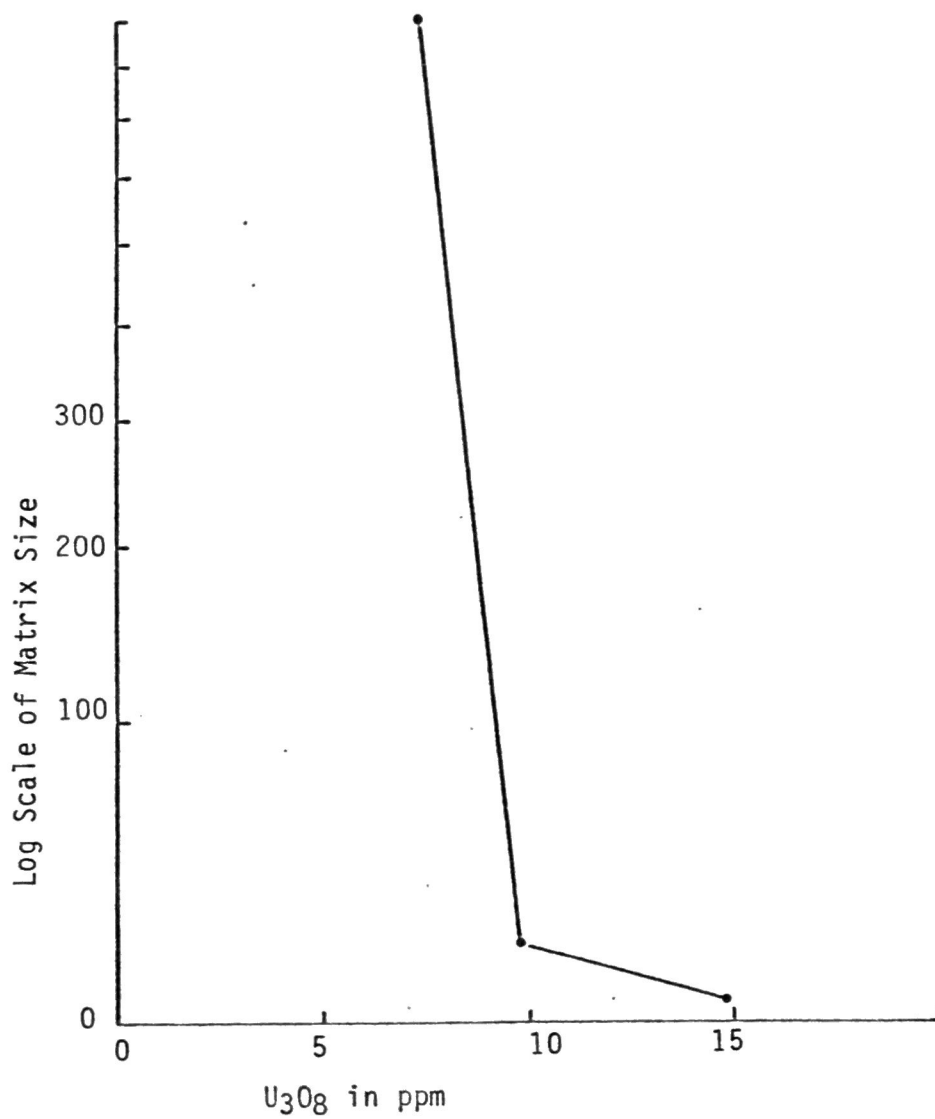


Figure 75. Plot showing U<sub>3</sub>O<sub>8</sub> concentrations in ppm versus maximum size of devitrified groundmass for the Cryptic tuff. The scale for the diameter of the groundmass is logarithmic.

| <u>Sample No.</u> | <u>U<sub>3</sub>O<sub>8</sub><br/>ppm</u> | <u>Description</u>                                   |
|-------------------|-------------------------------------------|------------------------------------------------------|
| RD-1              | 5                                         | Cryptic tuff, massive, riebeckitic, micropoikiolitic |
| RD-34             | 3                                         | Cryptic tuff, massive riebeckitic, micropoikiolitic  |
| RD-37             | 5                                         | Cryptic tuff, massive riebeckitic, micropoikiolitic  |
| RD-45B            | 9                                         | Cryptic tuff, massive riebeckitic, micropoikiolitic  |
| RD-27             | 8                                         | Cryptic tuff, red                                    |
| RD-43             | 12                                        | Cryptic tuff, red                                    |
| RD-42             | 8                                         | Cryptic tuff, green                                  |
| RD-41             | 14                                        | Cryptic tuff, glassy                                 |
| RD-59             | 15                                        | Cryptic tuff, glassy                                 |
| RD-74             | 14                                        | Cryptic tuff, glassy, spherulitic                    |
| RD-82             | 19                                        | Campana tuff (blue)                                  |
| RD-84             | 10                                        | Chocolate tuff                                       |
| RD-22             | 6                                         | Acantilado, altered                                  |
| RD-74A            | 6                                         | Acantilado, fresh                                    |
| CF                | 4                                         | Acantilado, fresh                                    |
| RD-95             | 6                                         | Glassy andesite                                      |

Table 17-1. Analyses of U<sub>3</sub>O<sub>8</sub> by fluorimetry (Skyline Labs, Inc.)

junction of Canyons Las Norias and El Rosal. The hematite occurs as coatings and cement in fractured Acantilado tuff and overlying alluvium. The hematite is in a sliver of Acantilado tuff which has been left projecting through the surrounding Cryptic tuff. The occurrence may have resulted from the precipitation of iron from groundwater (the area is somewhat boggy) and subsequent deposition in highly fractured and altered Acantilado tuff.

### Zeolites

Small areas of Cryptic ruff, especially in the vitrophyres, have undergone alteration to clinoptiliolite. Larger deposits may occur where glassy sections are thicker.

## PETROCHEMISTRY OF PERALKALINE ROCKS

### General

The Cryptic and Campana ash-flow tuffs are peralkaline. Peralkaline magmas contain more alkalis than can be utilized by existing alumina in the formation of feldspars. This results in the formation of Na-pyroxenes, Na-amphiboles, aenigmatite, and other unusual minerals. Lithophile elements, rare earth elements and halogens are also concentrated in peralkaline rocks.

Peralkaline rhyolites can be divided chemically into comendites and pantellerites. Typically, comendites differ from pantellerites by their lower mafic mineral content, lesser enrichment in trace elements such as Nb, Ta, Zr, Mo, Zn, and Cd, and by their lower agpatic index (Carmichael and others, 1974). Macdonald (1975) divided peralkaline

rocks into four groups, comendites, pantellerites, commenditic trachytes, and pantelleritic trachytes, by plotting  $\text{Al}_2\text{O}_3$  against total iron contents. This usage follows an older classification by which normative femic minerals are plotted against normative quartz (Macdonald and Bailey, 1973). Slopes for boundary lines are arbitrary. They reflect the most efficient division for data points and agree with Lacroix's 12.5% normative femic content as the dividing line between comendites and pantellerites. Peralkaline rocks from the study area are comenditic although the Campana tuff borders on the pantellerite/comendite boundary (Figure 76).

#### Genesis of the Peralkaline Rhyolites

In synthetic mixtures containing  $\text{NaAlSi}_3\text{O}_8$  and  $\text{CaSiO}_3$ , calcium-bearing plagioclase precipitates first. Each Ca atom carries one "extra" Al atom into the plagioclase crystal. Continued crystallization of calcic plagioclase could deplete the liquid in Al. This is called the "plagioclase effect". The mechanism operates during crystal fractionation of a magma and can lead to an excess of  $\text{Na}_2\text{O}$  with accompanying depletion of  $\text{Al}_2\text{O}_3$ . A peralkaline magma can eventually be generated by this means (Carmichael and others, 1974). It should be noted that the original magma must be slightly alkaline for the plagioclase effect to operate. Once the mechanism starts; however, a progressively higher agpaitic index develops (Bailey and Schairer, 1964). Mildly alkaline basalt would be a reasonable parent magma for differentiation by crystal fractionation and the eventual production of a peralkaline liquid.

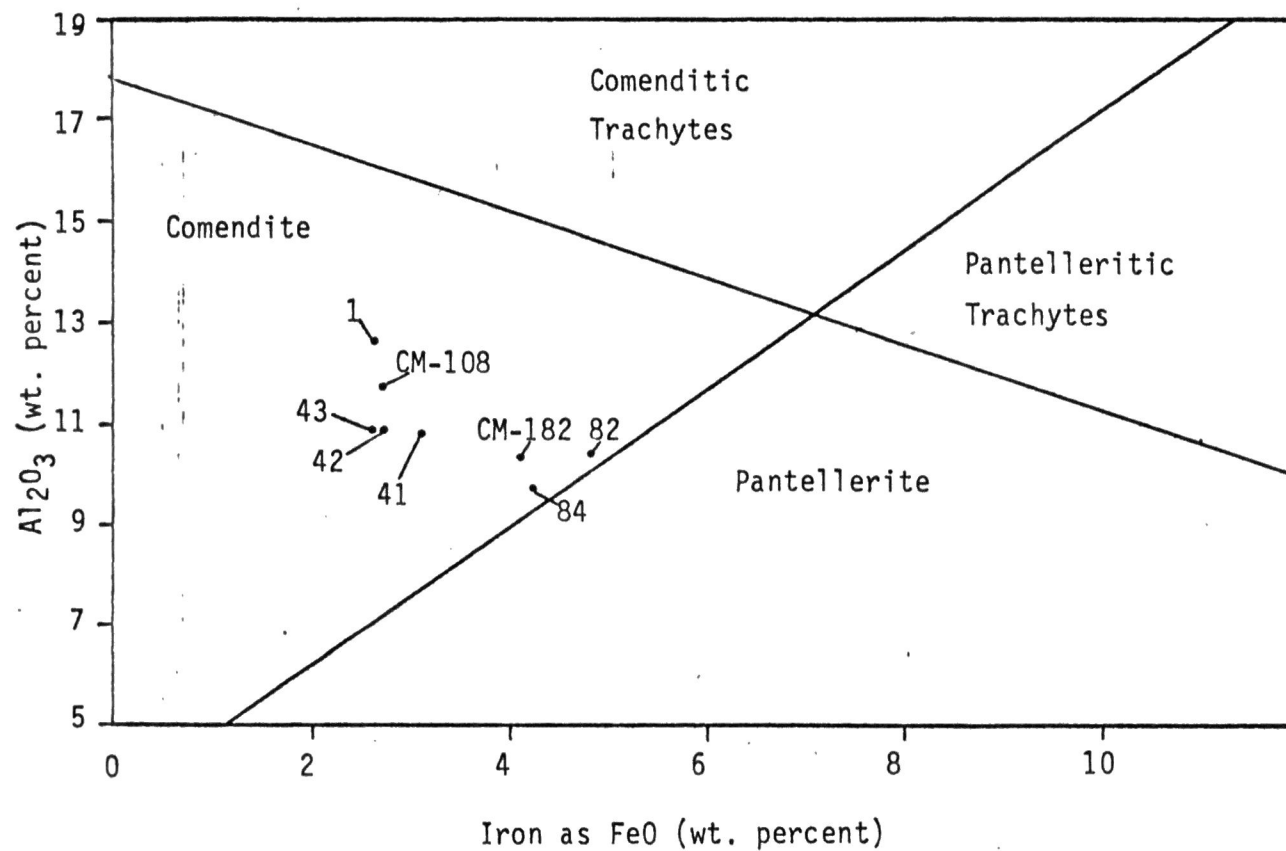


Figure 76. Classification of peralkaline rocks (Macdonald, 1974).



As  $\text{Na}_2\text{O}$  is added to synthetic feldspathic liquids, a more sodic feldspar precipitates. When the  $\text{K}_2\text{O}/\text{Na}_2\text{O}$  mole ratio for the feldspar is compared to that of the parent liquid, the precipitated feldspar proves to have the higher ratio (Bailey and Shairer, 1964; and Bailey and Macdonald, 1969). Fractional crystallization of sanidine is an effective way to enrich the residual melt in  $\text{Na}_2\text{O}$ . The process is called the "orthoclase effect". This condition has also been demonstrated in peralkaline vitrophyres (Chayes and Zies, 1962; Vallari, 1975). To test for this, the  $\text{K}_2\text{O}/\text{Na}_2\text{O}$  mole ratio for a sanidine phenocryst is compared to that of its glassy matrix. If the ratio for the matrix is lower,  $\text{Na}_2\text{O}$  has been partitioned into the melt, and the orthoclase effect is demonstrated.

Table 19 shows the relationship between sanidine phenocrysts and matrix for glassy samples of Cryptic tuff. The molecular Na to Na/K ratio shows that the phenocrysts are enriched in K and that Na remains in the melt. The exception is No. 73 which has undergone Na loss (Table 20a).

| Sample No. | Phenocryst Composition | Glass Composition | Minimum $\text{Na}_2\text{O}$ Loss in % |
|------------|------------------------|-------------------|-----------------------------------------|
| 41         | 0.58                   | 0.64              | 0                                       |
| 59         | 0.55                   | 0.62              | 0                                       |
| 73         | 0.58                   | 0.51              | 10                                      |

Table 19. Molecular Na/Na+K for glass and for sanidine phenocrysts contained in glass. Analyses by microprobe.

Microprobe data for sanidine phenocrysts in samples RD-41 (Table 13) and RD-82 (Table 17) indicate an increased  $\text{Na}_2\text{O}$  content outward in the

crystals. This also suggests that  $\text{Na}_2\text{O}$  was increasing in the associated magma.

The agpiatic indexes of the major units are listed in Table 20a and b. Overall there is a progressive increase in the agpiatic index from the Acantilado to Campana tuffs. The total iron content increases up-section and calcium decreases. The agpiatic index of the Chocolate tuff is the highest of all rocks studied and it represents the most advanced peralkaline composition. The sequence from the basalt flows to the comenditic tuffs represent a differentiation series that became enriched in silica and alkalis and finally became peralkaline.

Average compositions for sanidine phenocrysts are plotted in Table 21. The phenocrysts from Campana tuffs are slightly less sodic than those from the Cryptic tuff. Slow cooling of the liquid allows the feldspar phenocrysts to become more potassic while the liquid becomes more sodic. From this information one might expect sanidine phenocrysts in the Campana tuff to be more potassic than those in the Cryptic tuff since the Campana is richer in crystals and was erupted at a somewhat lower temperature. On the other hand the small difference in Na content of the phenocrysts in the two rocks may not be significant.

Pyroxene compositions (Figure 23) indicate that in the calcium-rich pyroxenes, crystallization progressed from more Mg-rich augites to Mn-hedenbergite. In the low-calcium varieties, the trend was from orthopyroxenes (hypersthene) to ferropigeonite and finally to Fe-rich fayalite. Iron is also enriched in the magma which allows "excess" sodium to be combined and form groundmass aegirine and riebeckite (Ewart and others, 1976).

| No.    | Comments                                   | Composition |      |     |
|--------|--------------------------------------------|-------------|------|-----|
|        |                                            | Ab          | Or   | An  |
| 13     | basal Acantilado tuff (spherulitic)        | 45.4        | 54.4 | 0.2 |
| 59     | hydrated glassy Cryptic tuff               | 54.3        | 44.6 | 1.2 |
| 41     | hydrated glassy Cryptic tuff               | 56.5        | 42.7 | 0.8 |
| CM-108 | micropoikilolitic riebeckitic Cryptic tuff | 52.9        | 47.0 | 0.1 |
| 82     | blue Campana tuff                          | 53.1        | 46.8 | 0.0 |
| 84     | Chocolate tuff (Campana)                   | 52.3        | 47.5 | 0.0 |

Table 21. Average microprobe analyses of sanidine phenocrysts from rock units in the field area.

#### Sodium Loss

Sodium, silica, and potassium are mobile during hydration and devitrification of comendites and pantellerites (Lipman, 1965; Noble and others, 1970a). There is normally less  $\text{Na}_2\text{O}$  lost from comendites than from pantellerites, presumably because pantellerites contain more excess  $\text{Na}_2\text{O}$ .  $\text{K}_2\text{O}$  is often concentrated in alkali feldspar whereas  $\text{Na}_2\text{O}$  is lost as sodium silicate. A large part of the  $\text{Na}_2\text{O}$  loss probably occurs shortly after primary crystallization; however, older ash-flow tuffs and lava flows frequently show a greater  $\text{Na}_2\text{O}$  loss (Noble, 1968c). Noble (1965) reports a 25%  $\text{Na}_2\text{O}$  loss from crystallized Miocene-Pliocene volcanics rocks in Nevada.

Loss of  $\text{Na}_2\text{O}$  may be accomplished by volatilization during crystallization (Kogarko and others, 1968) or, more likely, by the removal of soluble silicate or  $\text{NaCl}$  phases during groundwater leaching (Roedder and Combs, 1967). Evidence to support the latter contention include the presence of alkaline groundwater from volcanic terrains, and a positive correlation between the extent of cation loss and the exposed surface areas of glassy rocks (Lipman, 1965).

Table 22 lists Na<sub>2</sub>O contents of rocks from the study area. The glasses are hydrated. Glassy samples Nos. 41 and 74A retain the highest Na<sub>2</sub>O content. The relatively high Na<sub>2</sub>O content of coarsely crystalline samples (1 and CM-108, Table 20b) may be attributed to their location deep within a thick cooling unit where Na-rich amphiboles and pyroxenes were formed. Noble (1965) reports that slowly cooled lavas and tuffs containing primary quartz in the groundmass show smaller Na<sub>2</sub>O loss than unhydrated glasses of the same stratigraphic unit. Cristobalite and tridymite allow considerable substitution of Al<sup>+3</sup> for Si<sup>+4</sup> with accompanying substitution of Na<sup>+</sup> to maintain electrical neutrality. The conversion of cristobalite to quartz would mobilize the Na<sup>+</sup> in the cristobalite. Stewart (1979) discusses the importance of circulating groundwater to Na loss in glasses. By removing Na, K may be relatively enriched. A direct relationship exists between increasing hydration and an increasing K<sub>2</sub>O/Na<sub>2</sub>O ratio. Sample No. 43 Table 20a, demonstrates a loss of Na and enrichment in K. Glass compositions (Table 12) indicate that K and Na were lost to some extent.

## TECTONIC IMPLICATIONS

### General

Peralkaline rocks occur in areas of crustal tension (Macdonald and others, 1975; Illies, 1969). Continental rift (e.g. East Africa) or rift-type environments (e.g. Basin and Range) contain more than 90% of known peralkaline rocks; the remainder occur in ocean islands near spreading centers or as late stage orogenic volcanics where rifting is absent (Macdonald, 1975). Macdonald (1975) cites two petrological

| No.                     | Description                                                            | Na <sub>2</sub> O wt. % |
|-------------------------|------------------------------------------------------------------------|-------------------------|
| <u>Acantilado tuffs</u> |                                                                        |                         |
| 22                      | middle zone, altered                                                   | 1.0                     |
| 74                      | middle zone, fresh                                                     |                         |
| <u>Cryptic tuffs</u>    |                                                                        |                         |
| 41                      | glassy                                                                 | 4.0                     |
| 74A                     | spherulites in glass                                                   | 3.9                     |
| 42                      | green zone                                                             | 3.1                     |
| 43                      | red, flow banded                                                       | 2.0                     |
| 64                      | mariolitic                                                             | 3.1                     |
| 34                      | micropoikiolitic, riebeckitic<br>(slightly altered)                    | 3.2                     |
| 1                       | micropoikiolitic, riebeckite                                           | 3.8                     |
| 45B                     | micropoikiolitic, riebeckite (altered)                                 | 2.7                     |
| Cm-108                  | micropoikiolitic, riebeckite                                           | 3.8                     |
| <u>Campana tuffs</u>    |                                                                        |                         |
| 82                      | blue Campana                                                           | 3.7                     |
| 84                      | Chocolate tuff                                                         | 3.7                     |
|                         | (Na <sub>2</sub> O analyses by Skyline Labs, Inc.<br>Denver, Colorado) |                         |

Table 22. Sodium content of rock samples in weight percent.

situations where peralkaline rocks occur: (1) where the volume of sialic rocks is low compared to basic types and there is no intermediate "silica gap" or "Daly gap"; and (2) in areas where pantelleritic or pantelleric-commenditic rocks dominate; the "Daly gap" is prominent and basic rocks are scarce or absent.

Magmas enriched in alkalis and depleted in alumina are generally considered to be highly differentiated. This would imply a large reservoir of basic parent magma. Locating vast amounts of alkaline basic rocks is not a problem in mid-oceanic islands environments but certainly is a problem in regions where great sialic ash-flow deposits predominate (e.g. Basin and Range Province or Sierra Madre Occidental). Bailey (1975) alludes to the importance of volatile transfer and recognizes the importance of alkali and iron mobility during the early stages of magma generation in an open system. This process would allow  $\text{Na}_2\text{O}$  to migrate and to be concentrated in more sialic melts. It would also negate the requirement for vast quantities of basic rocks to be located nearby. This idea involves the melting of lower crust or upper mantle and would result in an intermediate initial  $\text{Sr}^{87}/\text{Sr}^{86}$  ratio. Spruill (oral communication, 1979) reports that the initial ratios for the Campana series are low. Noble (1971) envisions a simple mechanism for the production of peralkaline magmas in regions where bimodal basalt/rhyolite volcanism predominates. Low density, sialic magma would be able to rise diapirically to higher levels within the crust leaving the high density, parent magma behind. This process would allow for a low initial  $\text{Sr}^{87}/\text{Sr}^{86}$  ratio.

### Specific

The volcanic rocks in this field area are a bimodal, basalt-rhyolite assemblage. This assemblage is typical of other peralkaline terrains (Barberi and others, 1975; and Noble, and others, 1974). Cameron and others (1978) divided the volcanic rocks of central Chihuahua into three groups based on age and chemistry. Their older "calc-alkaline suite" (~28 m.y.) is not present in the study area. Based on chemical analyses and phenocryst assemblages, the rhyolites of the Canyon Santa Clara area correspond to Cameron and others "ferroaugite rhyolite suite" (32 to 28 m.y.), and the basalts correspond to their "mildly alkaline basalt-basaltic andesite suite" (32 to 20 m.y.). These suites are similar to Christiansen and Lipman's (1972) "fundamentally basaltic" assemblage which is considered to be bimodal. In this region of Mexico, there are more felsic than mafic rocks exposed; however, this may be merely a function of the extent of erosion. The upper volcanic group in the Sierra Madre Occidental McDowell and Clabaugh (1978) was erupted between 34 and 28 m.y. ago. This group is also bimodal; however, plagioclase is the dominant phenocryst and the suite is regarded as calc-alkaline.

The glassy andesite near the top of the basalt section resulted from the mixing of felsic and mafic magmas and thus is in accord with the proposed bimodal suite. According to Cameron and others (1978), the basalt-basaltic andesite suite contains rocks that could fit into any one of three basaltic groups (alkalic, tholeiitic, or calc-alkaline) depending on which classification is used. This is probably true for

the basalt rocks of the field area. These rocks are not related to an older calc-alkaline suite and thus they represent a change in magmatic evolution that took place about 30 m.y. ago. This change in chemistry is probably related to an increasingly tensional tectonic regime.

The Rio Grande Rift, which extends from Colorado into northern Chihuahua, may be a northern extension of a larger rift zone that formed farther south in Chihuahua. Based on heat flow data, Seager and Morgan (1979) traced the rift as far south as Villa Ahumada, 115 km north of the field area. Structural trends appear to continue farther south (Ramberg and others, 1978). Chapin and Seager (1975) concluded that rifting may have begun about 29 m.y. ago in southern New Mexico. This date compares favorably with the  $29.5 \pm 1.0$  m.y. age for the Acantilado tuff (Mauger, 1978). A genetic relationship between rifting and bimodal volcanics is implied. Although some faulting and erosion of the basalt occurred prior to the eruption of the Acantilado tuff, the hiatus was probably not extensive and the two units are "contemporary". Also, the Cryptic and Campana tuffs are not much younger than the Acantilado tuffs.

Back-arc spreading has been proposed by Cameron and others (1979) and Mauger (1979) to account for tensional features and rock types found in central Chihuahua. This theory corresponds with ideas of other authors (Christiansen and Lipman, 1972; and Noble, 1972) who suggested that the "fundamentally basaltic" volcanism in the western United States is associated with an extensional back-arc environment. The tensional environment may have been initiated farther east in west Texas because similar alkaline volcanism began there while calc-alkaline volcanism continued in Chihuahua.



In the study area, peralkaline rocks show a compositional gap between basic and peralkaline members (Macdonald and others 1975). The basaltic magma appears to have the proper composition for fractionation into an increasingly peralkaline melt. The "plagioclase effect" would have been an effective means of producing an increasingly alumina-poor melt. In higher silica melts, the "orthoclase effect" may have become important. Fractional crystallization of sanidine with small amounts of the An molecule would leave a melt enriched in soda and depleted in alumina. A resulting sequence of ash-flow tuffs would show increasing peralkaline affinities higher in the section. This is the case for the sequence, Acantilado tuff-Cryptic tuff-Campana tuff. The apparent absence of vast quantities of mafic parent material may be explained by assuming that the magma differentiated at shallow depths and that the lower density rhyolite differentiates rose preferentially.

## SUMMARY AND CONCLUSIONS

### Stratigraphy and Petrography

1. The lower most rocks are olivine augite basalts (An<sub>59</sub>). The lower contact is not exposed. A few air-fall and ash-flow rhyolites are interbedded with the basalts and a glassy spherulitic andesite. They occur locally near the top of the section. The glassy andesite resulted from the mixing of mafic and felsic magmas.
2. Above the basalt lies the crystal vitric Acantilado tuff. It is about 30 m thick and forms prominent cliffs. The tuff contains one cooling unit and is subalkaline in composition.

3. Next in the sequence is a thick section of highly welded vitric Cryptic tuff. It is comenditic (A.I. = 1.1) and exhibits striking flowage features. A complete cooling unit contains: lower vitrophyric and spherulitic pods set in a greenish devitrified matrix of compressed, stretched and brecciated pumice lapilli; a red and white laminarly flowed and shear-folded zone; a highly porous vapor-phase zone which grades into a dense rock containing a micro-poikiolitic sanidine-in-quartz groundmass. Coarse-fiber spherulites are common; spherulite fiber diameters indicate 750°C as a minimum temperature of emplacement. Breccia flows occur at the top and bottom of the three cooling units. Their formation is thought to have resulted from an initial disruptive pulse which incorporated surficial debris into the ash flow and by auto-brecciation during flowage.

A north-south trending vent structure at least 3 km long is exposed in the southeastern quarter of the area along which Cryptic tuffs that are vertically foliated. East-trending normal faults form the northern edge of the vent and may form the southern edge. This structure closely resembles a rhyolitic flow dome in geometry and in the textural varieties of rhyolite.  $U_3O_8$  losses for the micro-poikiolitic Cryptic tuff average about 60%. There is a direct correlation between the coarseness of grain size in the groundmass and the amount of  $U_3O_8$  lost.

4. Highly welded, crystal vitric Campana tuff is the uppermost unit and forms massive, cliffs. It is also comenditic (A.I. = 1.3) and

includes light-colored crystal-rich pumice lapilli. The bluish color is caused by the presence of riebeckite in the groundmass. The Chocolate tuff, probably a cooling unit within the Campana section, overlies(?) the blue Campana tuff and is the most peralkaline of the comendites. It contains matted, acicular, groundmass aegirine which produces its distinctive color.

5. The stratigraphic section is nearly 1000 m thick in lower Canyon Santa Clara and is correlatable to the section in Canyon Bellavista, 40 km to the south.

#### Faults

6. Two, large, east-trending normal faults downthrown to the south, were probably active prior to the eruption of the Acantilado and peralkaline ash-flow tuffs. The faults extend westward beyond the study area and are truncated on the east by a north-trending Basin and Range fault. The main north-trending fault downthrows the eastern portion of the field area about 500 m. North of Canyon Santa Clara, the north-trending fault is offset to the east.

#### Petrography and Tectonic Implications

7. The slightly alkaline(?) basalt and the Acantilado, Cryptic, and Campana tuffs represent a genetic sequence. Peralkalinity may have developed due to fractional crystallization of basaltic magma. Plagioclase crystallization would enhance the trend toward peralkalinity during earlier periods of differentiation, and sanidine (with  $\text{Ca}^{+2}$  and  $\text{Fe}^{+2}$ ) crystallization would produce similar results during later periods of differentiation.

8. Low initial  $\text{Sr}^{87}/\text{Sr}^{86}$  ratios of the rocks suggest that the parent magmas were mantle derived.
9. Peralkaline rocks are known to occur in tensional tectonic environments. A tensional back-arc environment with a possible relationship to the Rio Grande Rift is hypothesized.

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Figure 2. View looking SSW from north side of Canyon Santa Clara. Canyon Las Tapias is in the right foreground. The two low hills in right center are composed of Cryptic tuffs. Canyon Santa Clara extends from right to left across the middle of the plate. South of Canyon Santa Clara on the left is the southeastern frontal scarp containing the north-trending vent structure. The first canyon to the right of the frontal scarp is El Oscuro; the second is Las Norias. The mapped area extends southward up to the point where Cryptic tuff cliffs intersect the canyons. Talus slopes are predominantly composed of Cryptic Tuff. The large cliffs in the far northeastern background are composed of Campana tuff, on Sierra La Campana.

Figure 4. View looking west up Canyon Las Norias from a hill north of Canyon Santa Clara. The northern east-west fault trace extends through the canyon. Cryptic tuffs outcrop on the west side of the canyon, basalts on the east side. Columnar-jointed Acanalado tuff outcrops in the foreground.

Figure 5. Laharic deposits outcrop in Canyon Las Novias at the junction of Canyon El Rosal. These deposits become thickest at the fault boundary that cuts through Canyon El Rosal. Hammer handle is 25 cm long.

Figure 7. Panorama from the southeastern frontal scarp, looking east-northeast. Low hills are downfaulted by a large Basin and Range fault which extends through the low area between the hills and the slope in the foreground. The hills are sliced by a series of small faults parallel to the large fault. Tuffs dip into the bolson. Laguna Encinillas is in the background.



Figure 2.

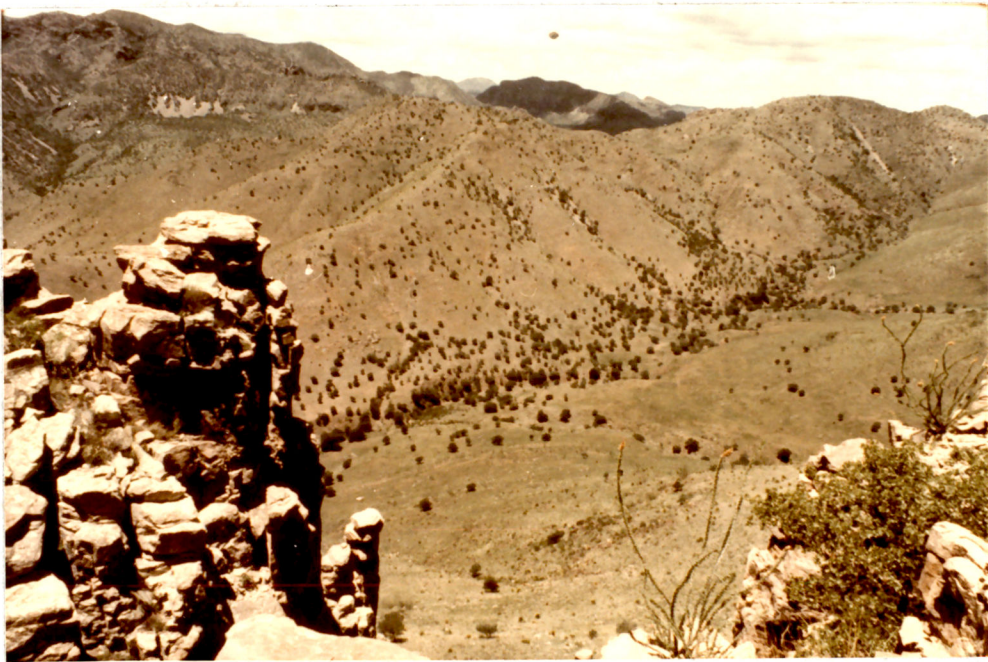


Figure 4.





Figure 5.



Figure 7.

- Figure 8. Typical basalt flows. A massive section outcrops in lower left side; above it is a scoraceous zone. Brecciated basalts outcrop on the right side. The person is 1.9 m tall.
- Figure 9. Photomicrograph of basalt. Plagioclase (An<sub>59</sub>) laths exhibit a crude pilotaxitic texture. Augite crystals have included plagioclase laths. Many of the small, dark colored blebs are olivine phenocrysts. X-nicols. Width of field 2.6 mm.
- Figure 10. Photomicrograph of laharic rock near the top of the basalt sequence. Yellow, highly birefringent mineral is clinoptilolite associated with quartz. Clinoptilolite usually replaces glass. Small, tabular crystals associated with clinoptilolitic lithics is another zeolite (heulandite?). Phenocrysts are fragmented; the groundmass is devitrified.
- Figure 11. Andesitic glass weathers into rounded boulders in the north-western corner of the field area. Spherulites become concentrated toward the top of the glassy section. The hammer handle is 25 cm long. Acantilado tuff outcrops in background.





Figure 8.

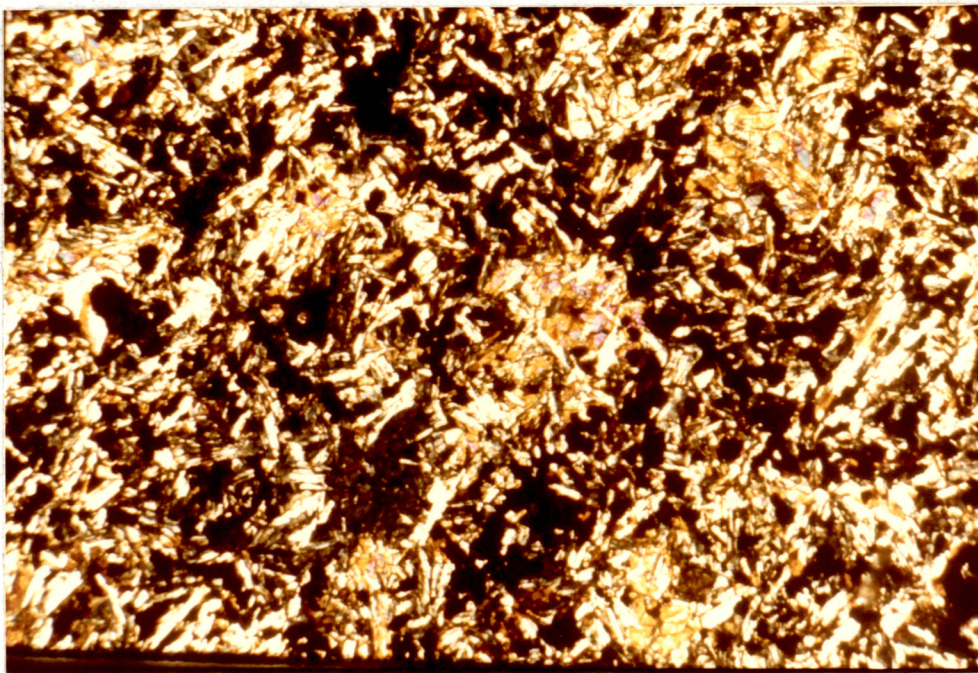


Figure 9.



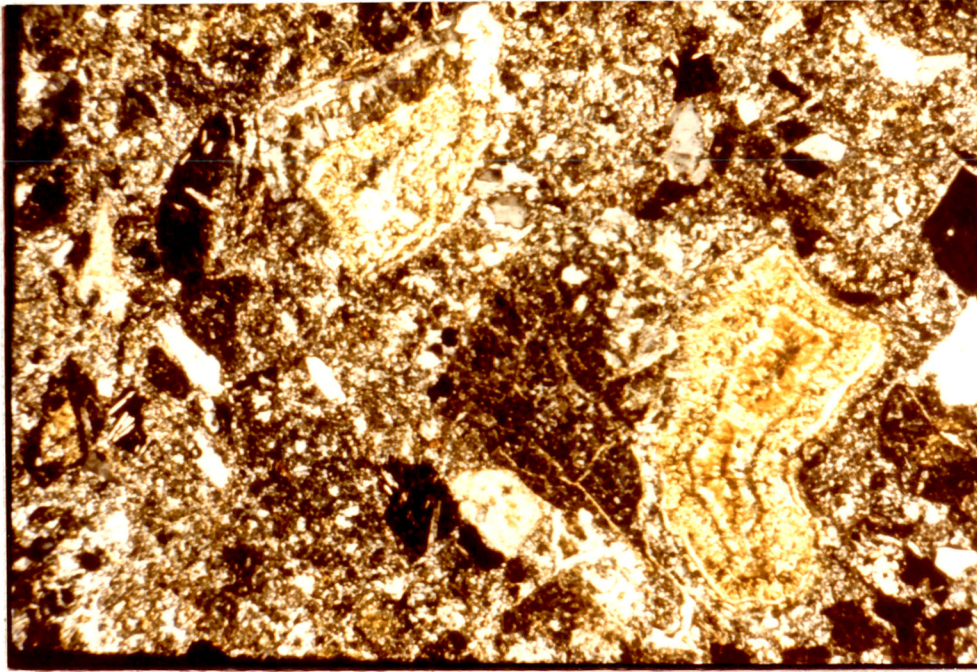


Figure 10.



Figure 11.

Figure 12. Close view of spherulitic andesite. Spherulites often form clumps; a vague foliation is imparted by the concentration on spherulites along flowage planes. The ground around these outcrops is littered with spherulites.

Figure 13. Photograph of spherulitic, glassy andesite thin section. A concentric texture can be seen in the spherulites. Xenocrysts of feldspar are euhedral to anhedral, individual to glomeroporphyrritic. The crystals frequently serve as nucleation points for the spherulites. Perlitic cracking is pronounced. Plane light. Width of field 35 mm.

Figure 14. Photomicrograph of glassy andesite. The large crystal in the upper left corner is a Type III feldspar with a small resorption rim. The photograph also shows a glomeroporphyrritic texture of feldspar and pyroxene xenocrysts. The groundmass contains small laths of feldspar. X-nicols. Width of field 6.8 mm.

Figure 16. Photomicrographs of glassy andesite. The euhedral feldspar on the left is a Type I sanidine. On the right is a Type IV feldspar containing a sanidine rich core which is out of equilibrium X-nicols. Width of field 6.8 mm.



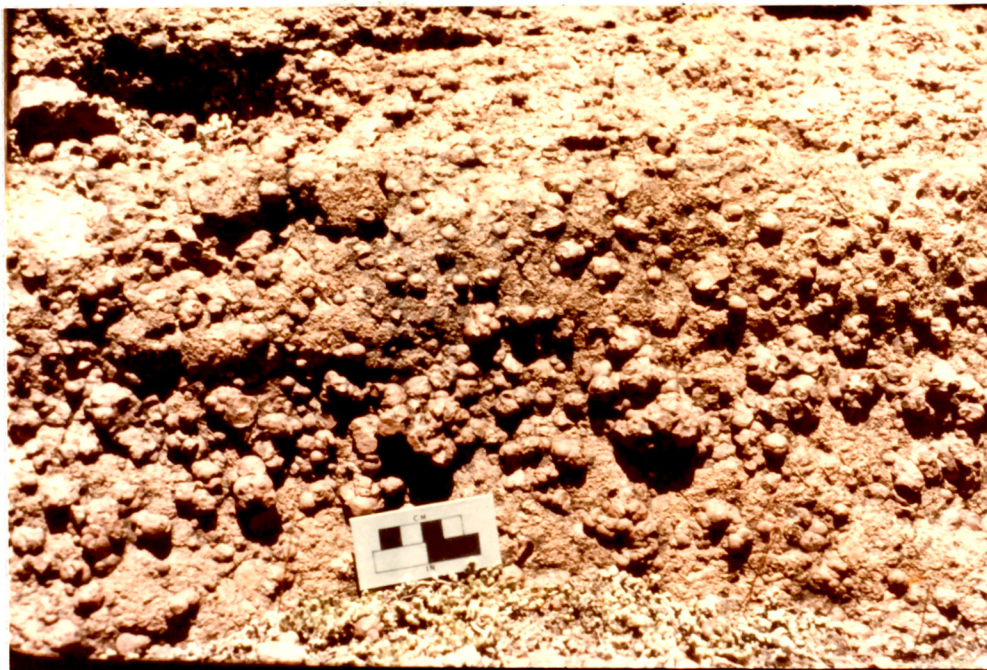


Figure 12.

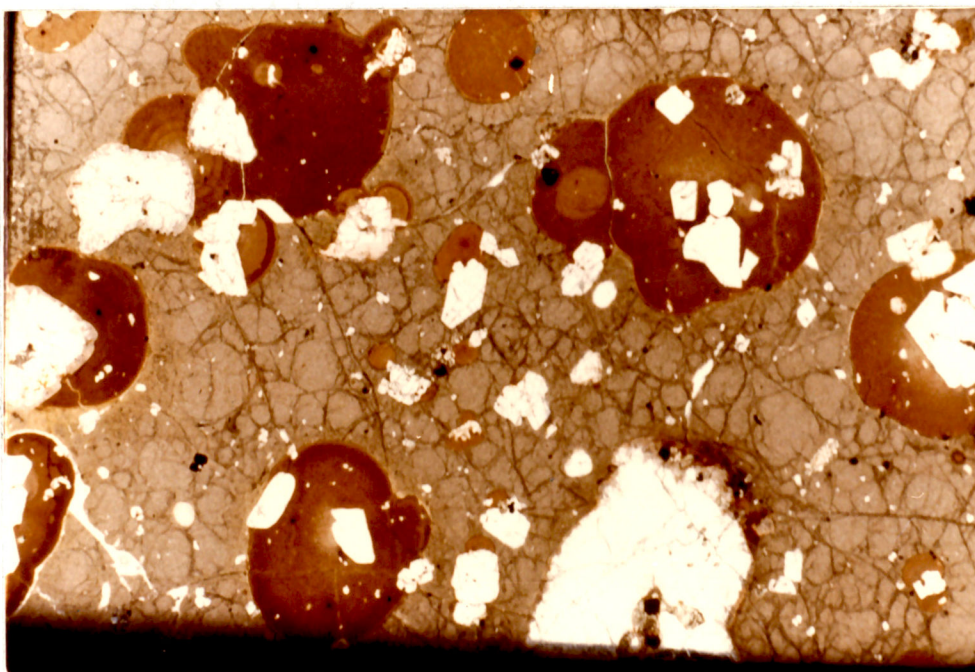


Figure 13.

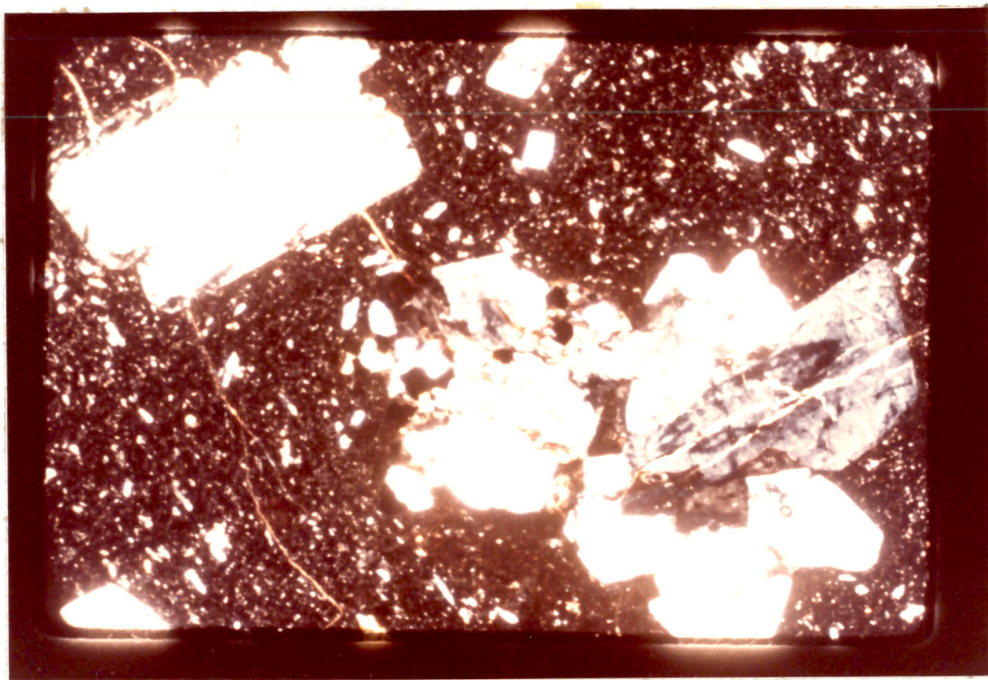


Figure 14.

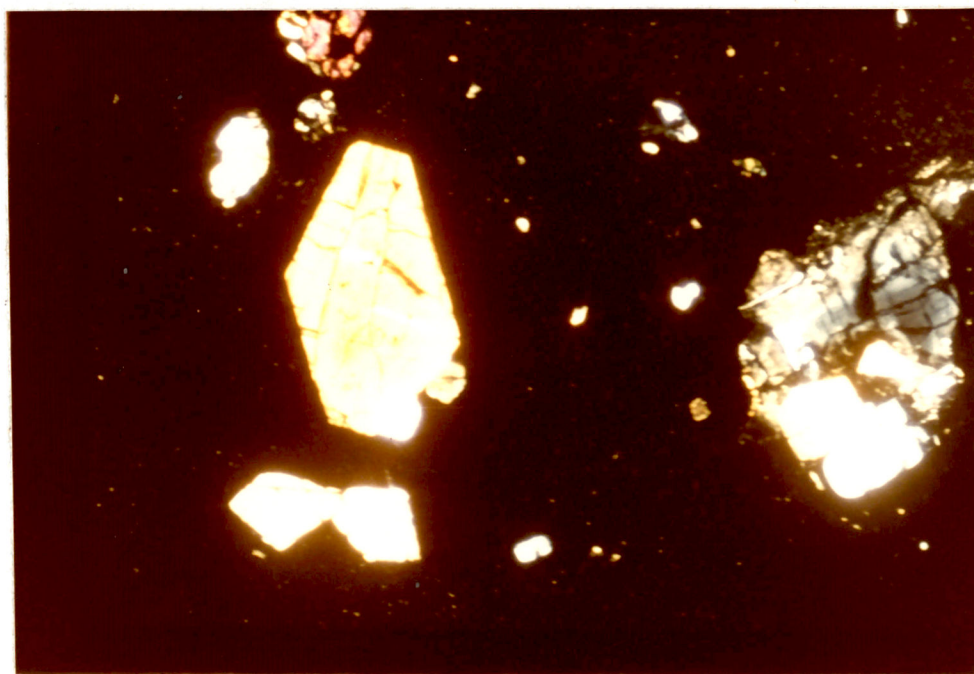


Figure 16.



- Figure 20. Photomicrograph of "glassy" andesite. This shows Type III altered plagioclase feldspar. Rims are resorbed and interiors are partly resorbed. The matrix is moderately crystalline. X-nicols. Width of field 2.6 mm.
- Figure 21. Photomicrograph of glassy andesite. Pictured on the right is a highly resorbed Type IV sanidine, only anorthoclase and plagioclase remain. The uniform texture of the two feldspars is visible. In the upper left is a lithic fragment of fine-grained gabbro. Type V plagioclase feldspars and orthopyroxenes are contained in the lithic fragment. X-nicols. Width of field 6.8 mm.
- Figure 24. Photomicrograph of altered pyroxene(?). Biotite appears to be contained in the core. The matrix is not glassy. This rock was found near the contact between normal basaltic rock and glassy andesite. X-nicols. Width of field 1.9 mm.
- Figure 25. Photomicrograph of partly devitrified glassy andesite. A rounded quartz grain is surrounded by acicular and granular clinopyroxene. This type of grain usually results from the mixing of felsic and mafic magmas. X-nicols. Width of field 3 mm.

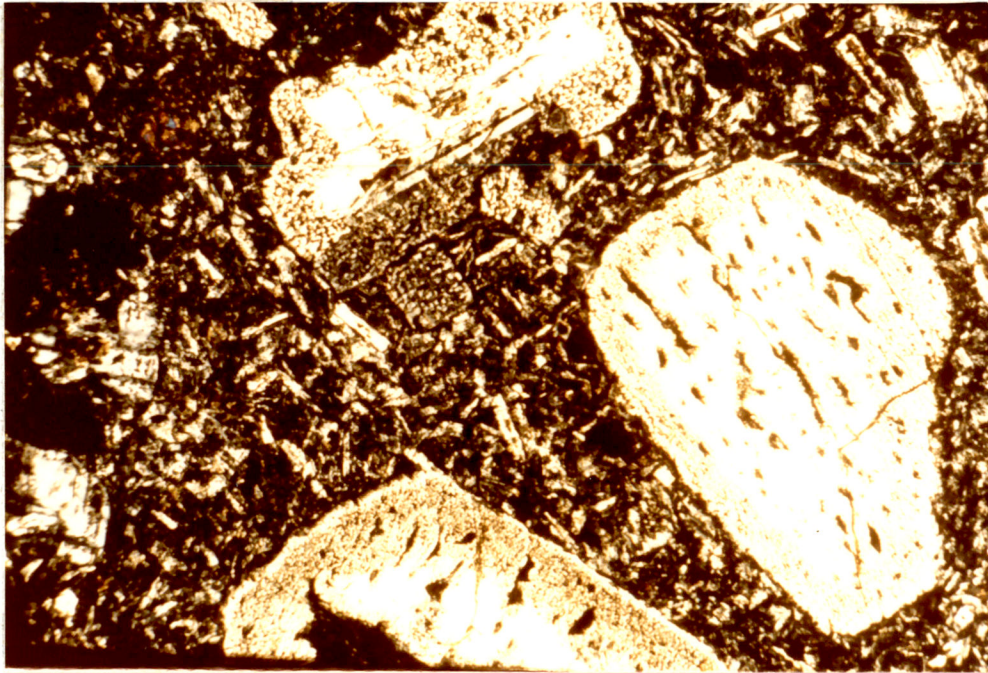


Figure 20.

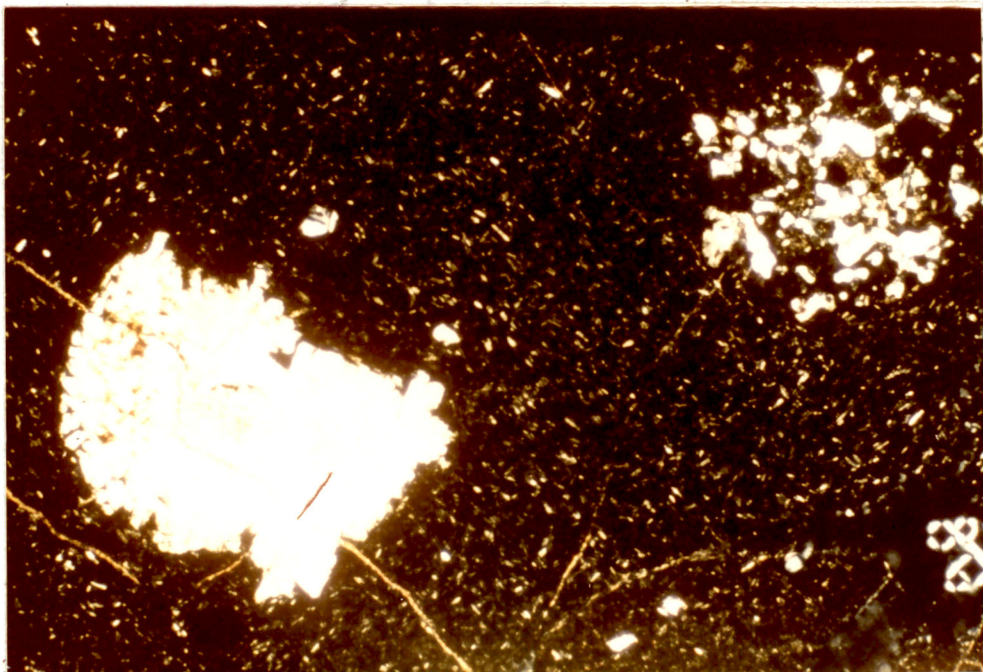


Figure 21.



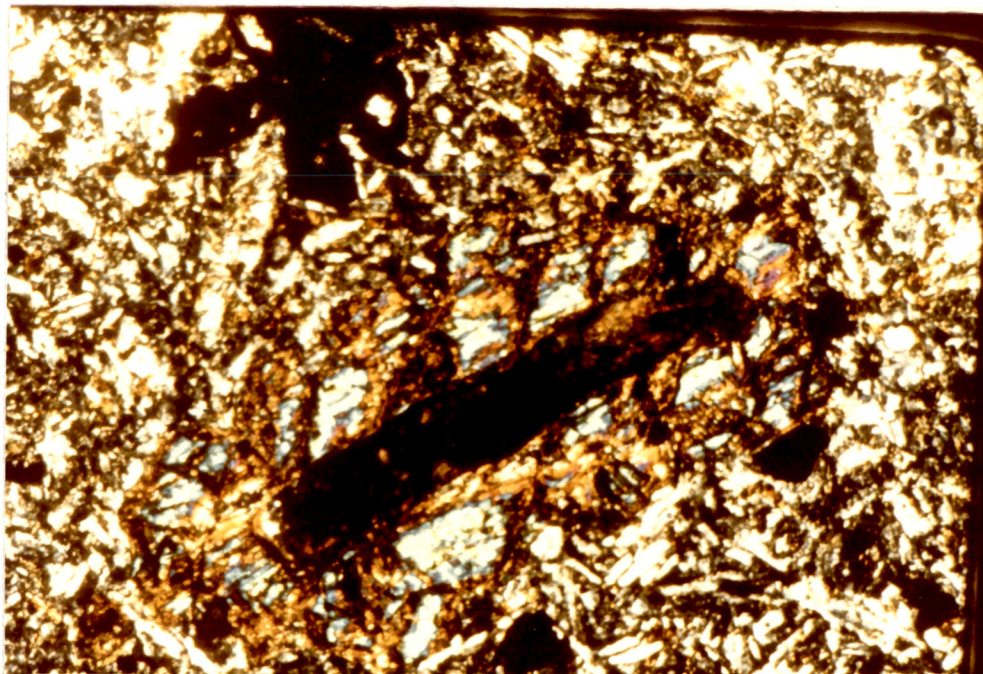


Figure 24.

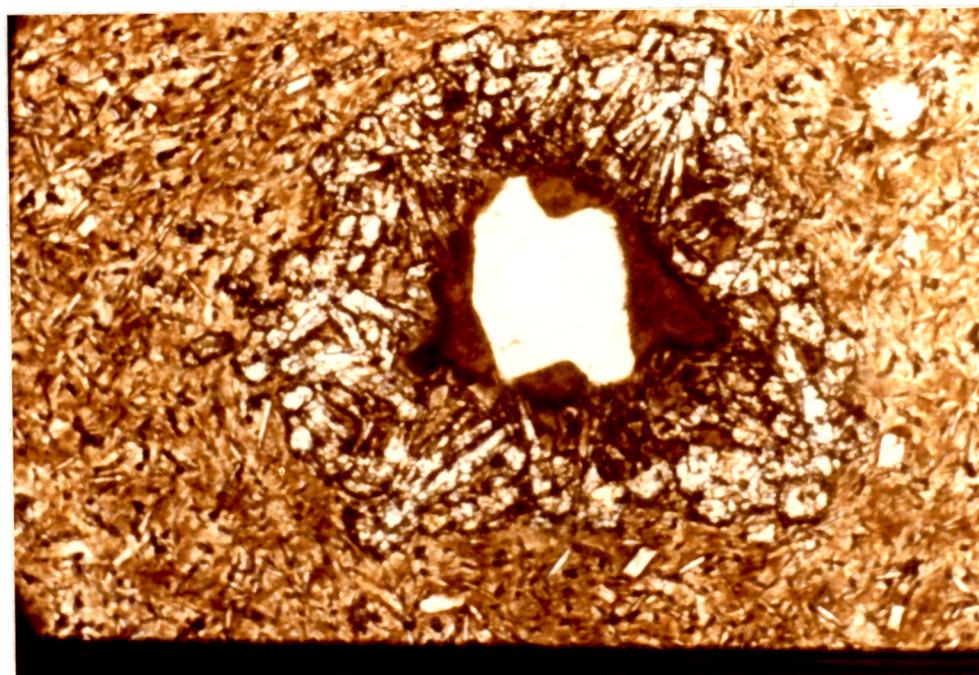


Figure 25.

Figure 26. View looking north from Canyon Santa Clara up the right side of Canyon Las Tapias. Columnar jointed Acantilado tuffs have been faulted three times; the downthrown side is toward the viewer. In the far background (left side), Acantilado tuff is overlain by cliff-forming Cryptic tuff breccia.

Figure 27. Photomicrograph of basal spherulitic Acantilado tuff showing embayment of quartz phenocrysts. Plane light. Width of field 1.2 mm.

Figure 28a. Photomicrograph of basal spherulitic Acantilado tuff. Shardy texture is prominent; shards are warped around phenocrysts. Large, rounded phenocryst is quartz; small phenocrysts are sanidine. Rusty colored areas are spherulites. Plane light. Width of field 2.6 mm.

Figure 28b. Same as 28a, nicols crossed. Radial and concentric textures of spherulites are seen better. Groundmass is fine-grained granophyric. Width of field 2.6 mm.





Figure 26.

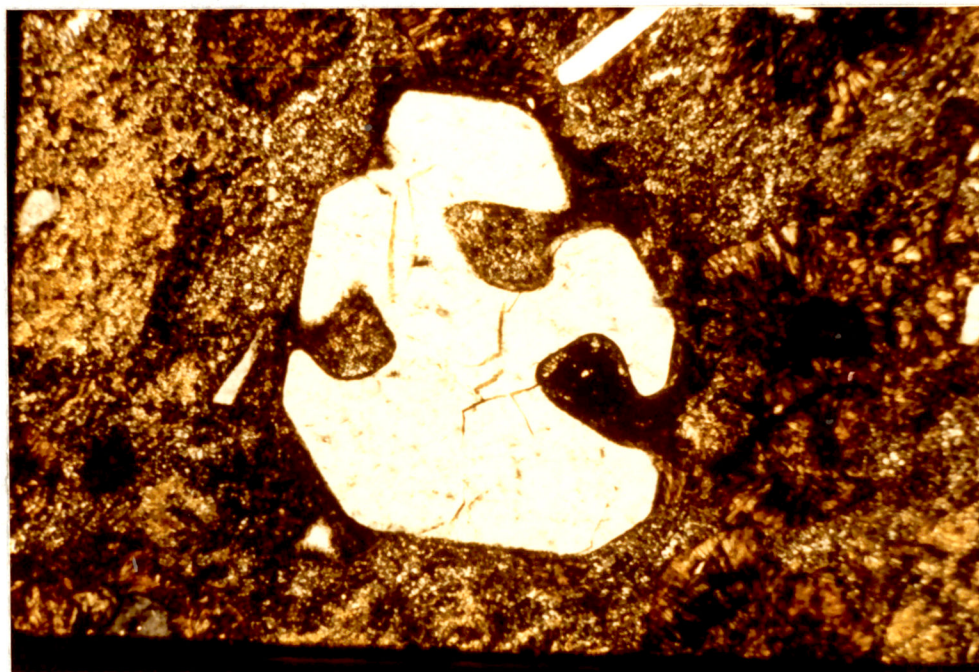


Figure 27.



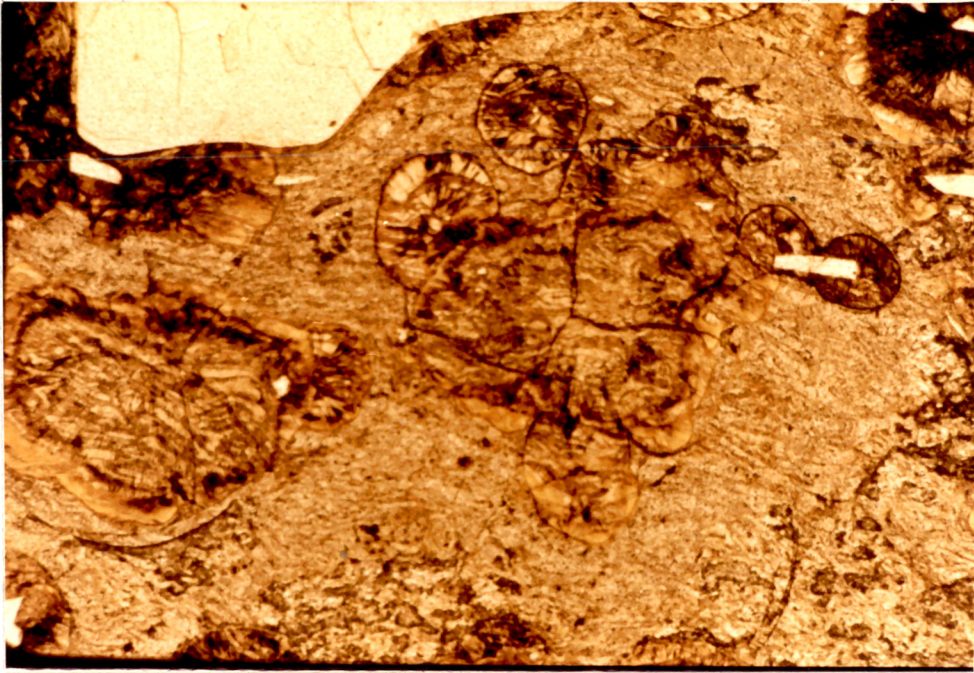


Figure 28a.

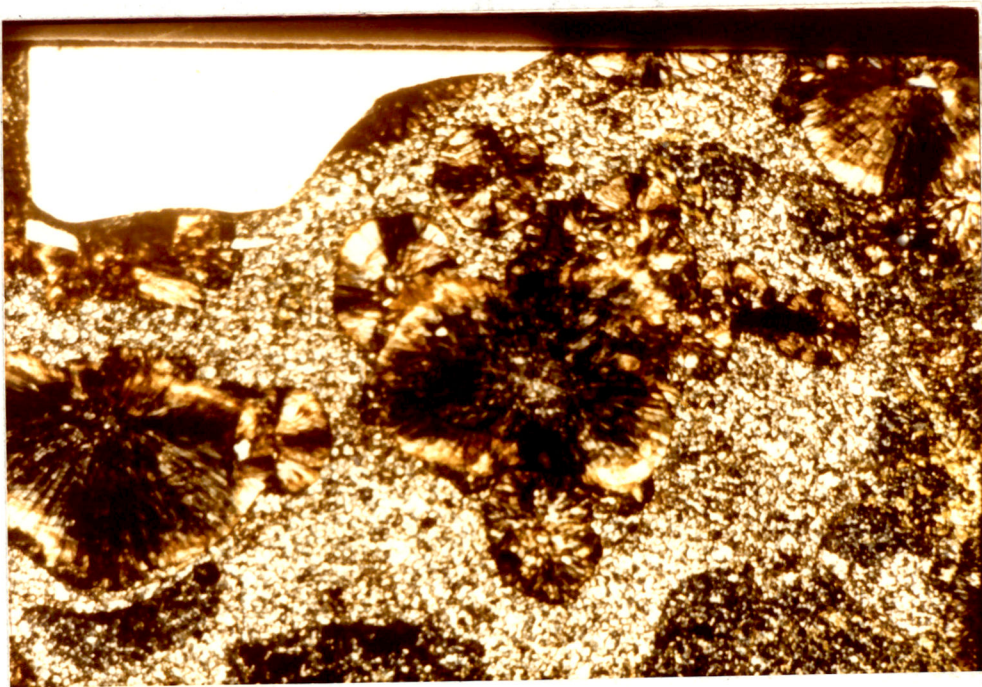


Figure 28b.

Figure 29. Acantilado tuff exhibits a break in texture. This is one cooling unit; however, the degree of welding decreases upward, as illustrated here.

Figure 30. Photomicrograph of Acantilado tuff, middle zone. The matrix has a coarsely granophyric texture. Lithophysal cavity contains fluorite (black) in center and sanidine phenocryst on left. X-nicols. Width of field 2.6 mm.

Figure 32. Photomicrograph of glassy Cryptic tuff. Sanidine microlites have split tails. This is considered to be typical during the initiation of spherulitic development. Spherulites occur elsewhere in this thin section. X-nicols. Width of field 0.04 mm.

Figure 35. Photomicrograph of spherulitic Cryptic tuff. Spherulites are asymmetric, protrusions indicating a breach in the impurity layer during growth. Dark phenocrysts in the center is sanidine. X-nicols. Width of field 2.6 mm.





Figure 29.

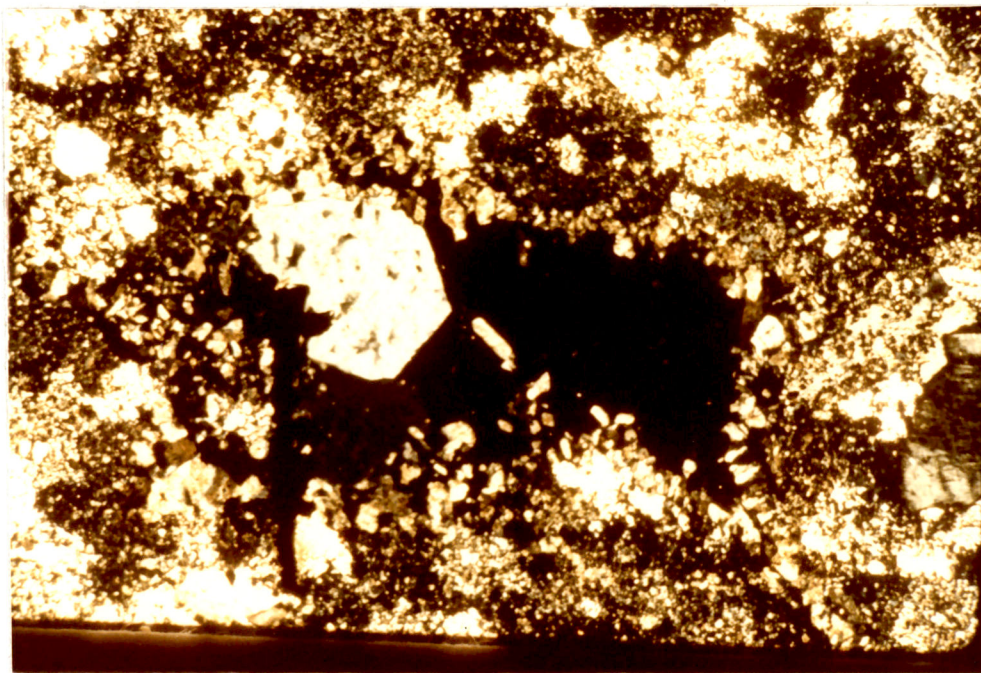


Figure 30.



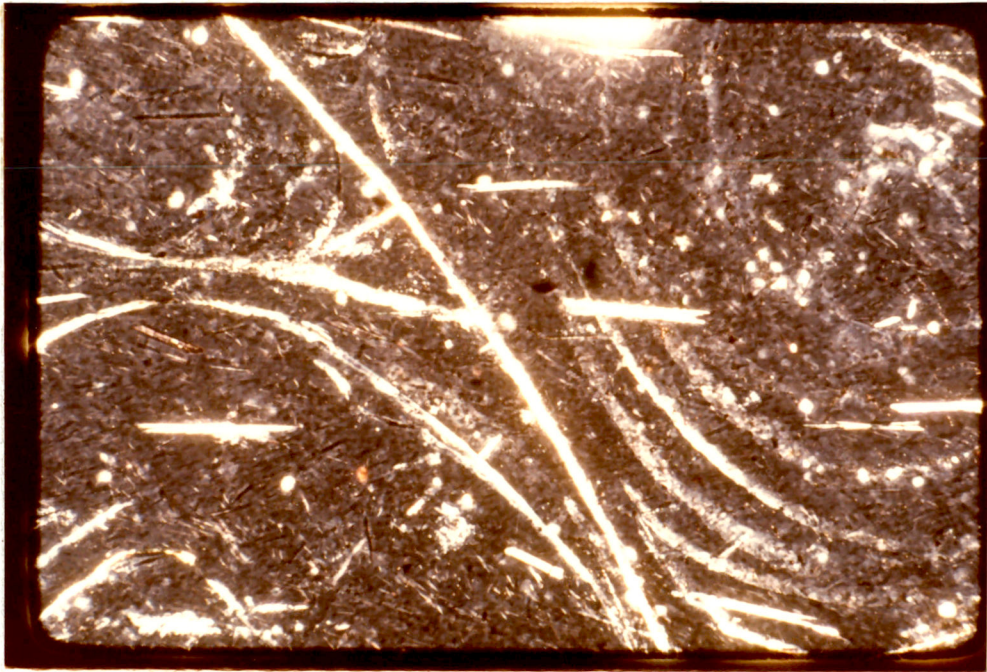


Figure 32.

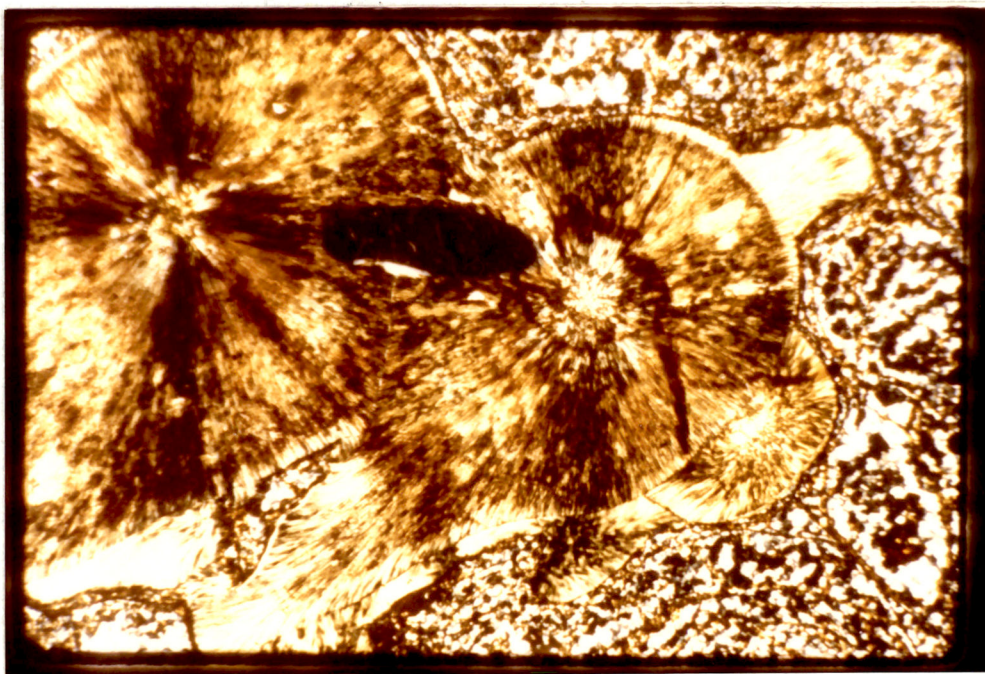


Figure 35.

Figure 36. Photomicrograph of spherulitic Cryptic tuff. Triple junctures are well developed. Devitrified glass fills interstices. X-nicols. Width of field 3 mm.

Figure 37. Photograph of thin section containing Cryptic tuff spherulites. The radial and concentric structure of the spherulites is observed. Impinging orbs produce triple junctions. The matrix is devitrified glass. Plane light. Width of field 35 mm.

Figure 38. Photograph of thin section showing glassy Cryptic tuff lapilli in glassy matrix (No. 41). A vague foliation is seen. Glassy fragments show different degrees of flowage. This rock has not undergone flowage. The large, light-colored, lithic fragment in the lower left corner is a rounded piece of riebeckitic micro-poikiolitic Cryptic tuff. It is surrounded by a yellowish devitrification zone. Two yellow spots in an elongate brown lapilli above the lithic are spherulites which are connected to the crystallized lithic fragment by thin devitrification veins. Plane light. Field of view 35 mm.

Figure 39. Photomicrograph (No41) of glassy Cryptic tuff. Foliation is much clearer than in Figure 38. Bubble trails(?) can be seen in the central light-colored fragment. Many fragments are very ragged. A highly flow-banded fragment can be seen in the right center. Plane light. Field of view 6.8 mm.



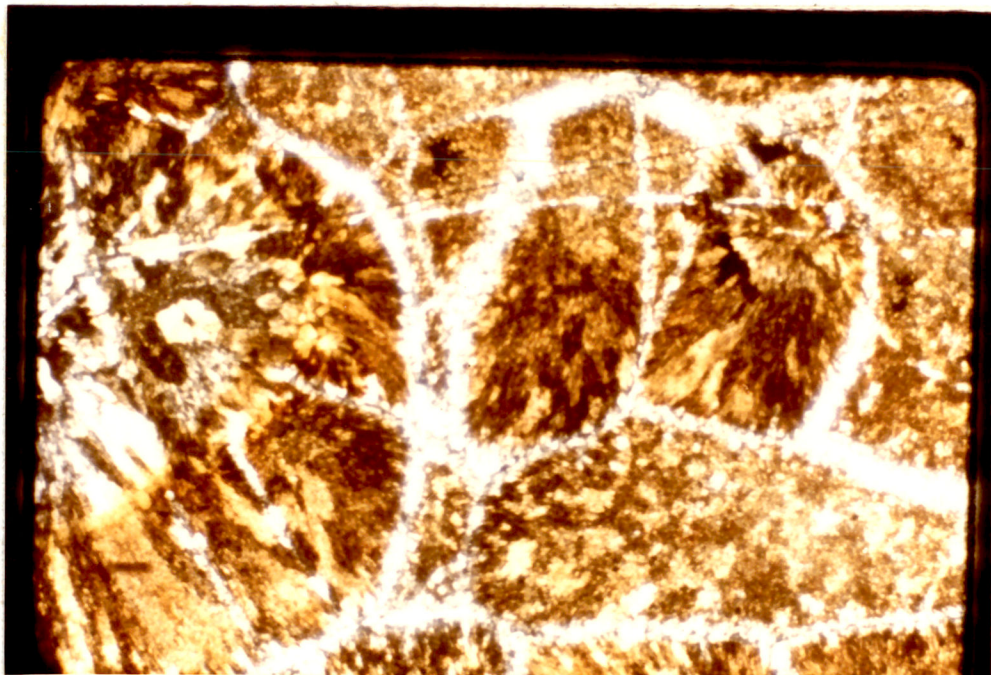


Figure 36.

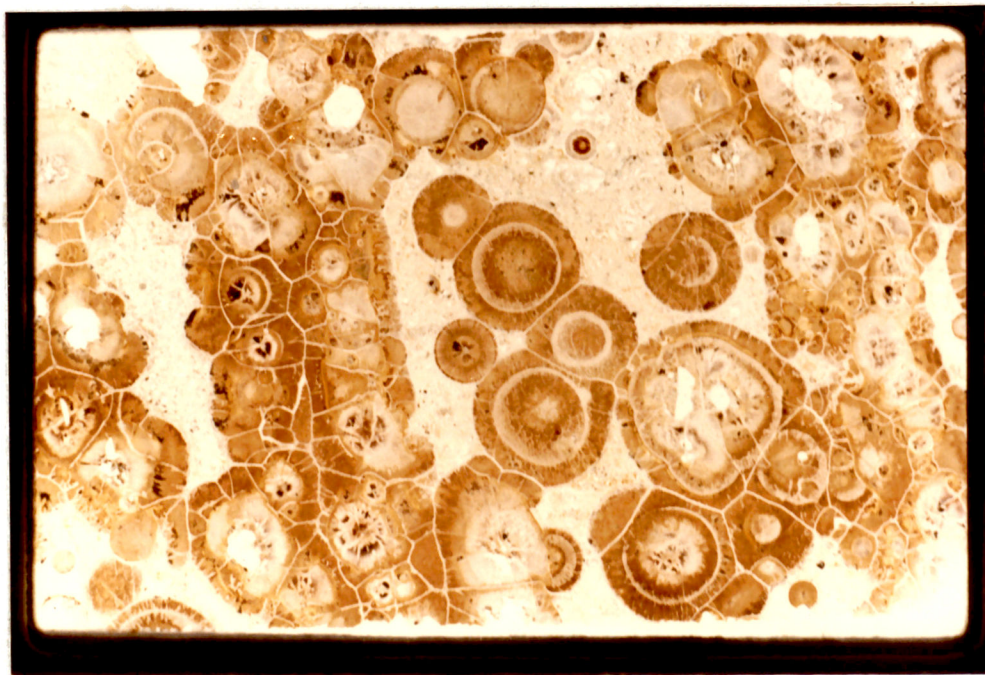


Figure 37.



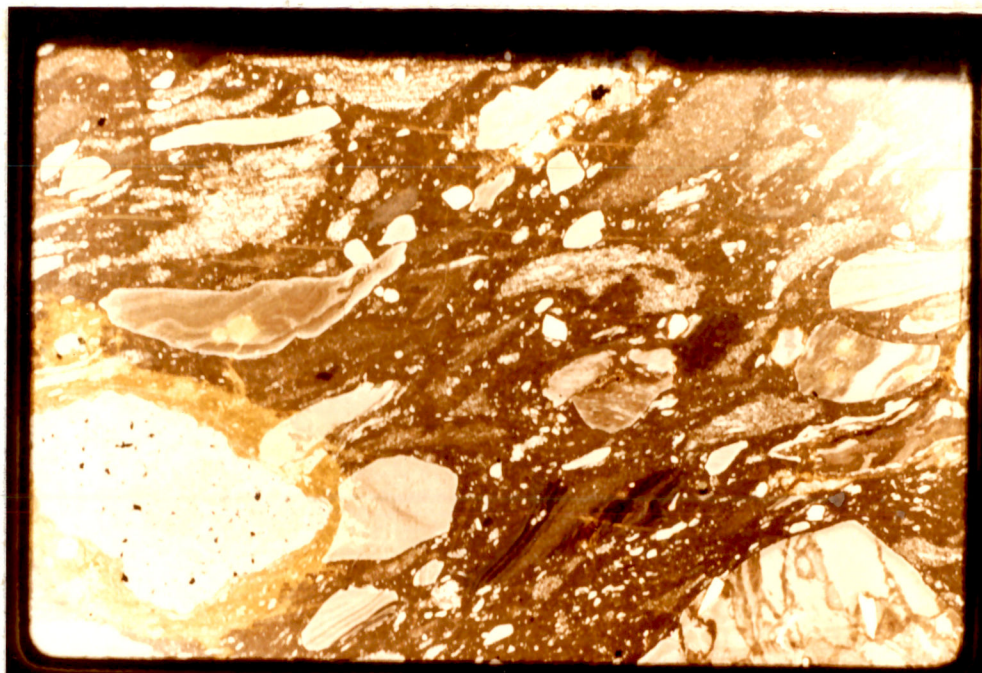


Figure 38.

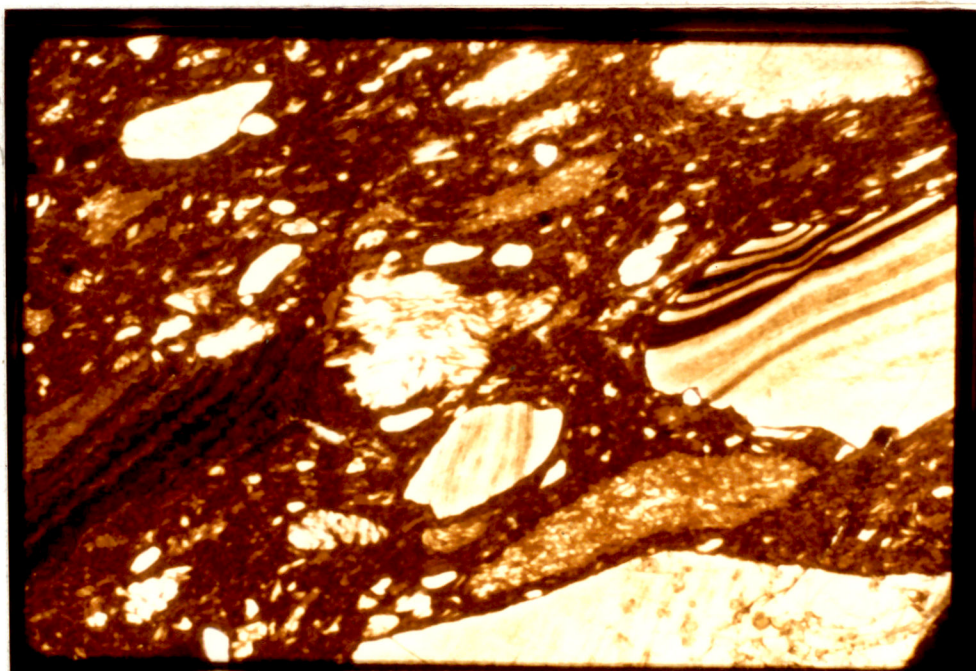


Figure 39.



Figure 40. Photomicrograph (No.41) of glassy Cryptic tuff. The phenocryst is a euhedral hedenbergite. Shards wrap around phenocryst and show thin, dark borders of dust. The large, clear glassy fragment in the upper right corner contains unoriented microlites suggesting a lack of flowage in the fiamme. Plane light. Field of view 1 mm.

Figure 41. Photomicrograph of glassy Cryptic tuff. Shards and lapilli are extremely elongated. Numerous ramp structures or oblique thrusts emanate from a complexity of shear surfaces. Perlitic cracks are seen. Plane light. Field of view 1.2 mm.

Figure 42. Photomicrograph of glassy Cryptic tuff. Elongated shards wrap around euhedral hedenbergite. A pressure zone on the left side of the phenocrysts and pressure shadow or eddie on the right indicate flowage from left to right (Schmincke and Swanson, 1967; Cummings, 1964). Perlitic cracking is obvious. Plane light. Width of field 1.2 mm.

Figure 43. Photograph of glassy Cryptic tuff. This glass shows the complete obliteration of lapilli and shards by laminar flowage. Shear folds occur in lower left corner. Flow bands bend around sanidine phenocrysts. Black areas are concentrations of microlites and devitrification features. Plane light. Width of field 35 mm.

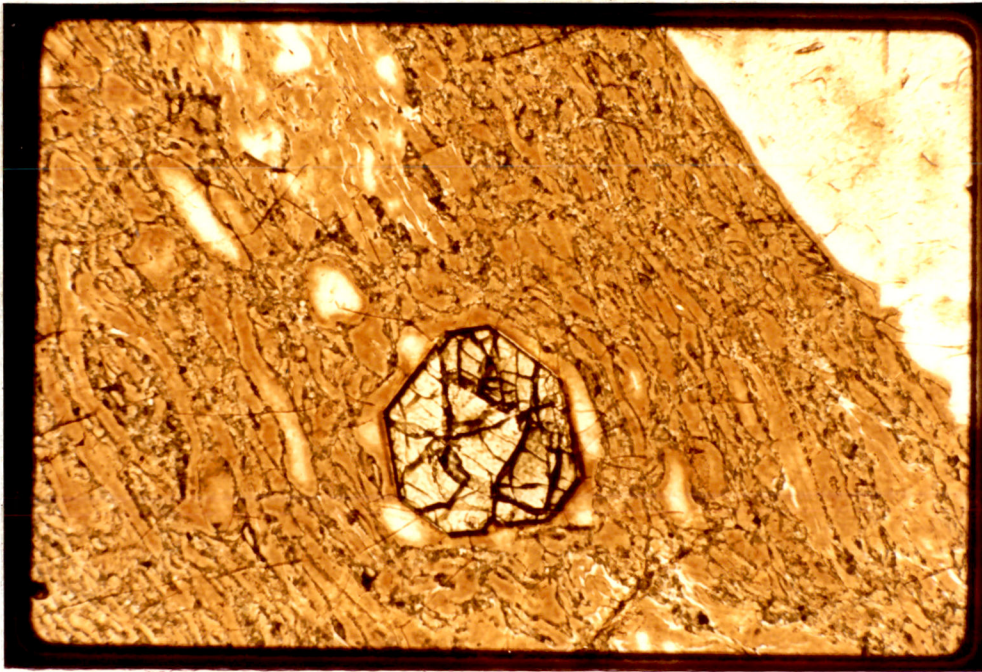


Figure 40.



Figure 41.



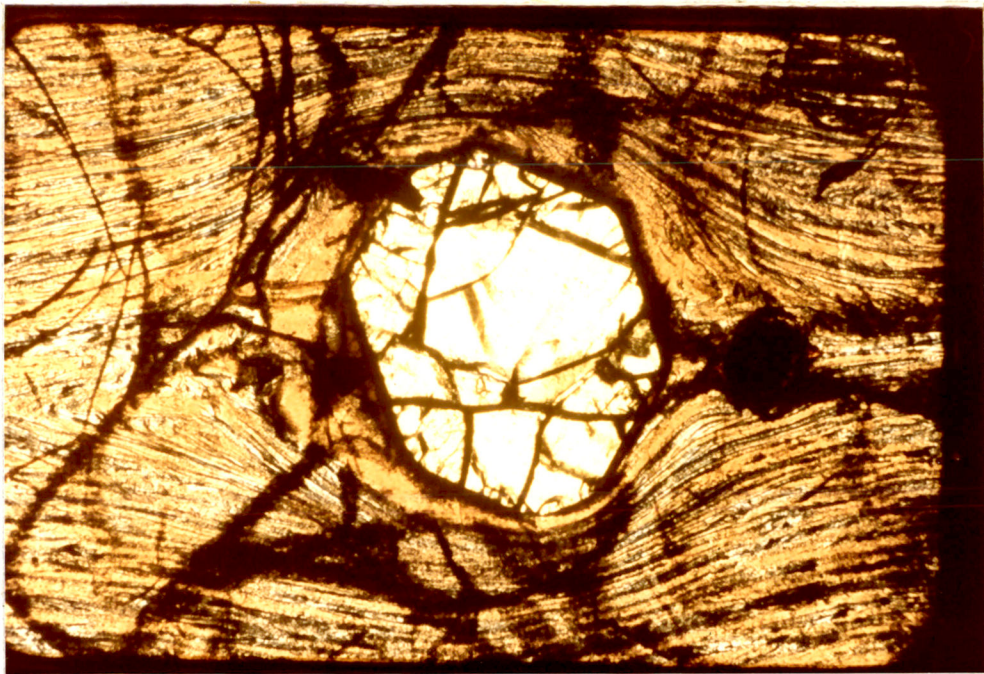


Figure 42.

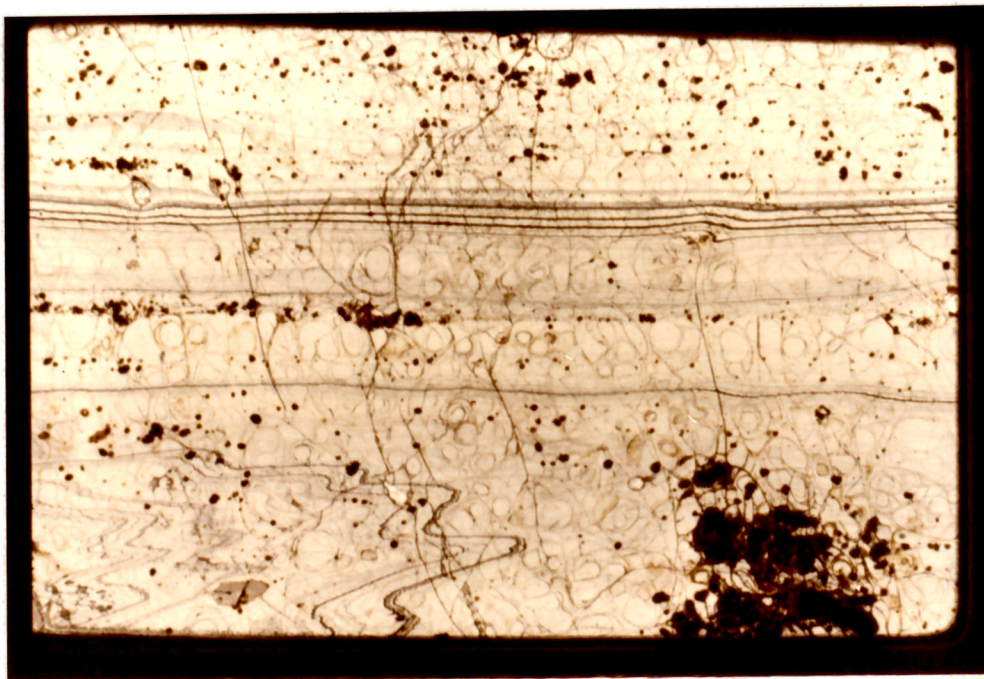


Figure 43.

- Figure 44. Photomicrograph of glassy Cryptic tuff. Photograph of lower left corner of Figure 43 shows shear folds and shear cleavage associated with flowage. Shear cleavage is well represented on the upper kink of the top fold. The progressive displacement along fractures by shearing produces thickening of layers at the apexes of folds and thinning along the limbs. Plane light. Width of field 6.8 mm.
- Figure 45. Photomicrograph of glassy Cryptic tuff (No. 59). Cracks in glass show progressive devitrification toward center. Spherulites occur along cracks. Dark material in cracks is also devitrification products. For composition of different colored glasses see Table 12. Plane light. Width of field 2.6 mm.
- Figure 46. Photograph of green Cryptic tuff cut parallel to bedding. Pumice lapilli show pronounced elongation parallel to the flow direction. Delicate white lines in lapilli are due to stretching.
- Figure 47. Photograph of green basal zone in Cryptic tuff. A series of compressed, imbricated, pumice lapilli are shown. Pumice lumps show stretching as does the matrix.



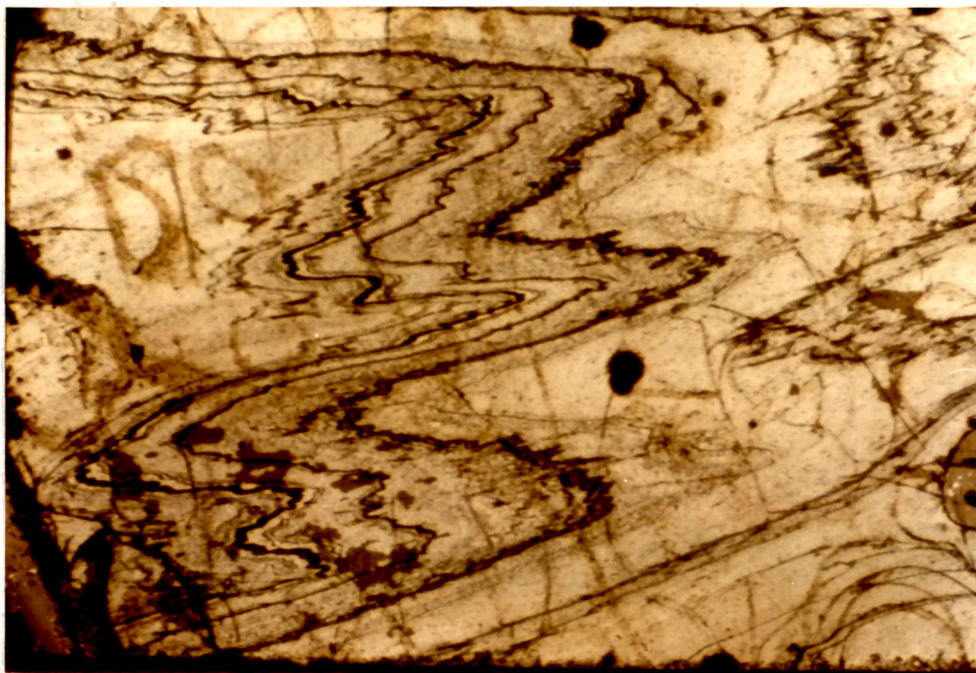


Figure 44.

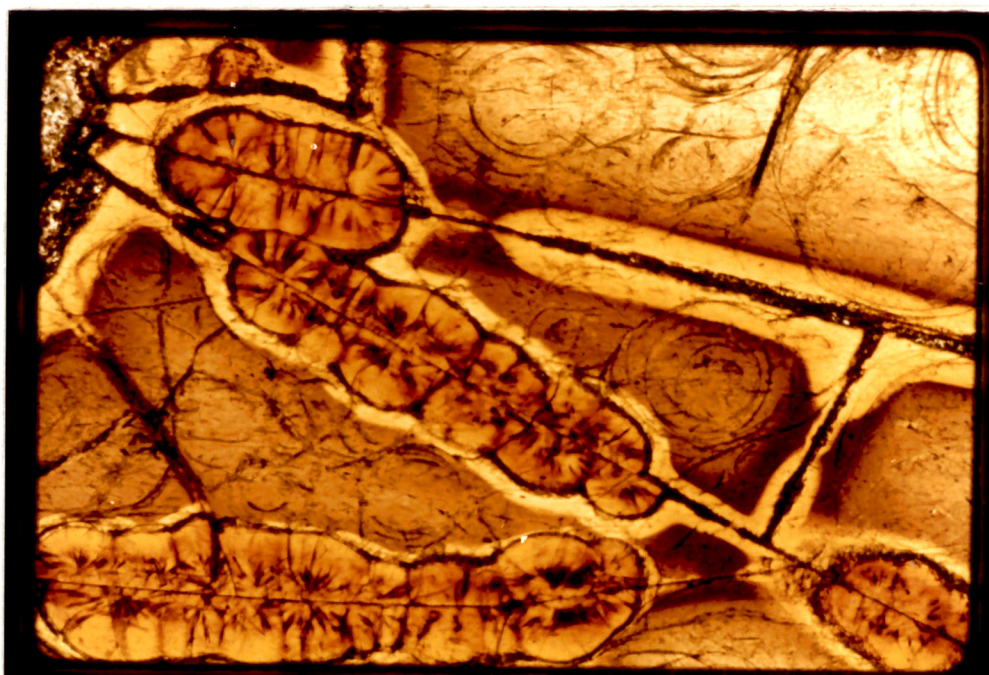


Figure 45.

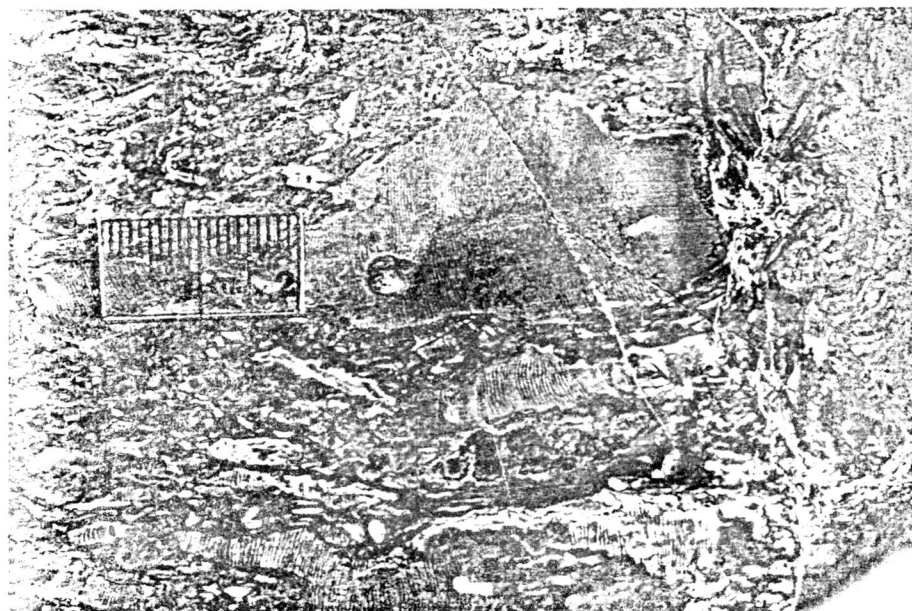


Figure 46.

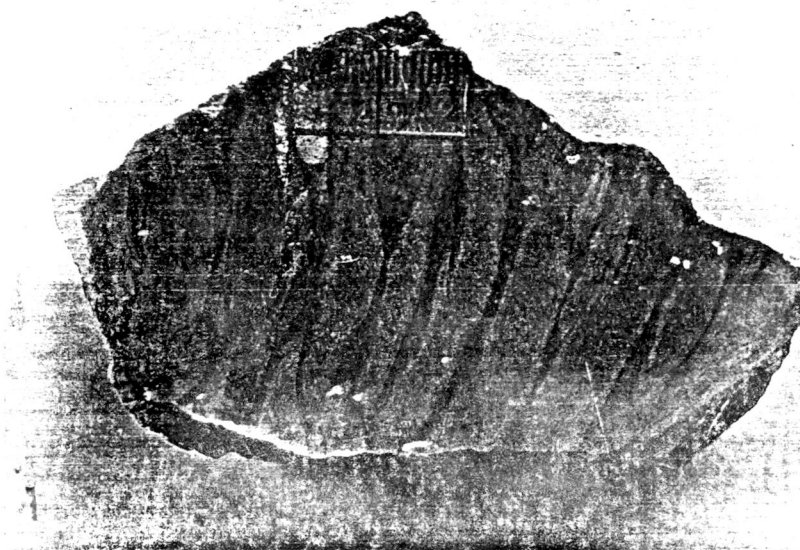


Figure 47.

Figure 48. Photograph of green Cryptic tuff thin section. Pumice lapilli are squashed and stretched. Section is cut perpendicular to bedding. Plane light. Width of field 35 mm.

Figure 49. Photomicrograph of green Cryptic tuff showing squashed and stretched pumice lapilli. Round or elliptical areas inside lapilli are due to postdepositional vesiculation. Plane light. Width of field 6.8 mm.

Figure 50. Photomicrograph of green Cryptic tuff, postdepositional-vesiculation cavity. Tiny crystals are aegirine. Plane light. Width of field 0.65 mm.

Figure 51. Photomicrograph of green Cryptic tuff showing postdepositional bubble trains in pumice lapilli. Bubbles do not extend past the lapilli boundary. Plane light. Width of field 6.8 mm.



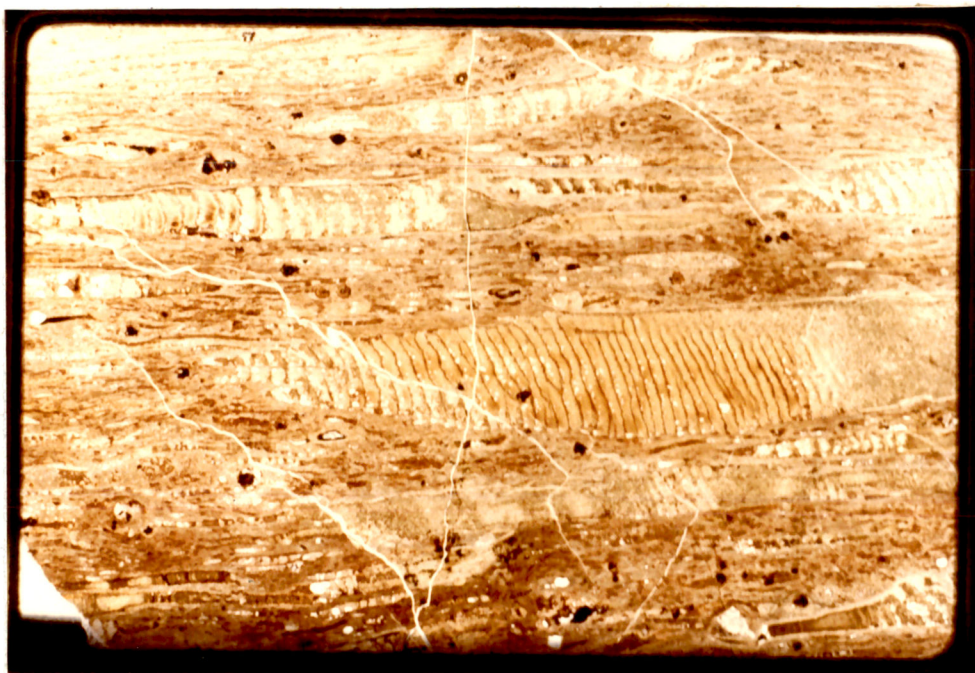


Figure 48.

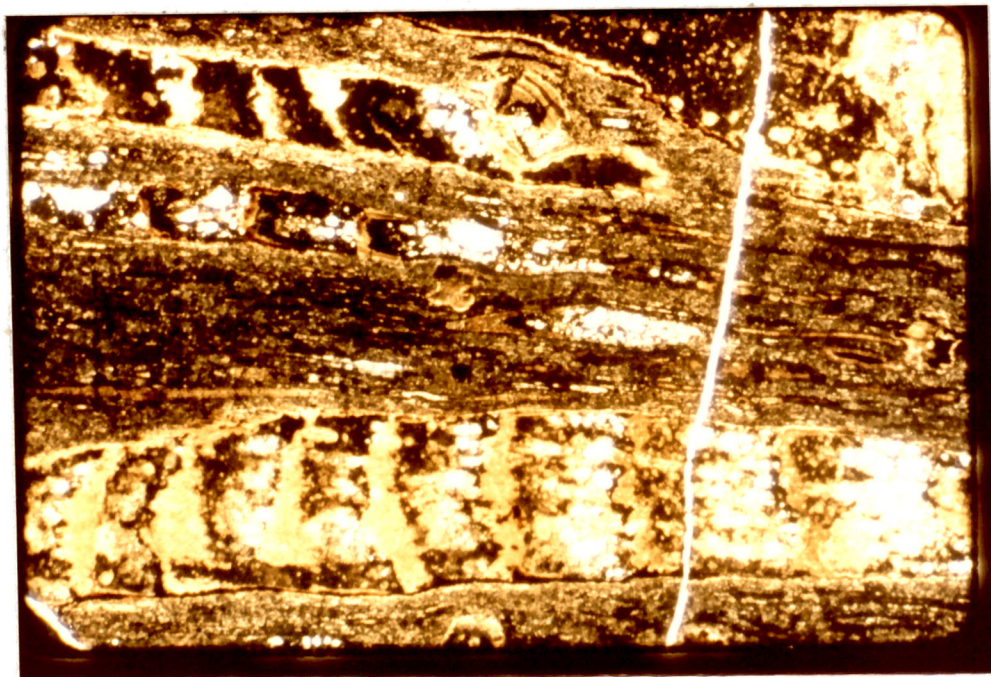


Figure 49.



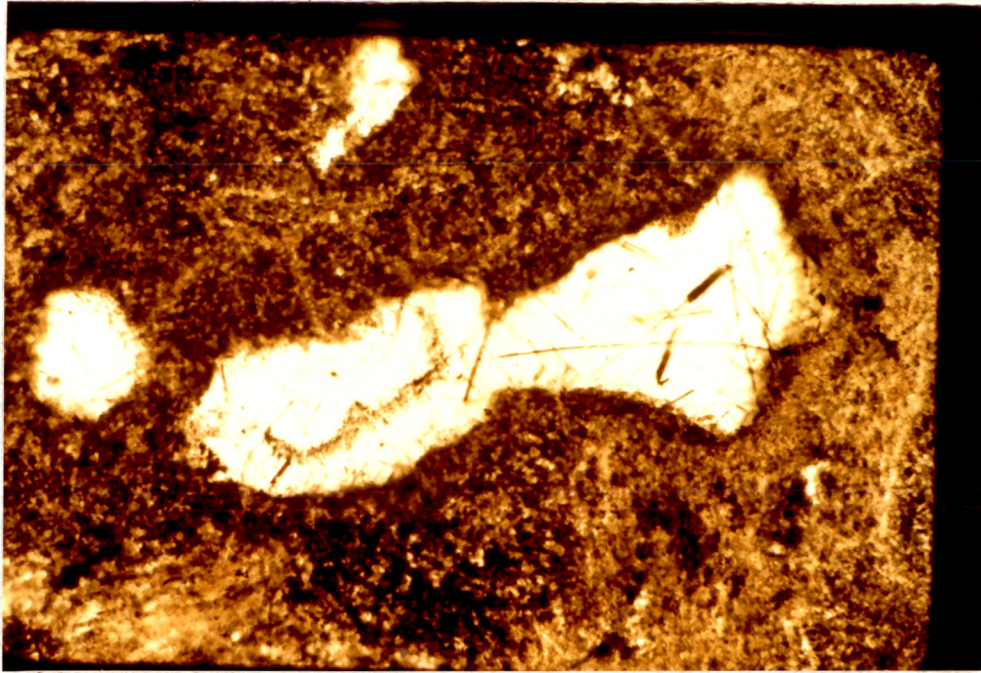


Figure 50.

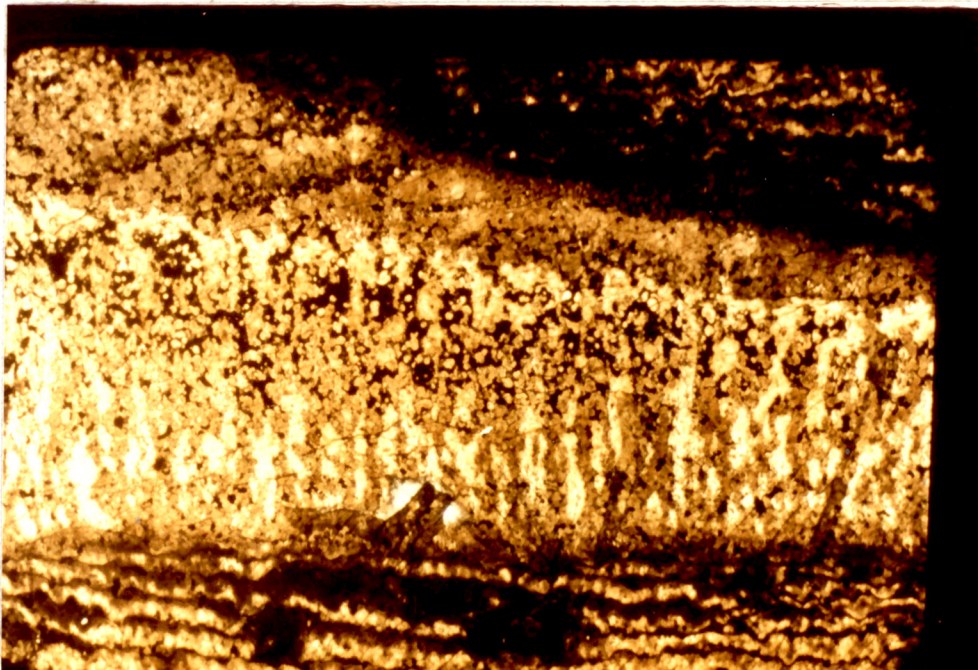


Figure 51.

Figure 52. Red, laminarly-flowed Cryptic tuff outcrops near the fault boundary in Canyon El Obscuro. Although the rock is highly fractured, a fold can be seen directly above the hammer.

Figure 53. Photograph of red Cryptic tuff thin section illustrating shear folding. The rock is completely devitrified and phenocrysts of sanidine are altered. Tension cracks trend horizontally across the photo and across the fold axes. These cracks would have formed after the folds were established but before final movement had taken place. Plane light. Width of field 35 mm.

Figure 54. Photomicrograph of "frothy" Cryptic tuff. Shards are not highly compressed. Tan areas are open space. Tiny aegirine and hematite crystals protrude into the cavities. Plane light. Width of field 6.8 mm.

Figure 55. Photograph of miarolitic Cryptic tuff. Dark lamellae represent shardy layers, light layers with open spaces represent pumice lapillae. The cavities are lined with vapor phase, sanidine, aegirine, tridymite(?), and quartz.





Figure 52.

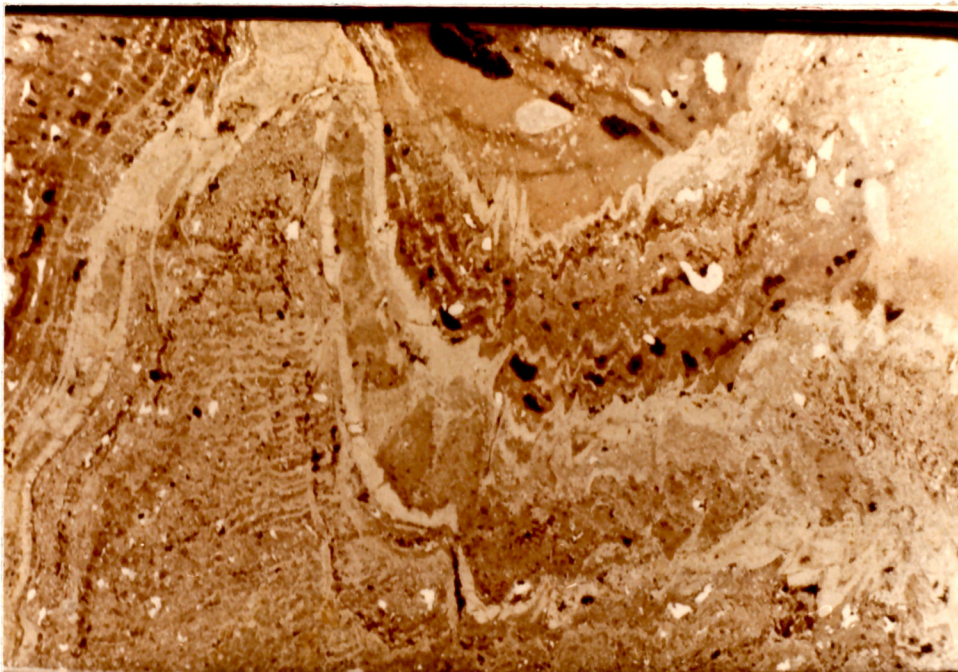


Figure 53.





Figure 54.

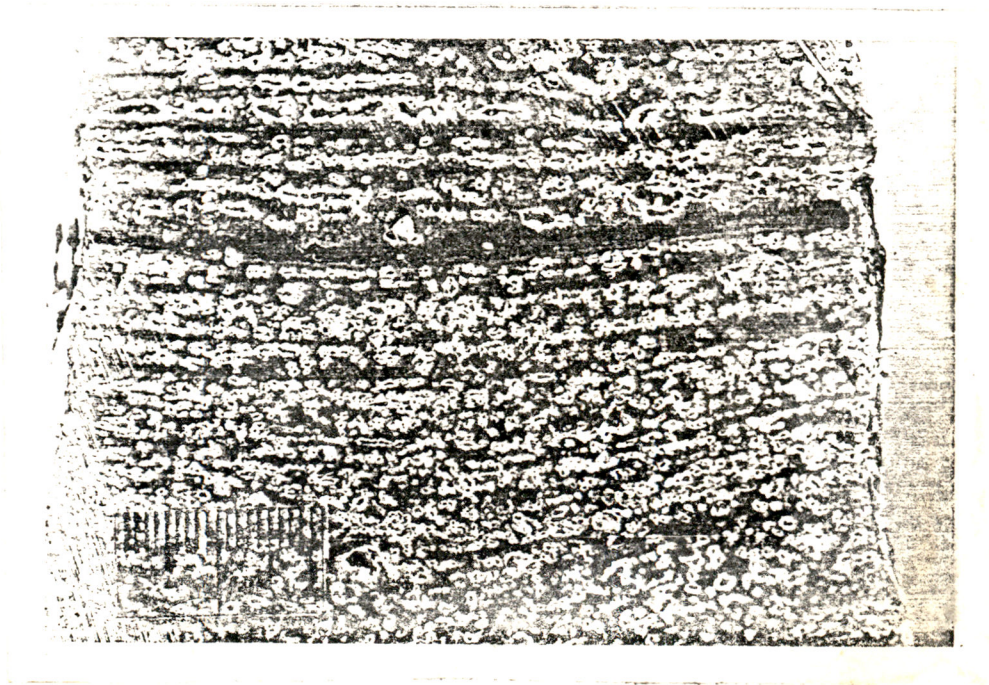


Figure 55.

Figure 56a and b. Photomicrographs of miarolitic cavity in Cryptic tuff. In plane light (a) sanidine and dark, altered aegirine project into the cavity. Aegirine needles and tabular aegirine grow in the cavity. Quartz and fluorite (high relief) fill the center of the cavity. In cross-polarized light (b) fluorite is black. Width of field 0.8 mm.

Figure 57. Photomicrograph of miarolitic Cryptic tuff. Spherulites of sanidine laths increase toward the open cavity across the upper middle of photo. An orb texture is developed in this type of rock. Tabular aegirine crystals perch on sanidine laths in central cavity. Inner portions of the aegirines are dark and cloudy. Quartz partly fills the void. x-nicols. Width of field 6.8 mm.

Figure 58. Photomicrograph of micropoikilitic, riebeckitic Cryptic tuff. These are unusually large patches of groundmass quartz. Even with x-nicols an orb texture is seen. As the quartz grew it pushed microlites and debris in front of the advancing crystalline front. The results is a mosaic of quartz crystallizations separated by lines of fine debris. Width of field 6.8 mm.



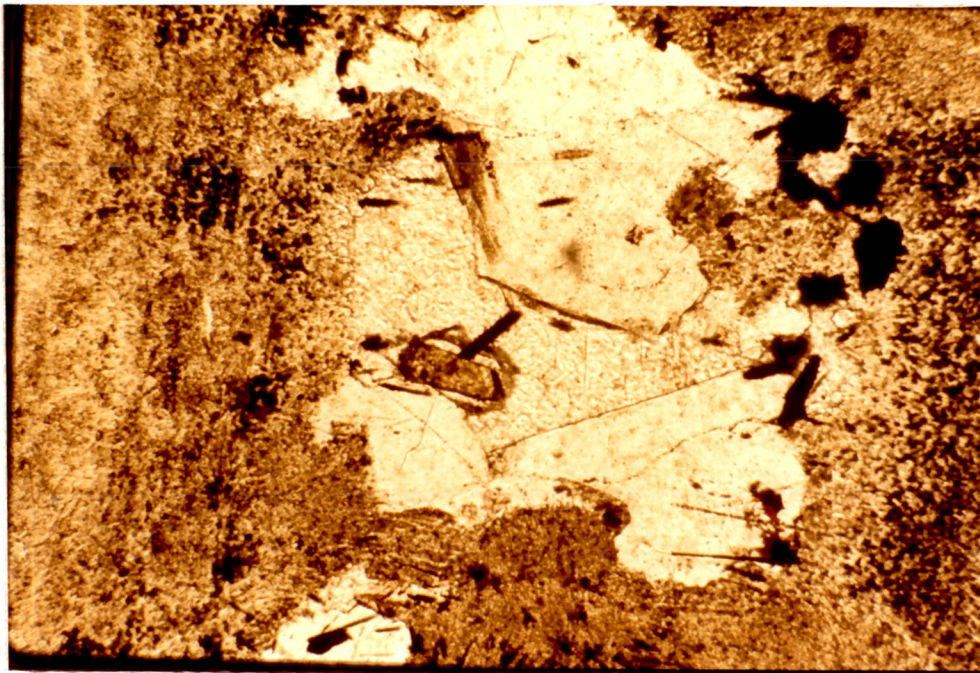


Figure 56a.



Figure 56b.



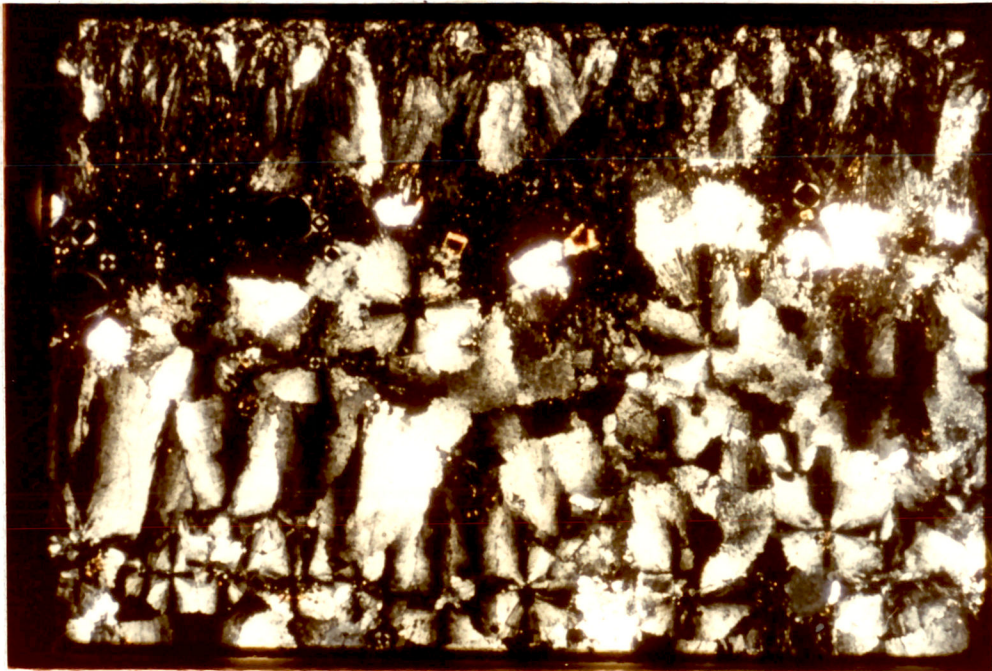


Figure 57.

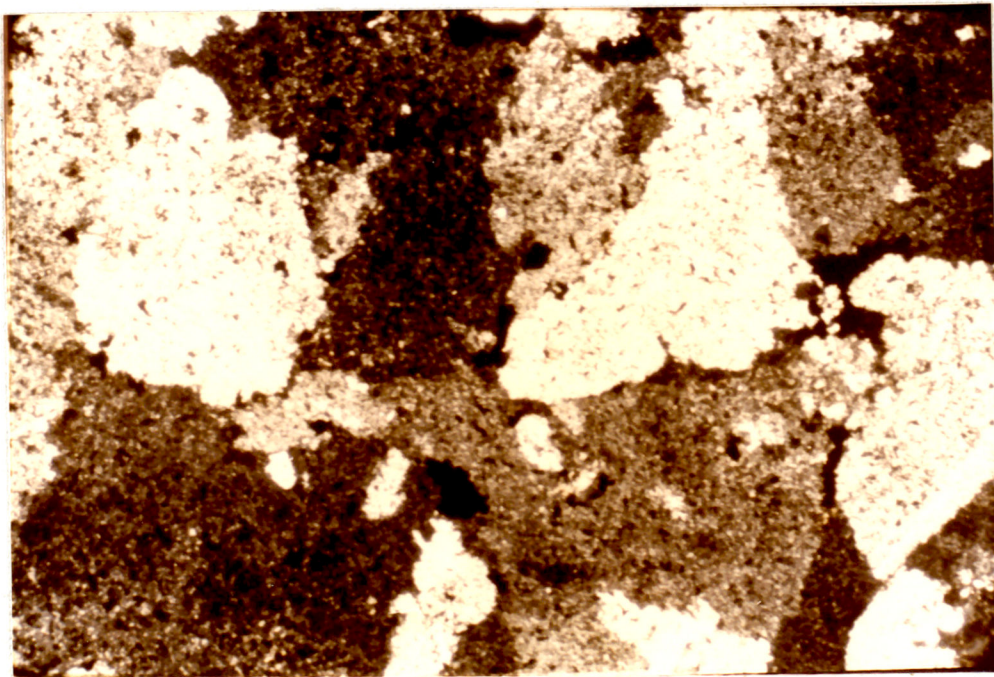


Figure 58.



Figure 59. Photograph of upper micropoikilitic Cryptic tuff near gradational contact with micropoikilitic riebeckitic Cryptic tuff. Light areas are pumice rich and are more porous than dark layers. Laminae wrap around lithic fragments of micropoikilitic riebeckitic Cryptic tuff. A crude lithophysa is seen on left side of sample. Tiny dark traces that cut across bedding probably represent bubble trails from post-depositional vesiculation.

Figure 60. Photograph of micropoikilitic, riebeckitic Cryptic tuff. Rock is cut perpendicular to bedding (flowage); a foliation can be seen. The dark specks are groundmass riebeckite, aegirine, fayalite, and aenigmatite(?).

Figure 61. Typical looking micropoikilitic, riebeckitic Cryptic tuff. The greenish mafics are mostly riebeckite, darker areas are altered aegirine of fayalite plus minor aenigmatite. Plane light. Width of field 6.3 mm.

Figure 62a and b. Photomicrographs of micropoikilitic, riebeckitic Cryptic tuff. In plane light (a) the coarse spherulitic groundmass is apparent. Groundmass mafics often form the core of spherulites. With nicols crossed (b), the micropoikilitic groundmass texture becomes clear. A hedenbergite phenocryst is seen in the lower middle of the photograph. Width of field 2.6 mm.

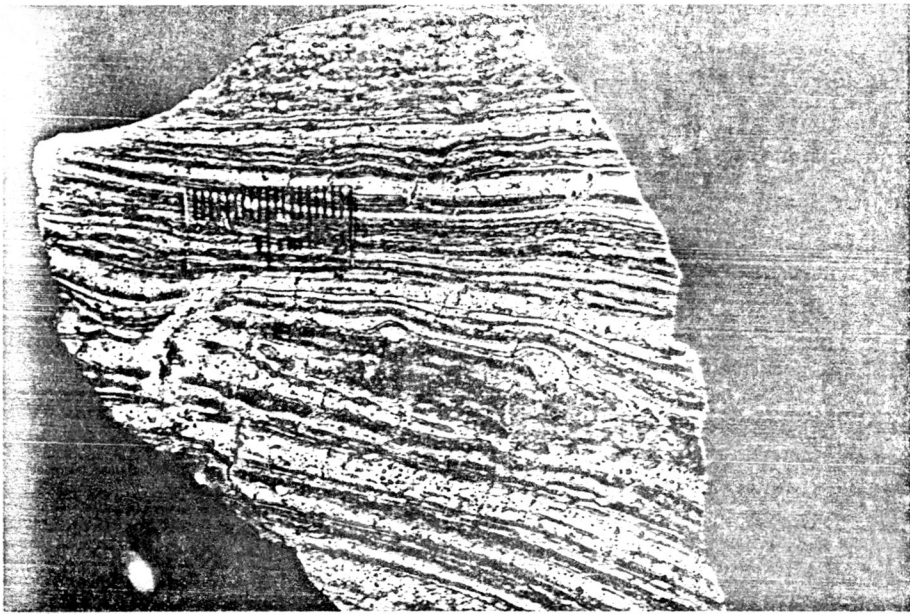


Figure 59.

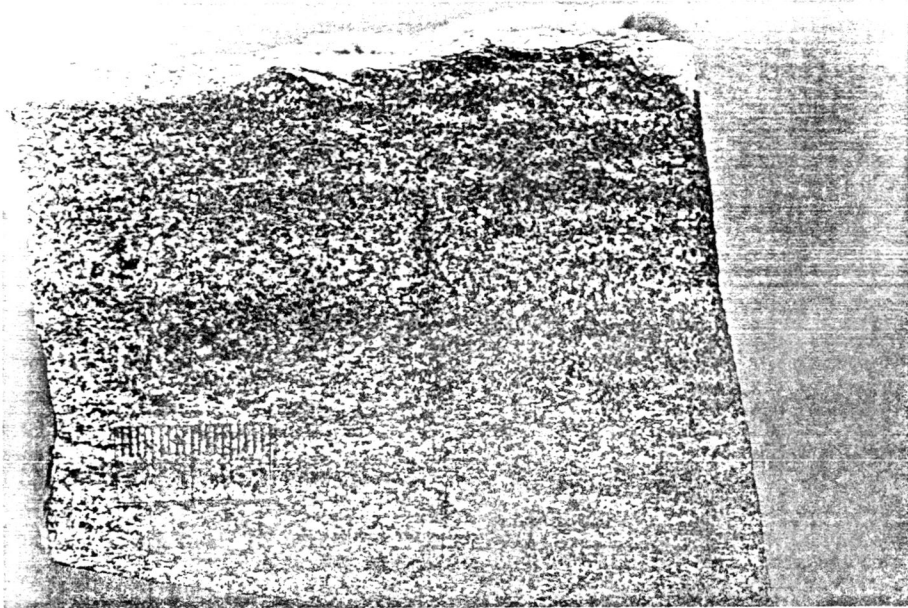


Figure 60.

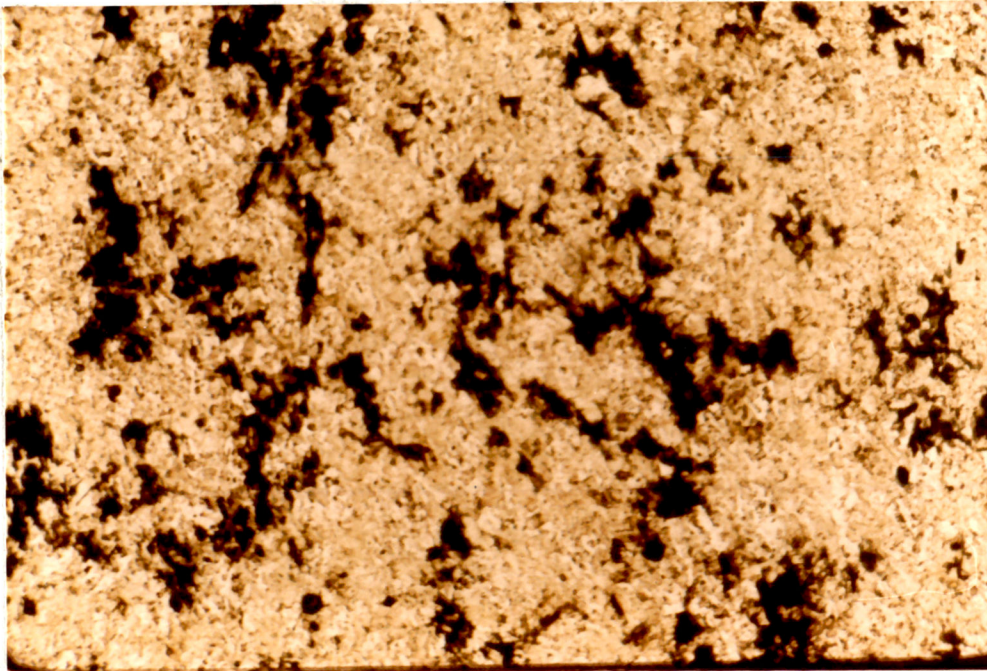


Figure 61.

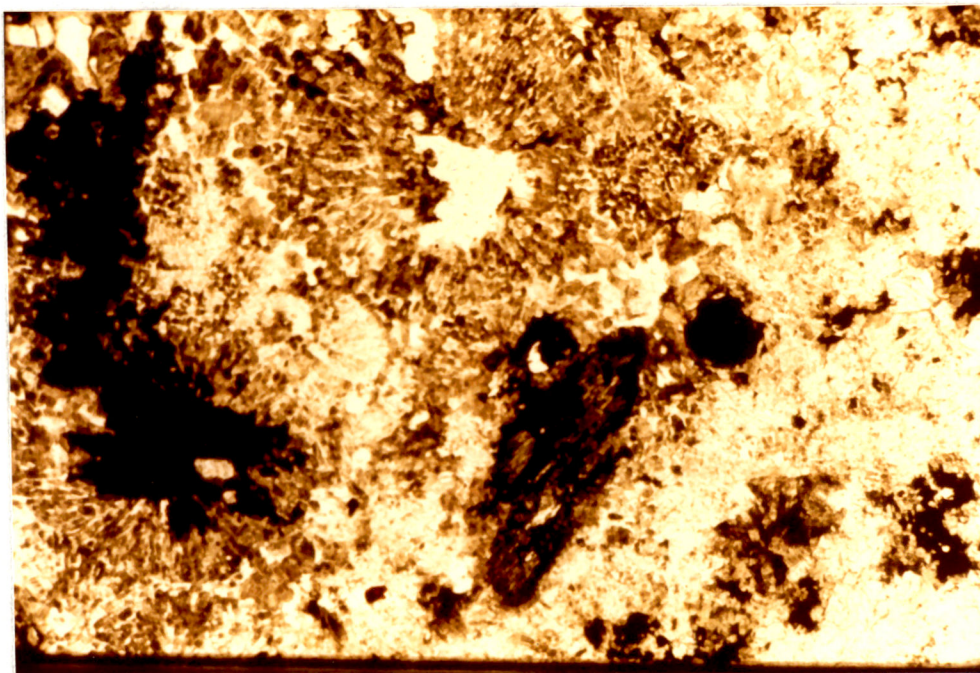


Figure 62a.

Figures 62a and b. Photomicrographs of micropoikiolitic, riebeckitic Cryptic tuff. Under plane light (a) the core of a coarse-fiber spherulite is seen. The dark minerals are probably altered fayalite associated with riebeckite. Farther out from the core a green, Na-rich amphibole forms some of the spherulite fibers. With nicols crossed (b) a highly birefrigent pyroxene (aegirine) can also be seen as part of the spherulite rays. The micropoikiolitic groundmass is easily seen. Width of field 0.8 mm.

Figure 64. This is a typical outcrop of the massive, riebeckitic Cryptic tuff. Buff colored, highly jointed rocks and rounded boulders are common weathering features. View is east from the first hill north of Canyon Santa Clara.



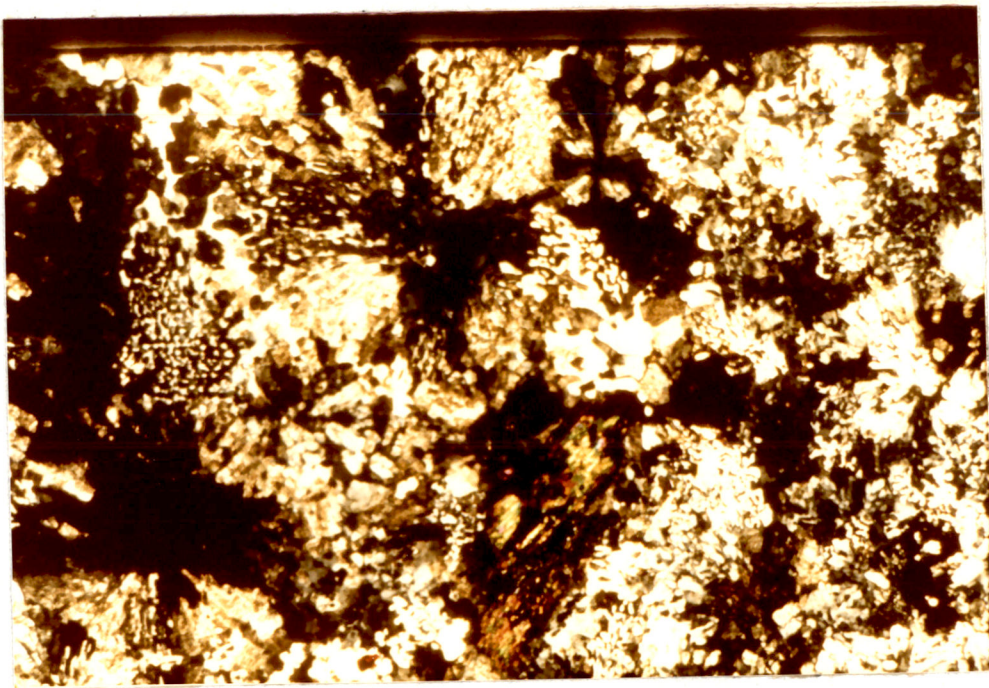


Figure 62b.

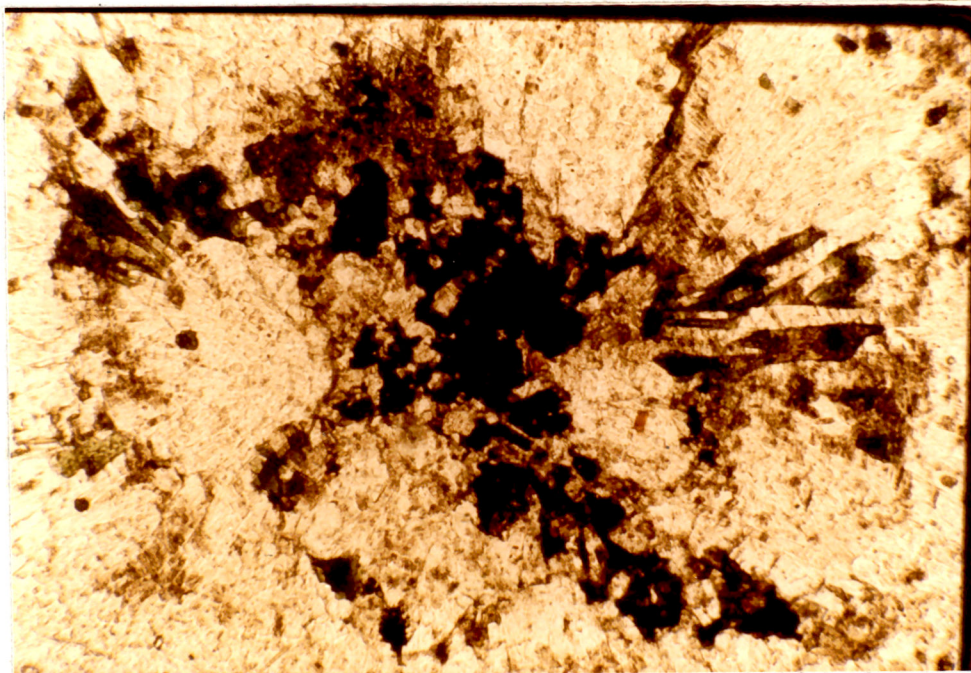


Figure 63a.



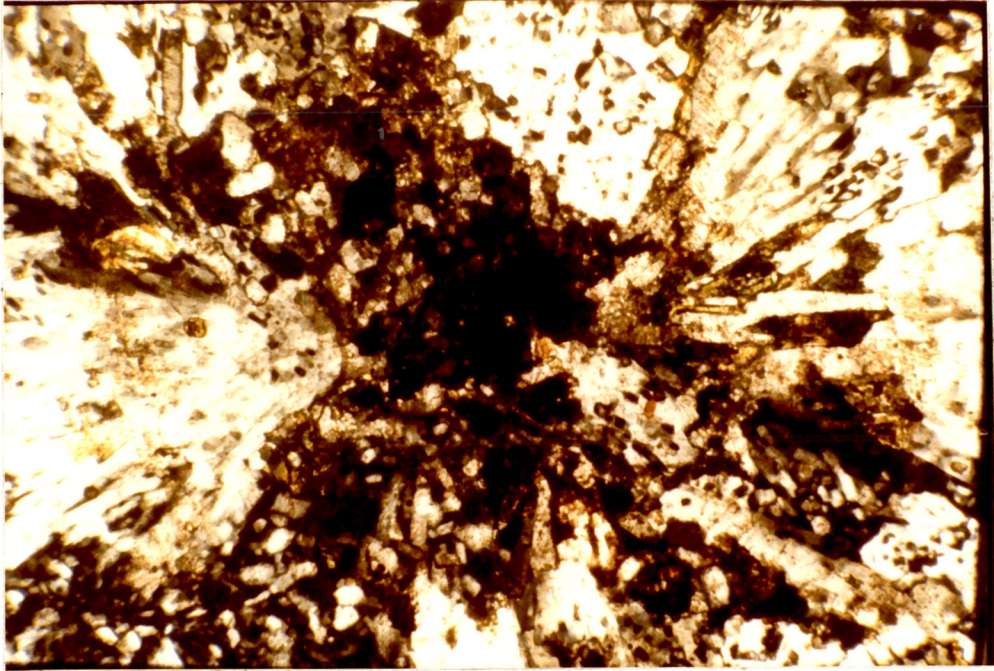


Figure 63b.



Figure 64.



- Figure 65. Photograph of lithic tuff or breccia in the Cryptic tuff sequences. Dark boulders are vitrophyre. Spherulitic, red flow-banded, miarolitic, and micropoikilolitic lithic fragments also occur in the breccia. Hammer handle is 25 cm long.
- Figure 66. Photograph of matrix-support vitric tuff or breccia found between successive Cryptic tuff cooling units. Lithic fragments in this specimen are mostly spherulites; however, red flow-banded lithics are more common. Notice 2 cm scale.
- Figure 67. Close view of Campana tuff. The blue color, prominent light-colored, squashed, pumice lapilli, and clumps of crystals are shown. Scale is in centimeters and inches.
- Figure 68. Lithic tuff from base of the Campana section (right side up). Welding increases from the base; lithic fragments become flattened and pore space disappears. Most dark lithic fragments are Cryptic tuff glass. The large lithic fragment in the top center is basalt.



Figure 65.



Figure 66.





Figure 67.

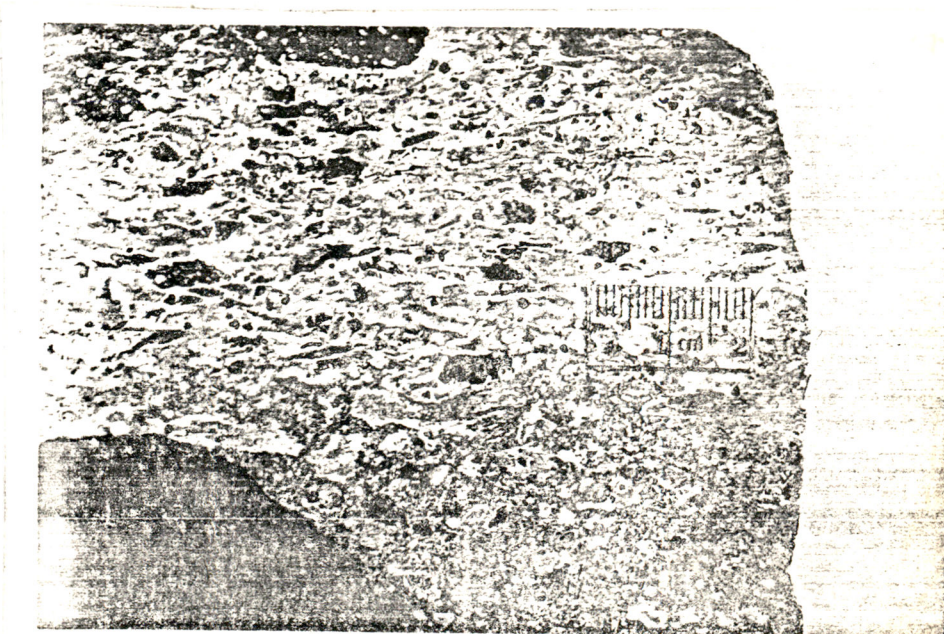


Figure 68.

Figure 69. Blue Campana tuff showing a concentration of phenocrysts and lithic fragments. This crystal-rich layer represents a crystal-rich (and lithic-rich) pumiceous mass that became squashed during compaction of the tuff. Most lithic fragments are micro-poikiolitic riebeckitic Crÿptic tuff.

Figures 70a and b. Photomicrographs of blue Campana tuff. In plane light (a) compressed pumice lapilli displays the axiolitic growth of aegirine needles and sanidine laths. The center of the squashed pumice lump contains dark tabular riebeckite crystals, quartz, and open space. Compressed shards are present in the groundmass. Under cross nicols a symplectic quartz/sanidine phenocryst is easily recognized. A diagonal break in crystallization suggests a twinned crystal. Sanidine and quartz were in equilibrium during the formation of this phenocryst. Width of field 2.6 mm.

Figure 71. Photomicrograph of middle zone, Campana tuff. Lapilli are compressed; many have ragged tails. Axiolitic textures are well developed.



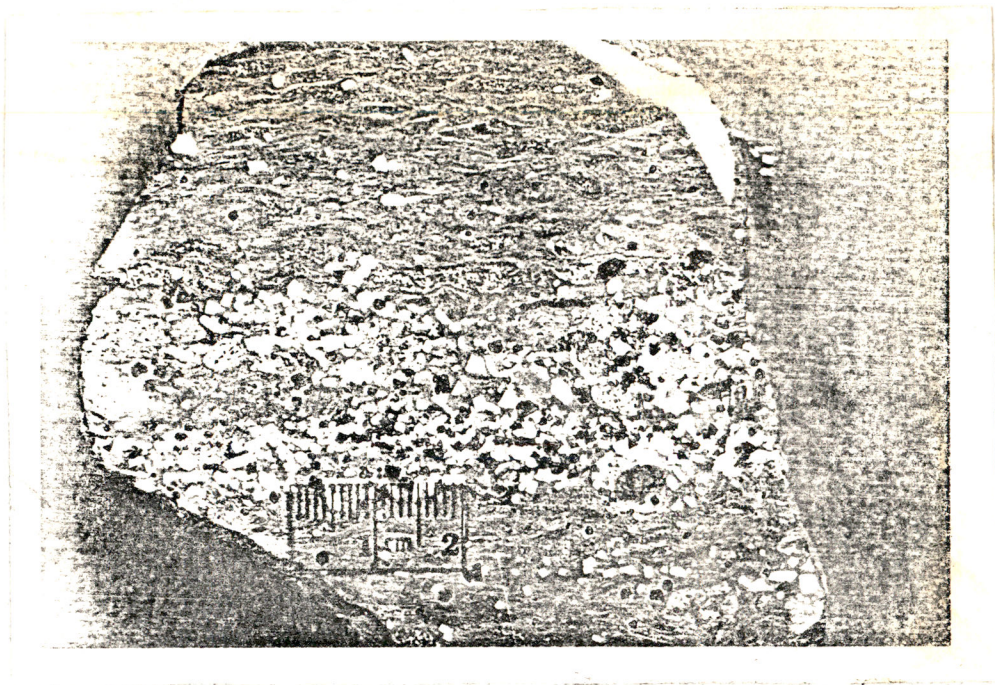


Figure 69.

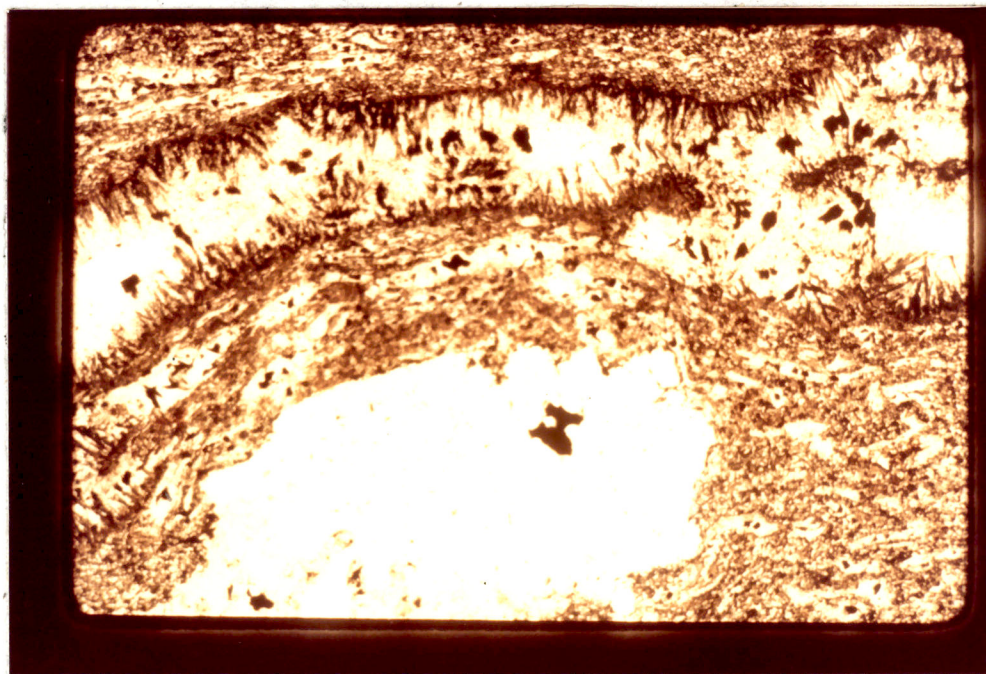


Figure 70a.



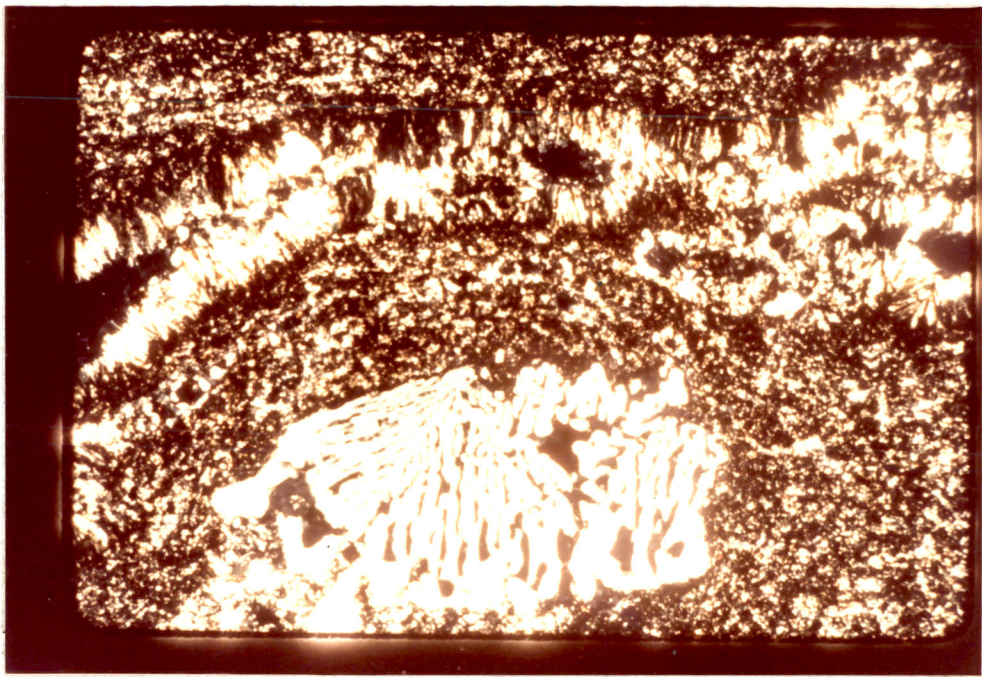


Figure 70b.

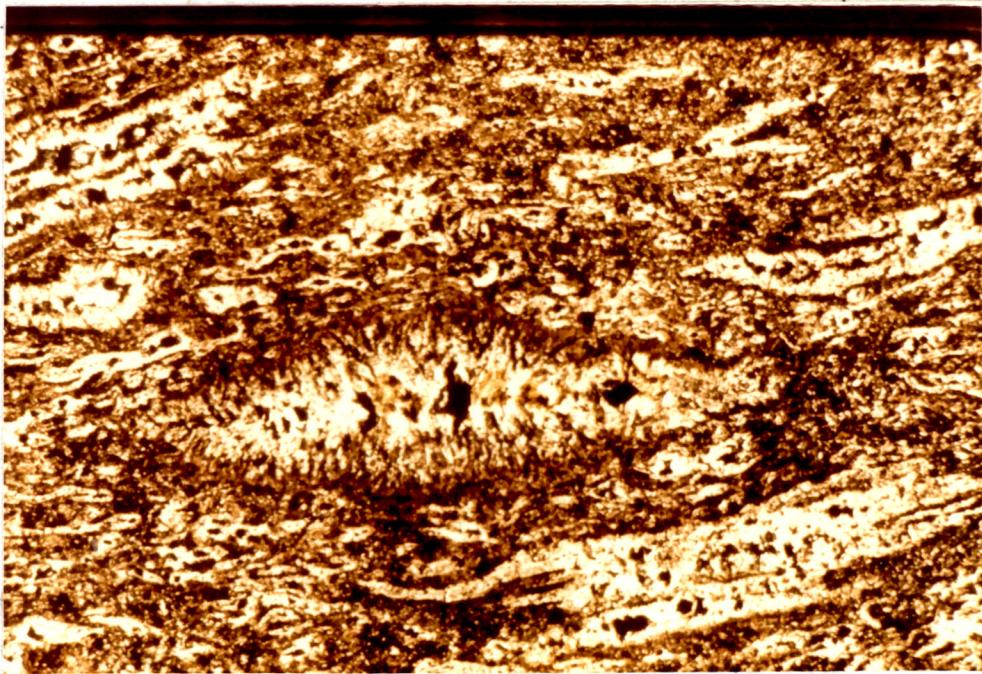


Figure 71.



Figure 72. Chocolate tuff (Campana section). This is a weathered surface showing denser "fiamme" in a moderately welded matrix. Phenocrysts of sanidine and quartz are weathering out of the matrix.

Figure 73a. Photomicrograph of Chocolate tuff (Campana section). Quartz phenocrysts exhibit optically continuous overgrowths of quartz. The groundmass, consisting of matted aegirine needles, is included in the overgrowths. x-nicols. Width of field 2.6 mm.

Figure 73b. Photomicrograph of Chocolate tuff (Campana section). This is a close view of groundmass aegirines in the quartz overgrowths. The chocolate-brown color of this rock is due to altered groundmass aegirine. x-nicols. Width of field 0.32 mm.

Figure 74. Photomicrograph of manganese prospect rock. Pyrolusite coatings cap calcite crystals. Plane light. Width of field 6.8 mm.



Figure 72.

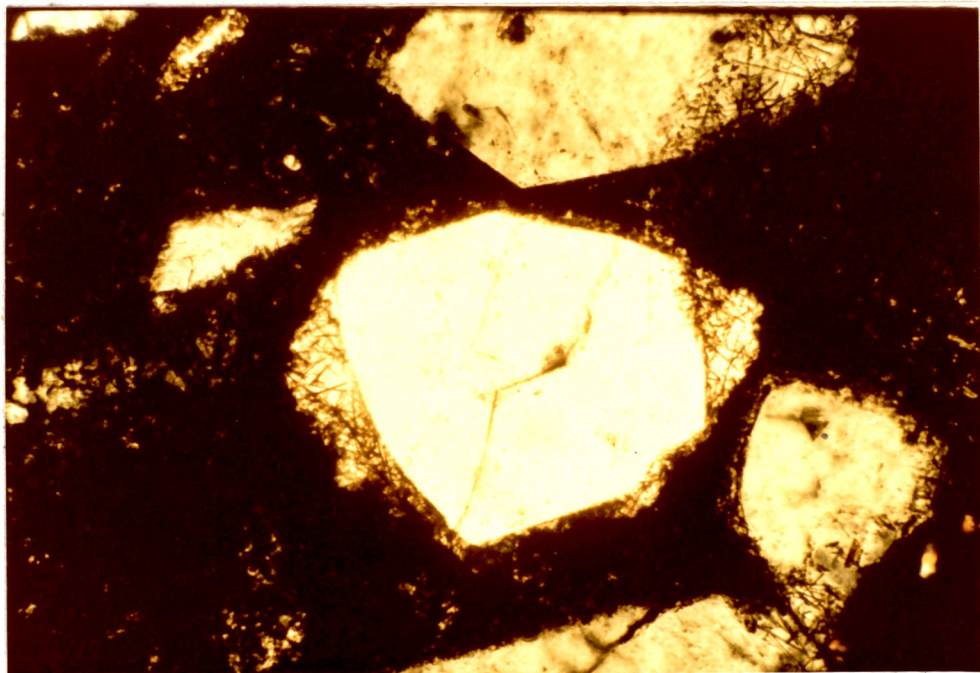


Figure 73a.

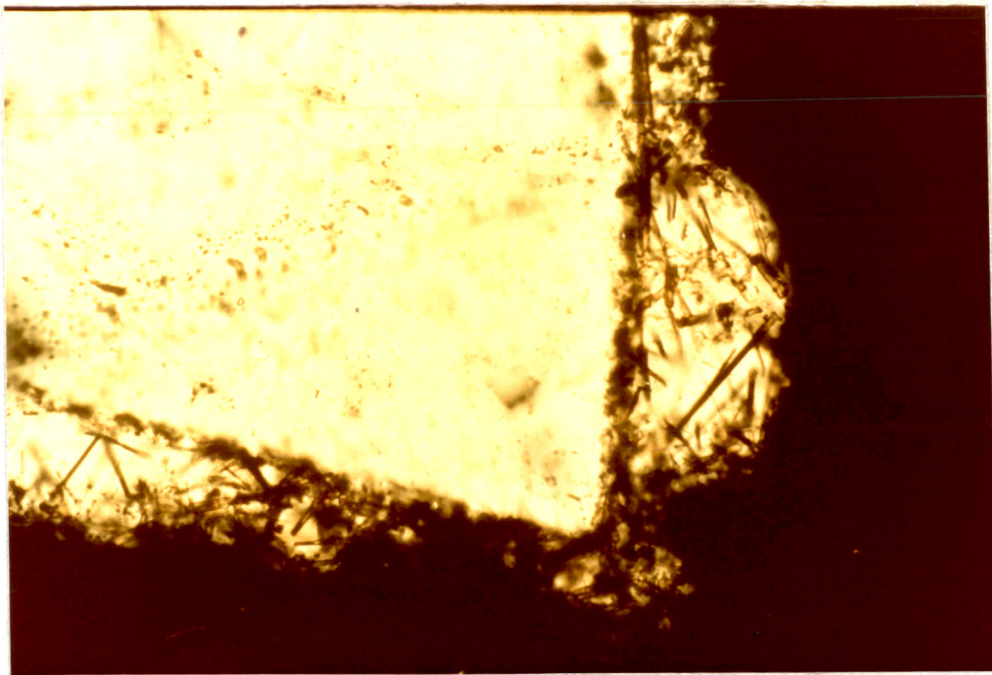


Figure 73b.

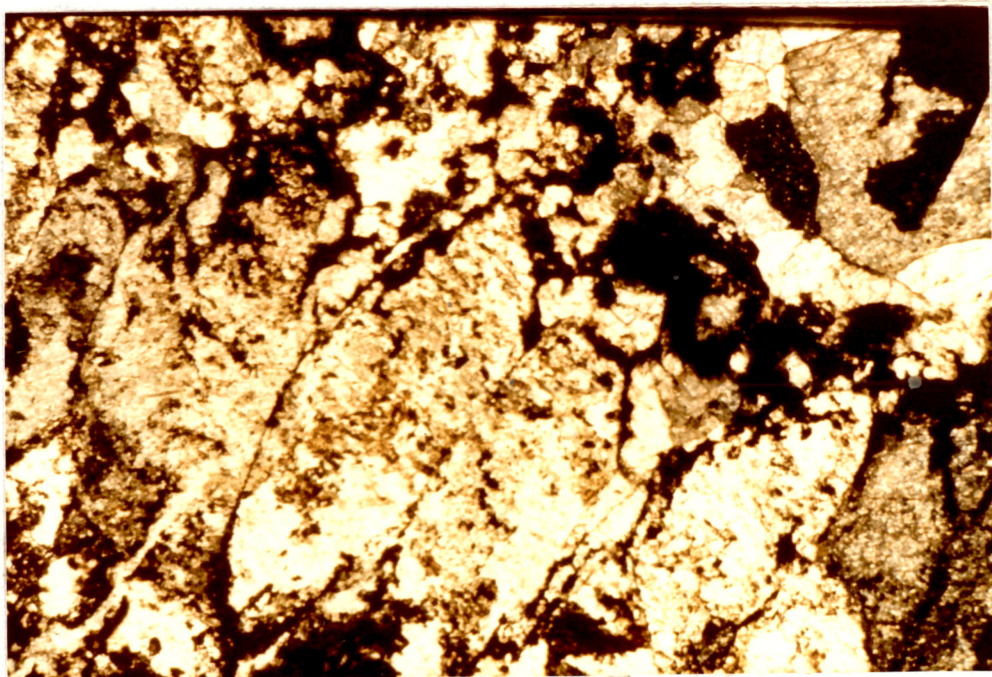


Figure 74.



## APPENDIX A

### Theory of Spherulite Formation

Keith and Patten (1963) developed a steady-state theory for the growth of spherulites using organic, high polymers. The following discussion has been taken from their work.

Spherical aggregates of crystalline fibers have a very high surface area to volume ratio. They are not considered to be in equilibrium with the surrounding liquid. This causes crystallization under abnormal conditions. Rhyolitic melts have abnormally high viscosities that retard the diffusion of molecules to and from the growing tips of the spherulite fibers. Molecules must have proper orientations to fit lattice sites and only high-temperature components are admitted. The crystallizing solid therefore rejects lower-temperature components and these are left behind as an impurity layer. These impurities cannot efficiently diffuse into the liquid because of the high viscosity. The impurity layer ( $\delta$ ) is equal to the diffusion coefficient ( $D$ ) divided by the growth velocity ( $G$ ) or  $\delta = D/G$  (Keith and Patten, 1963). This impurity layer stabilizes the growth rate of the spherulite fibers and helps to promote uniform, radial growth. The growth rate must be slow enough so that only a slight temperature gradient is required to sustain it. The system is considered isothermal. Unstable surface conditions on a (theoretical) smooth sphere would be enhanced by a supercooling gradient and the formation of small crystal projections would proceed from the surface. For alkali feldspar spherulites,  $\delta$  is approximately  $1\mu$  and the fiber growth rate is  $10\mu$  to  $100\mu$ /day in water

saturated rhyolites. Extreme cellulation or growth of fibers under nearly isothermal conditions is further enhanced because the low-temperature residual components retard crystallization between the fibers.

Growing spherulite fibers will split at angles smaller than those produced during normal dendritic crystallization. This repetition of slight divergences produces sets of nearly parallel fibers which accounts for the splaying texture observed in spherulites. Splitting of a fiber takes place at some point of crystallizing disruption or disorder on the growing surface. The thickness of the impurity layer controls nucleation at disorder sites. Only crystal fibers of the appropriate impurity-layer thickness will persist and grow into the long, uniform-width fibers, typical of spherulites. Smaller fibers will be engulfed by larger crystals and larger fibers will break down into smaller projections. The thickness of  $\delta$  must be large enough to accommodate continued fiber growth (of fibers already growing) and small enough to limit the angle of fiber branching. Variations of  $\delta$  control the distance between fibers and the diameter of the fiber. The diameter of mature (spherical) spherulites decrease as fiber diameters become smaller which indicates a smaller  $\delta$  value.

Pronged microlites may be produced by dendritic branching when the melt is cooled quickly (Figure 32). During this brief interval of cooling, the diffusion coefficients increase rapidly and crystallization changes from polyhedral growth favoring the uniform enlargement of the lath to dendritic growth and eventually to spherulitic growth.

Early studies of artificially grown spherulites reveal that they exhibit various stages of growth and in most cases do not assume a radial habit until maturity (Morse and Donnay, 1936). More recently, Lofgren (1971b) performed studies on remelted and quenched granitic rocks and produced similar results. When melts were quenched, both experimenters observed fibrous crystalline bundles that are constricted in the middle and divergent at both ends. The earliest stage is a crystalline bar with pumose ends. This stage is followed by the addition of microcrystalline fibers between enlarging bundles of splayed-out fibers. During successively later stages, the bowtie aggregate shows increased divergence or fanning-out until two hemispheres impinge along a plane approximately orthogonal to the original axis. Figure 3 shows this sequence in sketches.

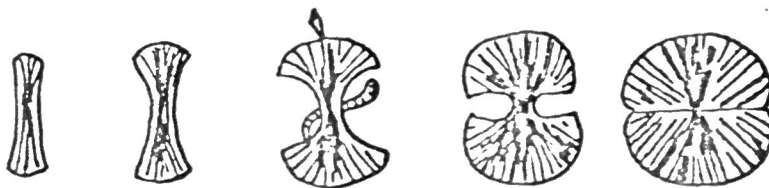


Figure 33. Growth stages of spherulites.

Important to this discussion is the dependence of  $\xi$  and  $G$  to  $T$  (temperature). The diameter of a spherulitic fiber will vary with temperature at a constant pressure. This has been verified by Lofgren (1971b) using experimentally devitrified rhyolitic glass (Figure 34).



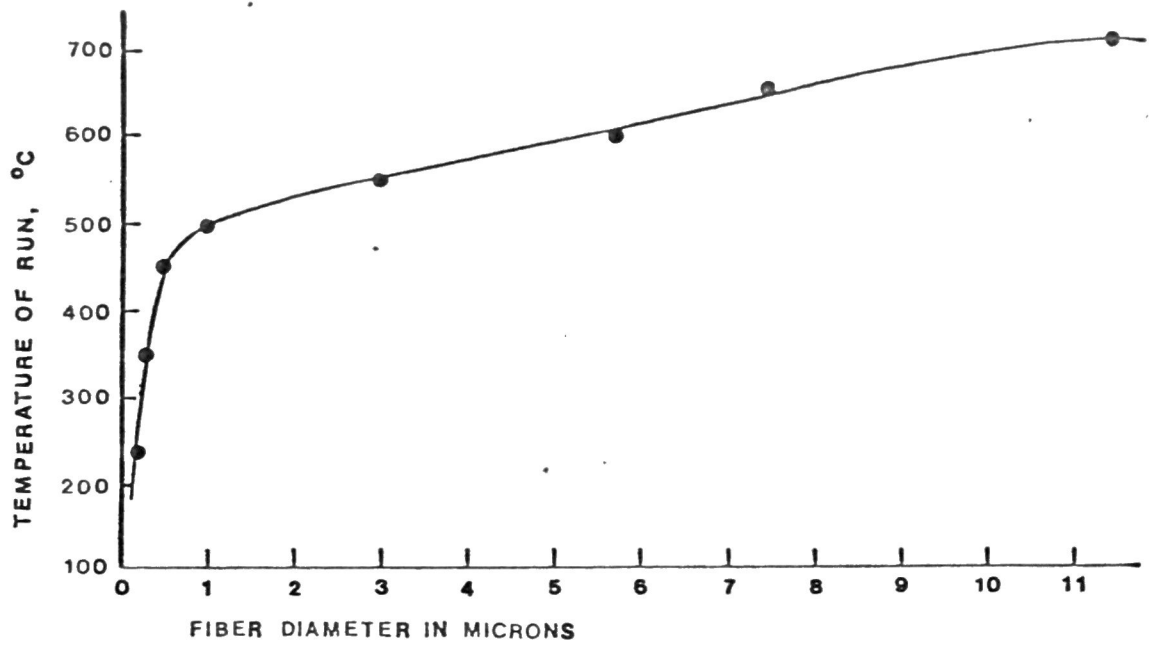
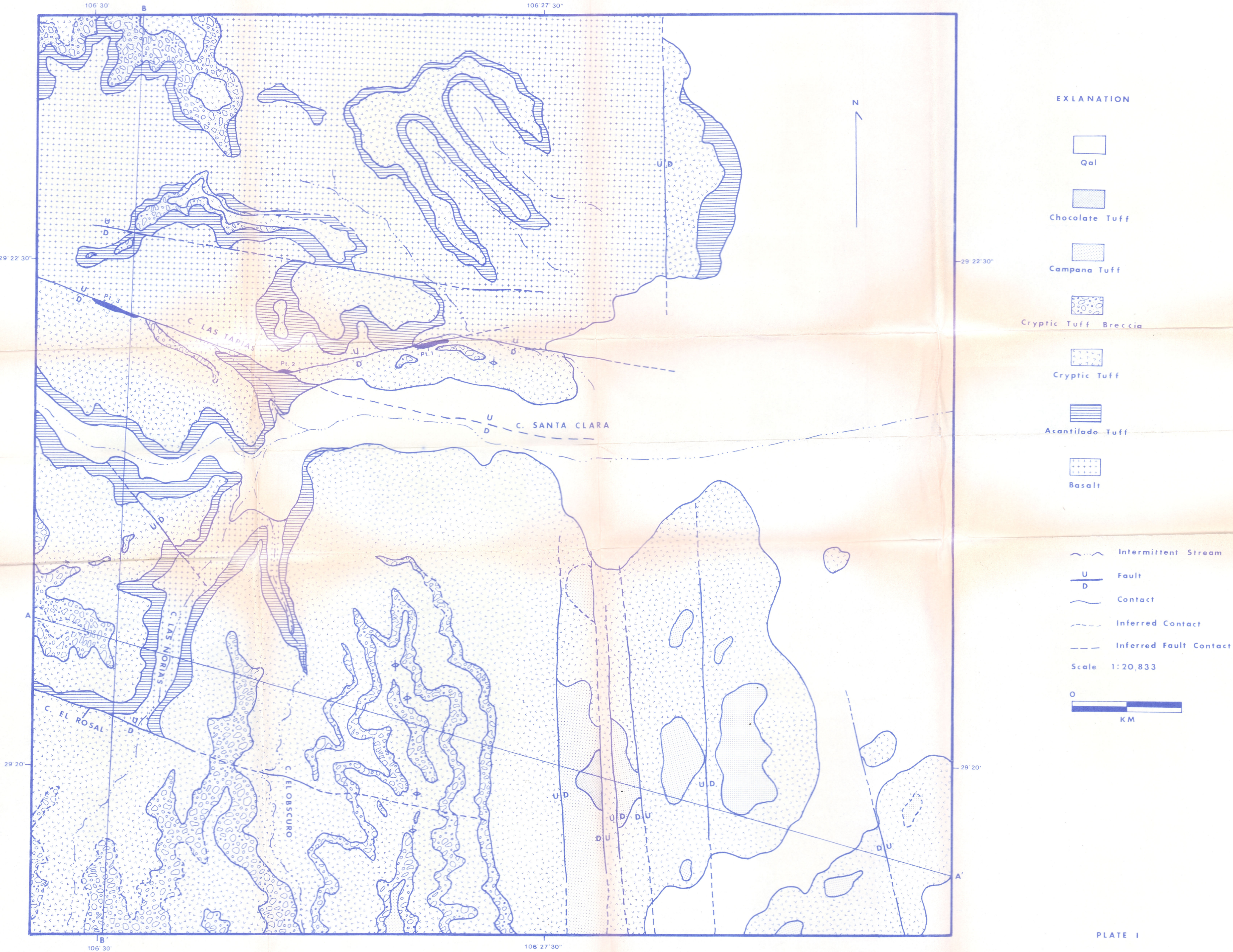


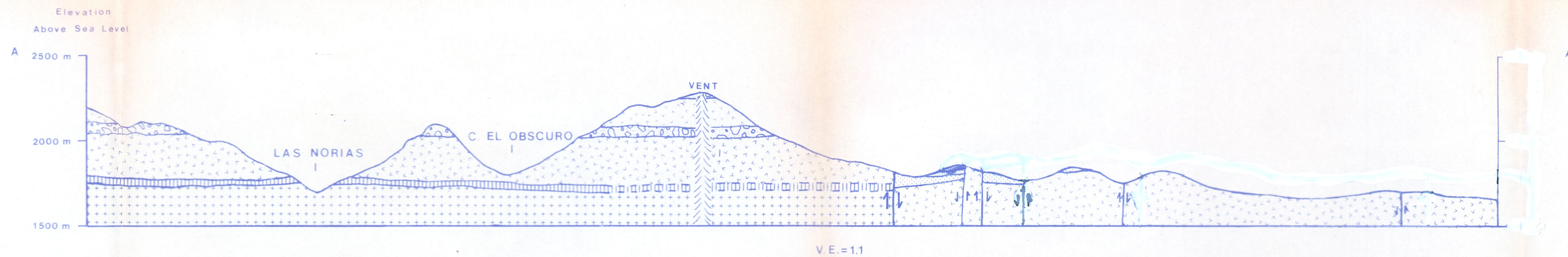
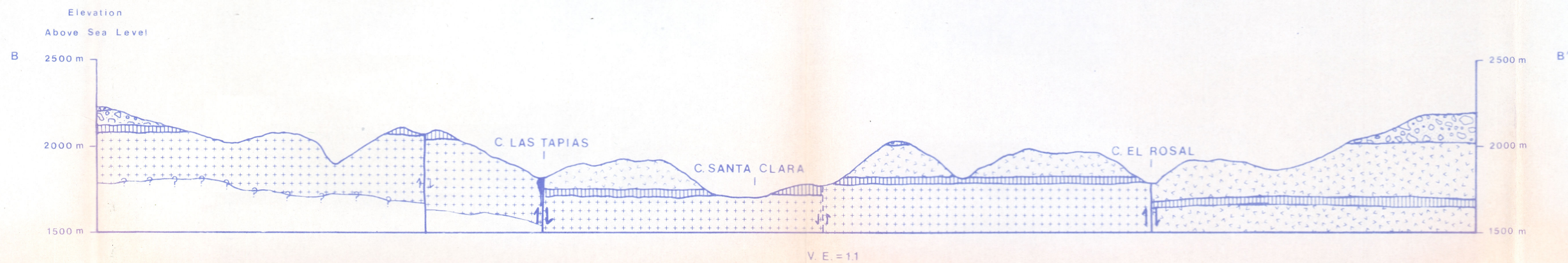
Figure 34. Plot of fiber diameters in experimentally devitrified rhyolite glass against run temperature (Lofgren, 1971b).



# GEOLOGIC MAP OF LOWER CANYON SANTA CLARA









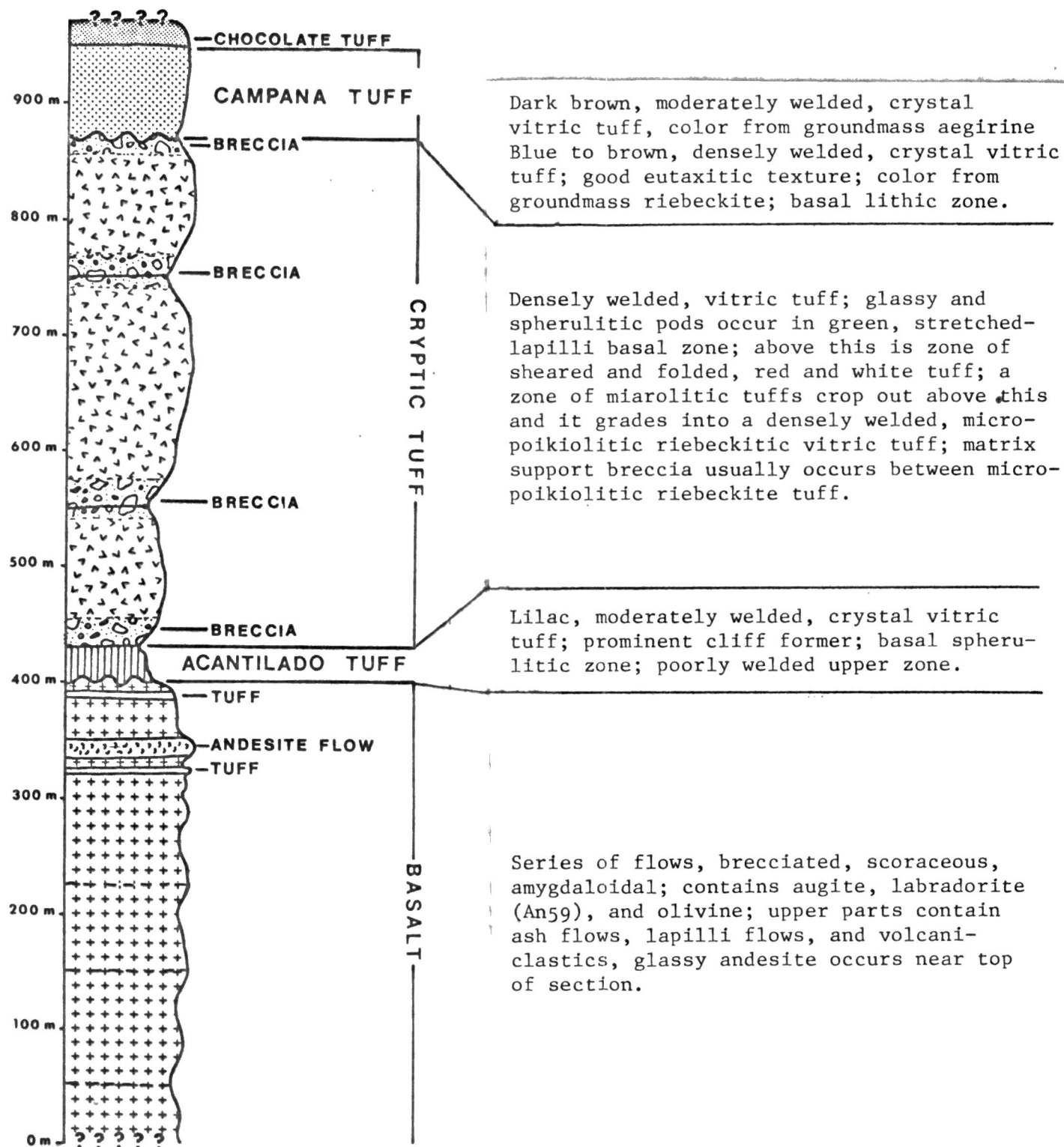


PLATE I