THE VOLCANIC
GEOLOGY OF THE RANCHO
PEÑAS AZULES AREA, CHIHUAHUA, MEXICO

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by

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Frontispiece

Panoramic view of the Rancho Peñas Azules area. View is toward the east from the erosional escarpment of Sierra Cumbres de Majalca. Rancho Peñas Azules lies in the low open area near the left-central part of the photograph. The prominent peak in the extreme left-center is Cerro Punta de Agua, and the two cone-like peaks in the right-center are composed of the Picos Gemelos Andesite. The high peaks of the Sierra Peña Blanca are visible in the background.

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ABSTRACT

A section of volcanic and volcaniclastic rocks in the Rancho Peñas Azules area is approximately 4650 meters thick and is divisible into eight informally named formations. From oldest to youngest, the formations are the Tres Cuchillas, Lavas Azules, Cumbres, Quintas Tuff, Capilla Amarilla Tuff, Picos Gemelos Andesite, Rancheria Roja Tuff, and Rancheria Tuff. The Tres Cuchillas and Lavas Azules Formations comprise the Peñas Azules Volcanic Group (4000+ meters), and the upper six formations constitute the Upper Volcanic Group (700+ meters). The stratigraphic section is known to be early Tertiary; however, the exact ages of the units are not known at the present time.

The Peñas Azules Volcanic Group is composed of steeply dipping interbedded basaltic andesites, welded tuffs, and laharic deposits and is overlain, in angular unconformity, by a nearly flat lying ignimbrite sequence. This older sequence is well exposed in the relatively flat area surrounding Rancho Peñas Azules. In thin section the basaltic andesites contain plagioclase, hornblende, and/or pyroxene phenocrysts in a pilotaxitic groundmass. The laharic breccias and conglomerates are composed of boulder-size fragments of andesite and devitrified tuffs, and formed by rapid erosion of topographically high lava flows and ignimbrites. The welded tuff units of the Tres Cuchillas Formation are exposed

in a series of conspicuous hogbacks in the vicinity of Rancho Peñas Azules. The laharic and pyroclastic rocks are capped by 3000+ meters of basaltic andesite, the Lavas Azules Formation, which may have accumulated in a sinking graben. An unusual tuff lava is present near the central part of the flow. The rock is believed to have formed by eruption and flow of a vertically differentiated magma body. Clots of a silica-enriched upper part of the magma body now occur as flattened and elongated lenses in a flow-banded matrix of basaltic andesite. Extensive block faulting and erosion of the older sequence took place before extrusion of the ignimbrites and andesite flows of the younger sequence.

The nearly flat lying units of the Upper Volcanic Group form resistant ridges which almost completely surround Rancho Peñas Azules. The Cumbres Formation is composed of interfingering basaltic andesite flows and red-bed deposits of varying coarseness. The red beds are the result of talus-type accumulation of breccia and fluvial deposits from rapid erosion of fault scarps. A thick, short, and spherulitic dacite flow 1 kilometer northeast of Rancho Peñas Azules occupies approximately the same stratigraphic position as the red beds of the Cumbres Formation. The Quintas Tuff, Capilla Amarilla Tuff, Rancheria Roja Tuff, and Rancheria Tuff are rhyolitic pyroclastic deposits with varying degrees of welding. The tuffs are generally rich in sanidine and contain small amounts of quartz and plagioclase. The Quintas Tuff has a basal vitrophyre zone which is overlain by a zone with well developed spherulites. The eruption of pyroclastic materials was locally interrupted by outpourings of the Picos Gemelos Andesite, a topographically prominent, porphyritic basaltic andesite. The Quintas Tuff, Picos Gemelos Andesite, and Rancheria Tuff display conspicuous, widely spaced (2-5 meters) columnar joints. Normal faulting followed cessation of volcanic activity.

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The Arizona Bureau of Mines and the Laboratory of Isotope Geochemistry provided the facilities for mineral separation.

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I N T R O D U C T I O N

The volcanic geology of northern Mexico is poorly known, and detailed studies of the volcanic rocks of the southwestern United States have not been extended for any great distance south of the Mexican border. In recent years, however, there has been great interest, enthusiasm, and speculation among geologists regarding the stratigraphy, age, and structure of the massive pile of volcanics of the Sierra Madre Occidental. This study is concerned with deciphering such information from a very small yet informative area of volcanics near Cuidad Chihuahua, Chihuahua, Mexico. The study area, referred to in this report as the Rancho Peñas Azules area, was selected as an ideal area to help initiate an understanding of the stratigraphic relationships between the volcanic units of the general region. The study is part of a larger regional study by Dr. Richard L. Mauger, East Carolina University.

AREA INVESTIGATED

This report is concerned with the stratigraphy and petrology of the volcanic rocks of the Rancho Peñas Azules area, Chihuahua, Mexico. The study area is located approximately 40 kilometers north-northwest of Cuidad Chihuahua and less than 2 kilometers east of the prominent erosional escarpment which marks the eastern edge of Sierra Cumbres de Majalca (Fig. 1). The area is 35 square kilometers in size and extends roughly from 28° 50' N to 28° 54' N, and from 106° 20' W to 106° 25' W.

An older sequence composed of andesite flows with interbedded tuffs and boulder conglomerates, and a younger sequence composed predominantly

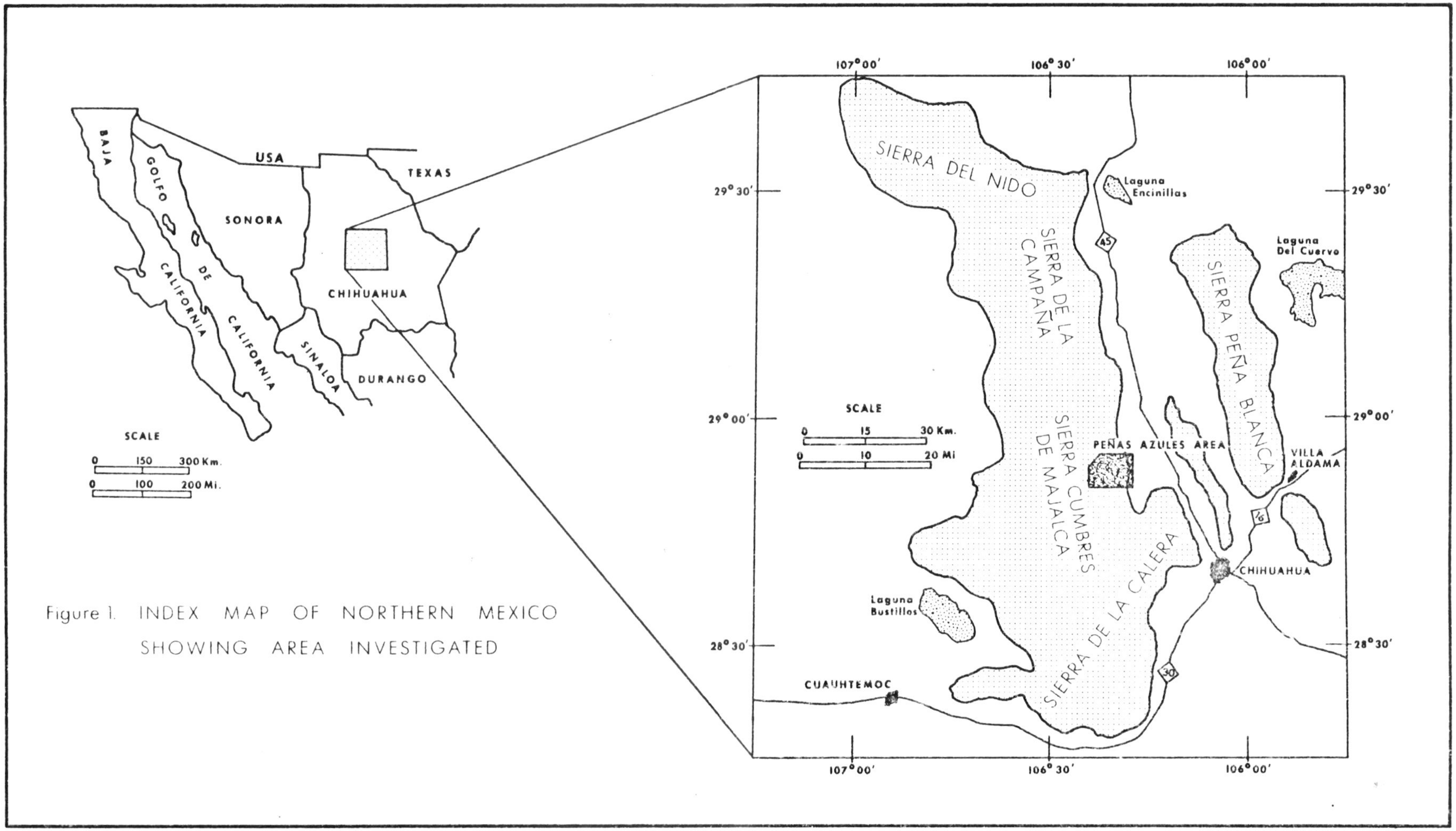


Figure 1. INDEX MAP OF NORTHERN MEXICO SHOWING AREA INVESTIGATED

of welded tuffs are exposed in the valley of the Arroyo Majalca, the major stream within the study area (Fig. 2). The sequences are separated by an angular unconformity. The older sequence is well exposed as an inlier within the broad and relatively flat area of Rancho Peñas Azules, and the overlying ignimbrite sequence forms conspicuous ridges to the east of the rancho (Fig. 3). The limited size of the study area reflects an attempt on the part of the writer to adequately map and describe the angular unconformity and the two distinct sequences of volcanic and volcanic-derived rocks.

PREVIOUS WORK

No detailed study of the stratigraphy and petrology of the volcanic rocks of the Rancho Peñas Azules area had been made prior to this investigation, although there had been a few abortive attempts at simple mining operations. The general geology of the surrounding region is mentioned briefly in the New Mexico Geological Society Field Trip Guidebook (1969). Regional geologic maps depict the study area, and indeed the entire Sierra Madre Occidental, as undifferentiated Tertiary volcanics.

PURPOSES OF INVESTIGATION

The purposes of this investigation are:

1) to establish the stratigraphic section of the Rancho Peñas Azules area (heretofore unknown) and to describe the lithostratigraphic units,
2) to determine the physical stratigraphic changes which the formations undergo within the area,

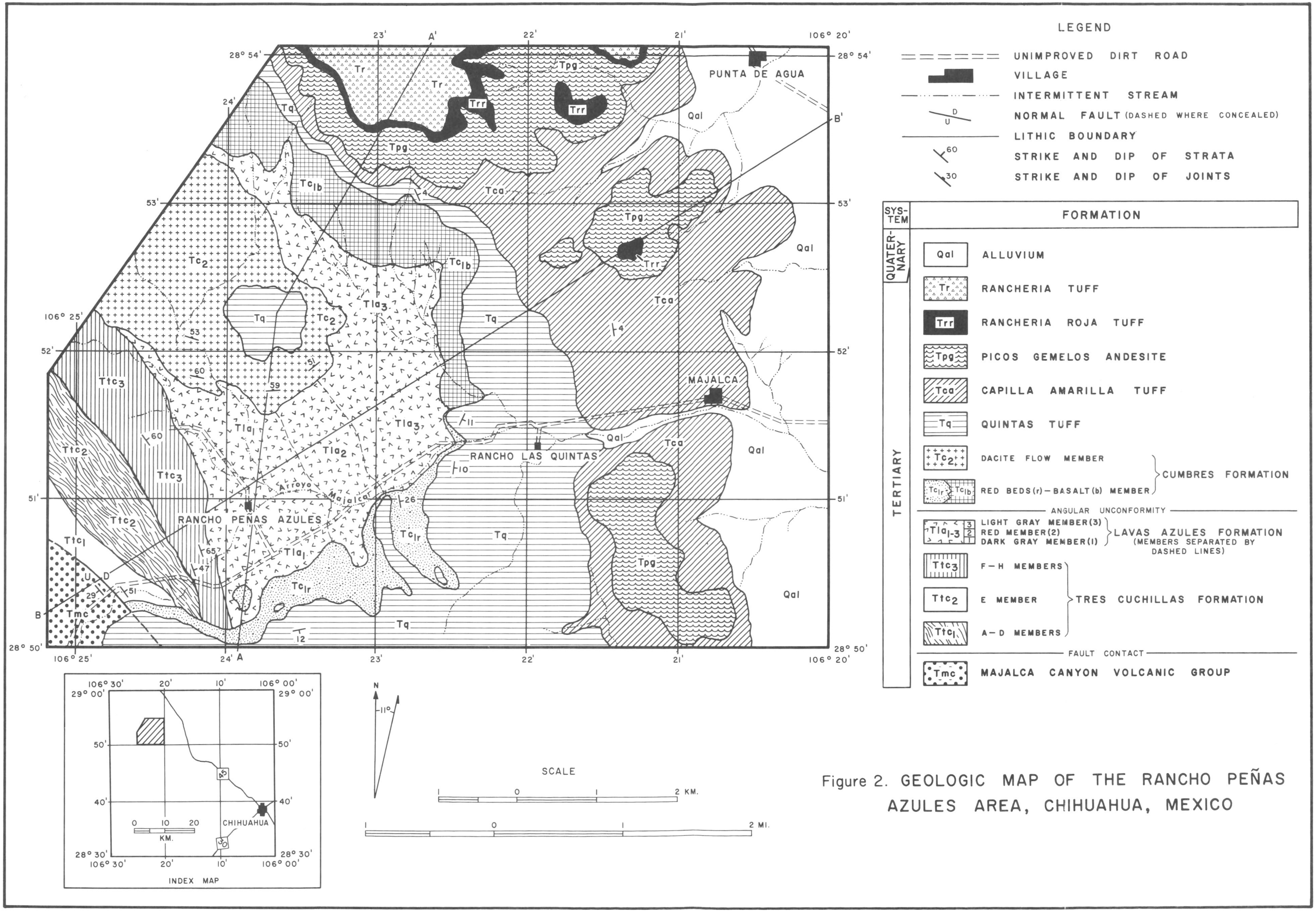


Figure 2. GEOLOGIC MAP OF THE RANCHO PEÑAS AZULES AREA, CHIHUAHUA, MEXICO

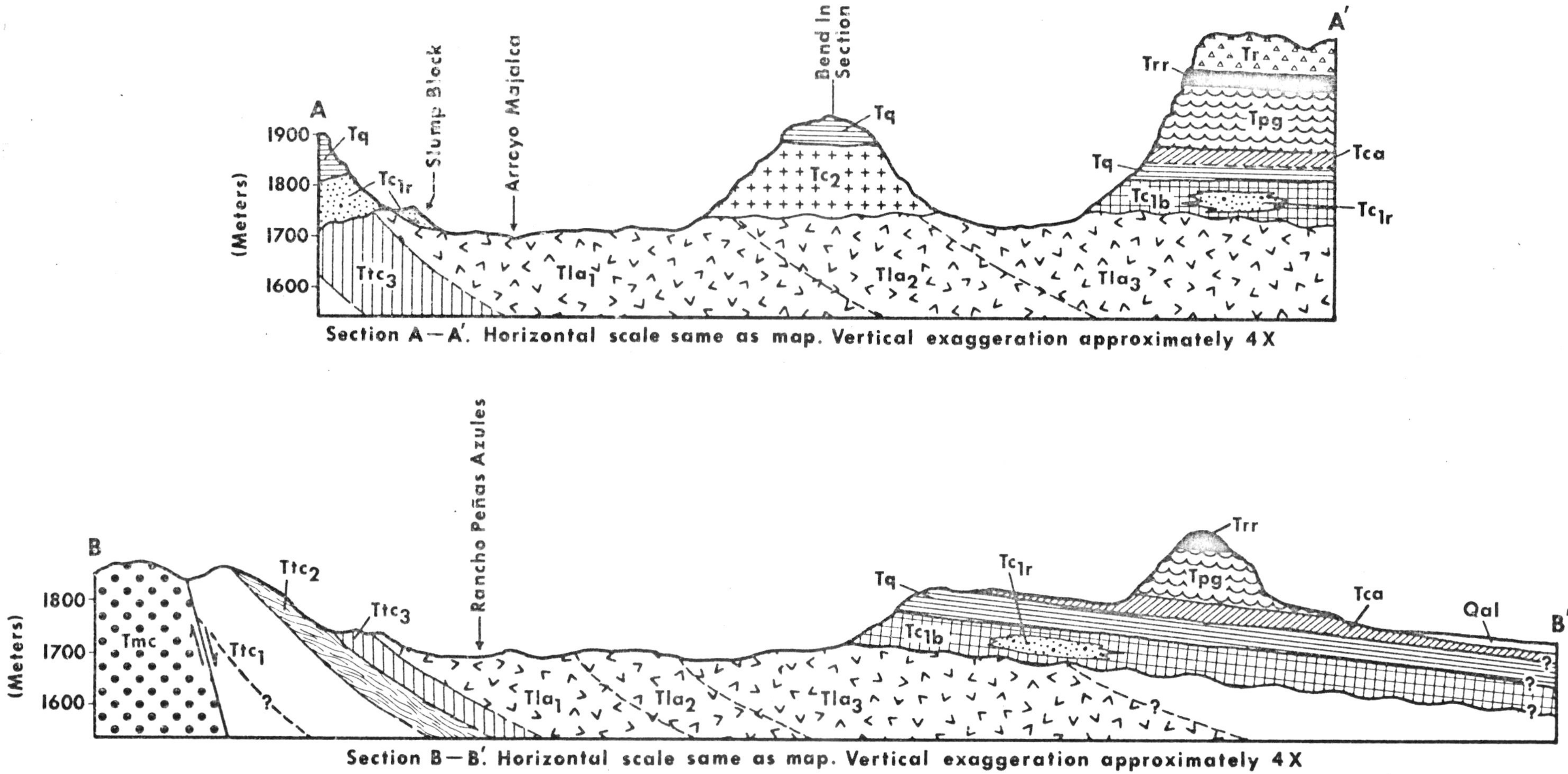


Figure 3. Structure sections of the Rancho Peñas Azules area (A-A' and B-B' in Fig. 2).

3) to map the volcanic and volcanic-derived rocks of the Rancho Peñas Azules area,

4) to study the rocks by means of detailed petrography and to use the data to interpret the modes of emplacement of the rocks,

5) to determine the age of the ignimbrite sequence by K-Ar age dates.

METHODS OF INVESTIGATION

Stratigraphic sections were measured and described at several localities. Sections were measured with a Brunton compass and tape. Geologic mapping was done on 1:58,000 (approximate scale) aerial photographs available from CETENAL, a Mexican governmental agency. Lithologic samples were systematically collected and their exact positions in the stratigraphic section were recorded. The Geological Society of America Rock Color Chart (Goddard, *et al.*, 1951) was used to describe the color of the rock samples. The rock samples were later studied in the laboratory by examining thin sections with a petrographic microscope and sawed surfaces with a binocular microscope. Photomicrographs of selected samples were taken with a Leica 35 mm camera and microphoto attachment. The K-Ar age dating is being performed at the University of Texas at Austin by Dr. Fred McDowell, and will be available in the spring of 1976. Sanidine separates were obtained at the University of Arizona, Tucson, utilizing facilities of the Arizona Bureau of Mines and the Laboratory of Isotope Geochemistry.

G E O G R A P H Y

TOWNS AND VILLAGES

Rancho Peñas Azules lies near the west-central section of the study area. The rancho includes a large ranch house, several tennant houses, and stables. Beef cattle ranching is the major economic function of the rancho. There are numerous other villages and privately owned ranches in the study area and the immediate vicinity. The most important of these are shown on the Index Map (Fig. 1) and on the Geologic Map (Fig. 2). The village of Majalca, the largest village (population approximately 50) within the study area, is a small agricultural and ranching center. Approximately 9 kilometers west of Rancho Peñas Azules is the village of Cumbres de Majalca (old Majalca of local usage), a summer resort for a small number of prominent families of Cuidad Chihuahua. Cuidad Chihuahua, population 363,850 (Schmidt, 1973), lies 40 kilometers southeast of the study area. It has long been the major transportation and trade center of the region.

ACCESSIBILITY

Mexico Highway 45, the major north-south highway connecting Cuidad Juárez and Cuidad Chihuahua, passes east of the village of Majalca and provides access to the Peñas Azules area. An unimproved dirt road connects the village of Majalca with Mexico Highway 45. Westward from Majalca, the road cuts through the very center of the study area and winds through a series of spectacular switchbacks up the Cumbres Escarpment to Cumbres de Majalca National Park and the village of Cumbres de Majalca. From this unimproved dirt road, smaller gravel and cobble roads lead to the various ranches within the study area (Fig. 2).

CLIMATE

The general climate prevailing in the foothills of Sierra Cumbres de Majalca is warm and semi-arid. Brand (1937) summarized the available information up to 1935, and classified the climate of the general region as ranging from mesothermal savannah (Cw) to hot steppe (BSh). According to Hawley (1969), the study area lies very close to Brand's boundary between the hot steppe (BSh) and hot desert (BWh) categories.

The average annual rainfall for the study area ranges from 300 mm to 600 mm, and the range in mean annual temperature is 10 C^{o} to 18 C^{o} (Hawley, 1969). Most of the precipitation comes in July and August in the form of torrential storms resulting in considerable runoff (Schmidt, 1973). Running water is believed by the writer to be the dominant agent of erosion in the region.

VEGETATION

A varied flora grows in the Rancho Peñas Azules area. The warm and semi-arid climate closely controls the types of vegetation and their distribution. The vegetation is dominated by cacti, other succulents, scrub oaks, and numerous other smaller trees and plants. The summer rain storms of July and August transform the area in a matter of a few weeks from a bleak and dry desert environment to an area covered by green grasses.

The most abundant cacti are *Opuntia lindheimeri* and *Fouquieria splendens*. *Opuntia lindheimeri*, a broad leaf form, is known in the United States as the prickly pear and in Mexico as the nopal. *Fouquieria splendens* is a long-branched form better known as ocotillo. The ocotillo is quite impressive, often exceeding 4 meters in height. In addition to these cacti, numerous other succulents occur in the Peñas Azules area. The well known century plant, a prominent species of *Agave*, is moderately abundant.

The lowland areas are characterized by dense thickets of *Acacia greggii*, commonly called catclaw, and by small groves of scrub oak. Larger trees, especially pines and other small conifers, are found in the higher elevations above 2000 meters. West of the study area, on the summit plain of Sierra Cumbres de Majalca, the presence of such trees has given rise to lumber industries.

REGIONAL GEOLOGIC SETTING

PHYSIOGRAPHY

A very large number of geographers and geologists have defined the general physiographic subdivisions of northern Mexico, but Brand (1937) and Almada (1945) are the only authors who have dealt specifically with the state of Chihuahua. The reader is referred to the excellent discussion by Hawley (1969) on the history of the nomenclature involving physiographic subdivision of the area.

J. W. Hawley (1969) synthesized field data and information concerning the geomorphology and late Cenozoic geology of a 71,000 square kilometer (27,600 square mile) area of northwestern Chihuahua and adjacent parts of Sonora and the southwestern United States. In 1969 he subdivided the area into three major physiographic units: the Sierra Madre Occidental Province, and two subsections of the Mexican Basin and Range Section (Fig. 4). The larger subsection, designated the Bolson Subsection, is characterized by very broad desert basins and isolated ranges. The Babicora-Bustillos Subsection, to which the study area belongs, is a topographically higher unit which is transitional between the Bolson Subsection and the Sierra Madre Occidental.

Table 1, slightly modified after Hawley (1969), lists the major characteristics of the physiographic units listed above. No attempt will be made here to completely describe each of the sections. Instead, the most important aspects of each unit, as described by Hawley (1969), are discussed in the following sections.

EXPLANATION OF FIGURE 4

Localities

B	Buenaventura
Ch	Cuidad Chihuahua
Cu	Cuauhtemoc
CG	Nuevo Casas Grandes
D	Delicias
Gu	Guerro
EP	El Paso-Juárez
MS	Medanos de Samalayuca
VA	Villa Ahumada

Mountain Ranges

1	Sierra de La Brena
2	Sierra de La Calera
3	Sierra de La Campaña
4	Sierra de Carcay
5	Sierra de La Catarina
6	Sierra del Cristo
7	Sierra Cumbres de Majalca
8	Sierra de Juárez
9	Sierra del Nido
10	Sierra del Presidio
11	Sierra de La Samalayuca
12	Sierra de San Joaquin
13	Sierra de San Luis
14	Sierra de San Pedro
15	Sierra de Santa Rita
16	Sierra de Las Tunas

Lake Plains

LBa	Laguna Babicora
LBu	Laguna Bustillos
LC	Laguna del Cuervo
LE	Laguna Encinillas
LG	Laguna de Guzman
LM	Laguna de Los Mexicanos
LLM	Laguna de Los Moscos
LP	Laguna de Los Patos
LS	Laguna de Santa Maria
LTa	Laguna Tarabillas
LTi	Laguna Tildio

Symbols

Mexico Highway 45

Continental Divide

Sierra Madre/Basin and Range Province Boundary

Basin and Range Section Boundaries

Mountain Ranges

Active Dune Fields

Lake Plains

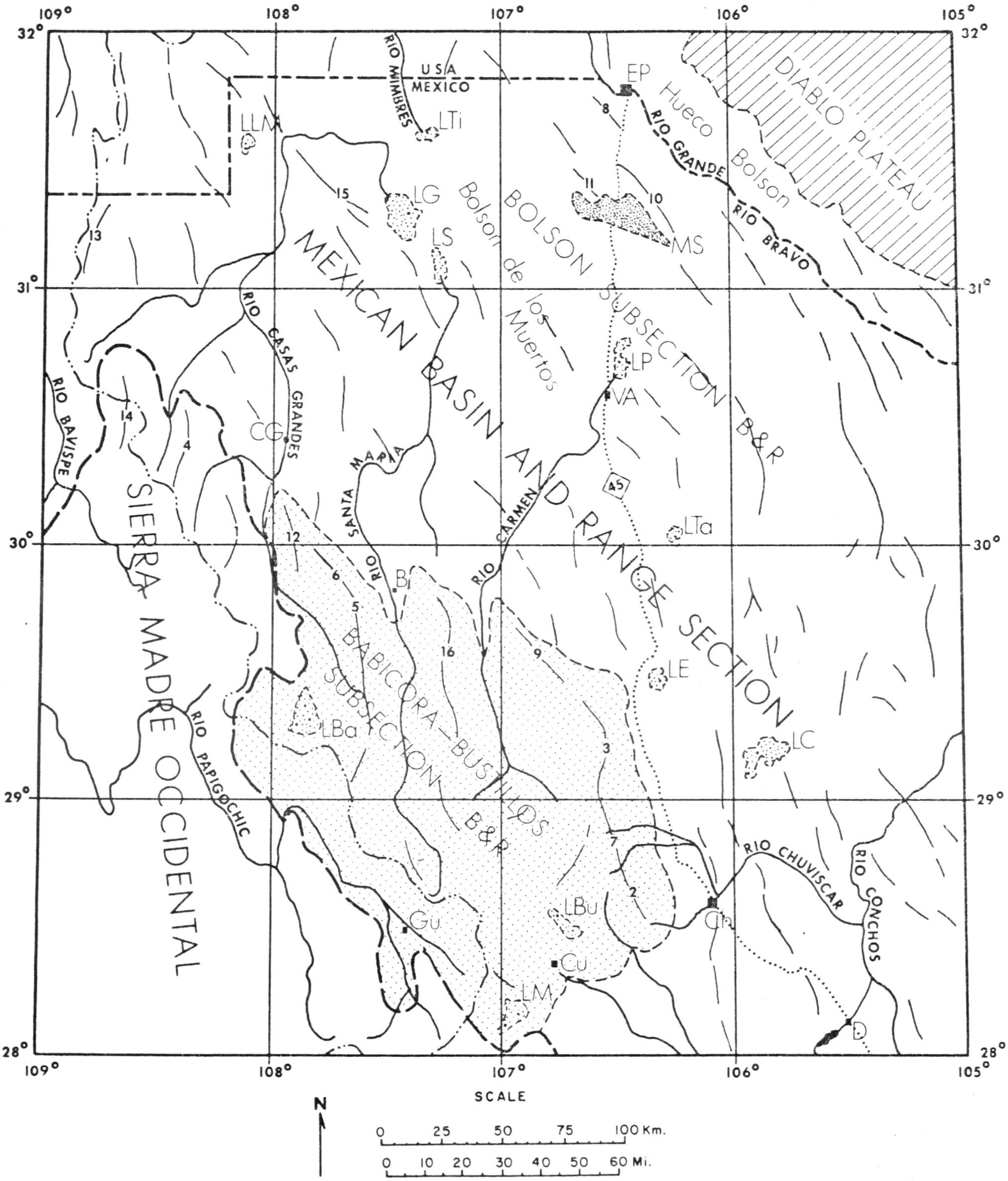


Figure 4. Index map of geomorphic features of northwestern Chihuahua and adjacent areas (After Hawley, 1969).
(Explanation on facing page)

PHYSIOGRAPHIC UNIT	SIERRA MADRE OCCIDENTAL	MEXICAN BASIN AND RANGE SECTION BOLSON SUBSECTION	BABICORA-BUSTILLOS
Total Area (Km^2)	31,000	107,500	25,000
Area of Internal Drainage/Total Area (%)		70	29
Area of Ranges/Total Area (%)		19	37
Percentage of Ranges Composed of:			
Mainly carbonate sedimentary rocks	<0.2	35	<0.3
Mainly rhyolitic and andesitic volcanics	>99.6	61	>99.7
Mainly igneous intrusive rocks	<0.2	<2	
Mainly basalt (Quaternary?)		<3	
Percentage of Basin Areas in Active Dunes		>0.5	
Percentage of Basin Areas in Playas (Barrials)		2.5	<2
Percentage of Total Area Below 1220m. (4000 ft.)	9	15	0
Percentage of Total Area Above 1830m. (6000 ft.)	54	2.4	97.5
Percentage of Total Area Above 2440m. (8000 ft.)	5.5	<0.02	3.5
Highest Elevation in Meters (Feet)	3103(10,180)	2602(8532)	2978(9774)
Lowest Elevation			
Basin Floor		1150±(3770±)	1980±(6490±)
River Valley Floor	550(1800)	850(2785)	1600(5250)
Range in Mean Annual Precipitation (mm)	<400->1100	<150->400	<300->600
Range in Mean Annual Temperature (°C)	<10-20	15-20	10-18

Table 1. Characteristics of physiographic units in northwestern Chihuahua and adjacent areas (After Hawley, 1969).

Sierra Madre Occidental Province.--The Sierra Madre Occidental comprises a compact mass of high ridges and plateaus separated by steep, narrow valleys (barrancas). It is called the Sierra Taruhumara in Chihuahua, where its eastern boundary is marked by the escarpments which face, from north to south, the basins of Llano de Carretas, Janos, Piedras Verdes-Colonia Juárez, San Miguel-Mata Ortiz, Laguna Babicora, Madera, Guerrero, and Laguna de los Mexicanos.

The province is characterized by a thick sequence of Tertiary volcanics, primarily welded to non-welded rhyolite tuffs, although significant amounts of volcanics of intermediate composition are present. Tertiary intrusives and pre-Tertiary sedimentary rocks are only locally exposed and basalts are not abundant (Table 1). Accordance of summit elevations is a striking character of the province. Also, the upper sheets of volcanics display local faulting and folding, but lack evidence of a major diastrophic disturbance other than immense regional uplift and slight tilting.

The major stream valleys and intervening ridges display a striking parallelism which probably reflects the NNW-SSE strike of the regional structural trends. The major rivers of this section of the Sierra Madre are the Rios Papigochic and Bavispe, which are major tributaries of the Aros-Yaqui system (Fig. 4). In addition to the major rivers listed above (which drain to the Pacific), the largest interior basin-draining stream in the region, the Rio Casas Grandes, has its headwaters in the northernmost of the Sierra Madre Ranges.

Mexican Basin and Range Section.--Hawley (1969) recognized that while the Mexican Basin and Range Section fits the broad "Basin and Range concept" of Fenneman (1931), Thornbury (1965), and Hunt (1967), it does not fit into a single category in terms of landforms or geologic setting. Expanding on the ideas of Brand (1937) concerning the transition zone between the Sierra Madre and the Basin and Range sections, Hawley created two subdivisions of the Mexican Basin and Range Section, the Bolson and the Babicora-Bustillos Subsections. The major distinguishing geomorphic features of these subsections are those listed in Table 1.

Bolson Subsection.--The Bolson subsection is a large belt of isolated ranges and broad, coalescent desert basins with interior drainage which extends from southwestern New Mexico, through Chihuahua, and into the central interior states of Mexico (Fig. 4). Cenozoic volcanics are predominant in the western sections, while Cretaceous carbonates dominate in the eastern and southern sections of the area. As shown in Table 1, Tertiary intrusive bodies are present locally.

The southern Bolson Subsection, roughly from Cuidad Chihuahua eastward, is drained by the Satevo-Conchos River system which has its headwaters in the Babicora-Bustillos Subsection and flows to the Gulf of Mexico. From this drainage system northward, the subsection is characterized by internally drained depressions. From south to north these depressions comprise the basins of Laguna del Cuervo, Laguna Encinillas, Laguna Tarabillas, and the very extensive Bolson de Los Muertos (Fig. 4). The Bolson de Los Muertos, 150 miles long and up to 40 miles wide, contains several smaller depressions into which the Rio Carmen, Rio Santa Maria, and Rio Casas Grandes drain. Its eastern edge is the site of the spectacular Medanos de Samalayuca dune field.

Babicora-Bustillos Subsection.--The Babicora-Bustillos Subsection, to which the study area belongs, receives its name from two ephemeral lakes, Laguna Babicora and Laguna Bustillos, in the northwestern and southwestern parts of the subsection respectively (Fig. 4). The subsection comprises an area of nearly 25,000 square kilometers and includes four major mountain chains and a group of high level intermontane basins. In this section the mountains form almost continuous chains with peak elevations often exceeding the general summit elevation of the eastern Sierra Madre Occidental. The ranges are composed of bedrock similar to that of the Sierra Madre Occidental.

The eastern to northeastern boundary between this subsection and the Bolson Subsection is roughly marked by the frontal escarpments of the following ranges or groups of ranges: (1) the elongate system made up of the Sierras de La Calera, Cumbres de Majalca, de La Campaña, and del Nido; (2) Sierra de Las Tunas; (3) Sierras de La Catarina and del Cristo; and (4) Sierra de San Joaquin (Fig. 4). The abrupt eastern escarpments of these ranges are readily visible from Mexico Highway 45 between Cuidad Chihuahua and Villa Ahumada.

The study area lies at the eastern edge of the Babicora-Bustillos Subsection less than 5 kilometers east of the prominent erosional escarpment of Sierra Cumbres de Majalca. From the volcanic rocks of the higher peaks of the study area, one can look eastward across a narrow bolson (about 15 kilometers wide) of the Bolson Subsection at mountains composed of carbonates and overlying volcanics.

LOCAL STRUCTURE

An angular unconformity separates an older sequence of andesite flows and mud-flow deposits from a younger sequence of ignimbrites in the Peñas Azules area. The angular unconformity is illustrated in the geologic cross-sections in Figure 3. Erosion has breached the younger sequence to expose an irregular area of older rocks (Fig. 2). The contact between the older and the younger sequences is often obscured by talus; however, the delineation of the unconformable surface is not difficult because of the large differences in strike and dip between the two sequences. Field evidence indicates that a surface of moderate relief was developed on the older rocks before extrusion of the younger sequence of ignimbrites began.

The older sequence dips steeply (30^{o}-85^{o}) to the east and is in fault contact with an even older sequence of volcanics near the western edge of the study area (Fig. 3). The fault is a high angle (approximately 75^{o}) normal fault which strikes north-northwest (Fig. 5). The displacement is down toward the east but the amount of displacement is unknown. The younger sequence dips gently to the east, except in the northern part of the study area where the beds are essentially horizontal. Numerous small, high angle normal faults occur within the younger sequence. Dips of the faults

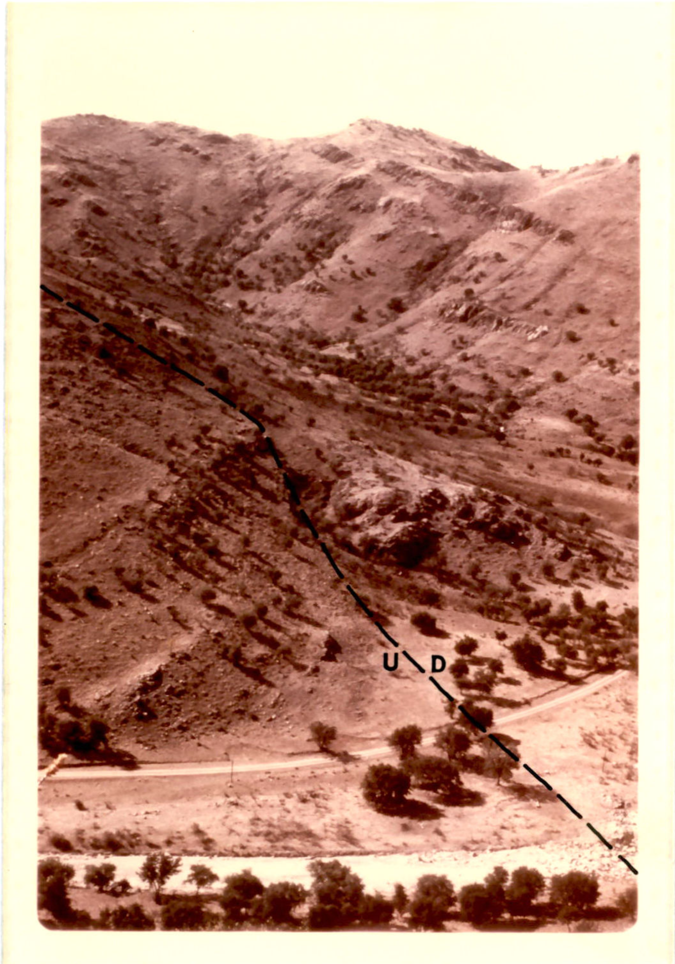


Figure 5. High angle normal fault cutting Tres Cuchillas Formation (right) and Majalca Canyon Volcanic Group (left), about 3 kilometers west of the village of Majalca. View is toward the northwest.

average about 80° and displacements are generally less than 10 meters. These faults are localized features most often confined to the younger sequence; however, displacement along at least one fault was sufficient to bring the older and the younger sequence into fault contact. Most of these faults are the result of slumping of large blocks in response to conditions of instability initiated by stream erosion. Their small size generally prevents representation on the geologic map; however, one large slump block is shown on the geologic map (Fig. 2) and in the structure section (Fig. 3). Displacement along this fault is approximately 25 meters.

The volcanic rocks of the Peñas Azules area are cut by joints, the only exception being the massive mud-flow units of the older sequence. Vertical columnar jointing is a common feature of the welded tuffs of the area. The joint spacings range from a few centimeters to many meters, with the more closely spaced joints usually found in the zones of most intense welding. In any given locality the joints seem to be uniformly spaced, although the spacing may vary greatly over several miles of outcrop. The joints were probably formed by stresses that developed during cooling and contraction. Spacing of the joints may be controlled by several factors such as rate of cooling, degree of welding, thickness, etc. (Ross and Smith, 1961). Columnar structures are rare in the andesites of the older sequence. These rocks are cut by at least three sets of closely spaced joints.

DRAINAGE

The drainage of the Rancho Peñas Azules area is dendritic and the streams are all ephemeral. The entire region has been greatly dissected by stream erosion, as can be seen from the geologic map (Fig. 2). The land surface is cut by deep canyons and widely spaced gullies. The largest stream in the study area is the Arroyo Majalca, a tributary of the Rio Sacramento. The Rio Sacramento joins the Rio Chuviscar at Cuidad Chihuahua. From Cuidad Chihuahua the Rio Chuviscar flows eastward to join the Rio Conchos (Gulf of Mexico) drainage system.

As can be seen from the geologic map (Fig. 2), the major streams of this area all drain east or southeast.

CLASSIFICATION OF THE VOLCANIC ROCKS OF THE PEÑAS AZULES AREA

The volcanic and volcanic-derived rocks of the Peñas Azules area fall into two distinct groups, both stratigraphically and lithologically. The older sequence is composed of interbedded tuffs, massive boulder conglomerates, and thick andesite flows. The younger sequence is composed essentially of ignimbrites and related pyroclastic rock types. In the opinion of the writer, no single classification scheme can adequately and accurately categorize such a diversity of rock types. However, the various rock types can be grouped together into two genetically distinct groups: volcanic clastic rocks (termed volcaniclastic in this paper), and fine grained volcanic rocks of flows of varying composition. Consequently, two basic classification schemes, based on the genetic groups mentioned above, will be used in this paper. These groups are discussed in detail below.

VOLCANICLASTIC SEDIMENTS AND ROCKS

The development of the classification of volcaniclastic sediments and rocks has been outlined by Fisher (1961). Table 2 traces the development of the various classifications of pyroclastic fragments from the Wentworth and Williams classification of 1932 up to Fisher's 1961 classification. The terminology and grain size limits of both pyroclastic and epiclastic rocks used in this paper (Table 3) will be those recommended by Fisher (1961).

Fisher (1961) divided the volcaniclastic rocks primarily on the basis of particle origin into autoclastic, pyroclastic, and epiclastic, and secondarily on constituent particle size. A modification of this classification will be used in this paper (Table 4).

Grain size	Wentworth and Williams, 1932	Twenhofel, 1950	Emmons, et al., 1955	Panto, 1959	Fisher, 1961
> 256 mm	BLOCKS AND BOMBS	BOMBS	BLOCKS, BOMBS, LAPILLI, AND CINDERS	BLOCKS AND BOMBS	BLOCKS AND BOMBS (COARSE)
256 mm – 64 mm	BLOCKS AND BOMBS	LAPILLI	BLOCKS, BOMBS, LAPILLI, AND CINDERS	BLOCKS AND BOMBS	BLOCKS AND BOMBS (FINE)
64 mm – 50 mm	BLOCKS AND BOMBS	LAPILLI	BLOCKS, BOMBS, LAPILLI, AND CINDERS	BLOCKS AND BOMBS	LAPILLI
50 mm – 32 mm	BLOCKS AND BOMBS	LAPILLI	BLOCKS, BOMBS, LAPILLI, AND CINDERS	LAPILLI	LAPILLI
32 mm – 10 mm	LAPILLI	LAPILLI	BLOCKS, BOMBS, LAPILLI, AND CINDERS	LAPILLI	LAPILLI
10 mm – 4 mm	LAPILLI	LAPILLI	ASH	LAPILLI	LAPILLI
4 mm – 2 mm	ASH (COARSE)	ASH (COARSE)	ASH	LAPILLI	LAPILLI
2 mm – 1 mm	ASH (COARSE)	ASH (COARSE)	ASH	LAPILLI	ASH (COARSE)
1 mm – 1/4 mm	ASH (COARSE)	ASH (COARSE)	ASH	DUST	ASH (COARSE)
1/4 mm – 1/16 mm	ASH (FINE)	ASH (FINE)	ASH	DUST	ASH (COARSE)
1/16 mm – 1/256 mm	ASH (FINE)	ASH (FINE)	ASH	DUST	ASH (FINE)

Table 2. Classifications of pyroclastic fragments (After Fisher, 1961).

GRAIN SIZE (mm)	EPICLASTIC FRAGMENTS	PYROCLASTIC FRAGMENTS	
> 256	BOULDERS AND BLOCKS	COARSE	BLOCKS AND BOMBS
256 – 64	COBBLE	FINE	BLOCKS AND BOMBS
64 – 2	PEBBLE	LAPILLI	
2 – 1/16	SAND	COARSE	ASH
1/16 – 1/256	SILT	FINE	ASH
< 1/256	CLAY	FINE	ASH

Table 3. Terminology and grain size limits for pyroclastic fragments (After Fisher, 1961).

<table>
<tr><th>PREDOMINANT GRAIN SIZE (mm)</th><th>AUTO-CLASTIC</th><th colspan="2">PYROCLASTIC</th><th>EPICLASTIC</th></tr>
<tr><td>256
64</td><td rowspan="2">FLOW BRECCIA,
AUTO-BRECCIA,
INTRUSION BRECCIA</td><td colspan="2">PYROCLASTIC BRECCIA,
AGGLOMERATE</td><td rowspan="2">EPICLASTIC VOLCANIC BRECCIA,
EPICLASTIC VOLCANIC CONGLOMERATE</td></tr>
<tr><td></td><td colspan="2">LAPILLISTONE</td></tr>
<tr><td>2</td><td rowspan="3">TUFFISITE</td><td>COARSE</td><td rowspan="3">TUFF</td><td>EPICLASTIC VOLCANIC SANDSTONE</td></tr>
<tr><td>1/16</td><td rowspan="2">FINE</td><td>EPICLASTIC VOLCANIC SILTSTONE</td></tr>
<tr><td>1/256</td><td>EPICLASTIC VOLCANIC CLAYSTONE</td></tr>
</table>

Table 4. Classification of the volcaniclastic rocks (Modified from Fisher, 1961).

Autoclastic rocks contain fragments that are produced within (but not commonly extruded from) volcanic vents, during initial movement of lava flows, or within solidified flows by gas explosions. Pyroclastic rocks are produced by explosive or aerial ejection of material from a volcanic vent. Epiclastic volcanic rocks contain fragments resulting from weathering and erosion of solidified or lithified volcanic rocks of any type. Under this classification, fragments have grain size limits similar to non-volcanic epiclastic rocks. Secondary classifications using different criteria may be set up under the classification scheme shown in Table 4. Because of the abundance of tuffs in the study area, especially within the younger sequence (Stratigraphic Column, Fig. 9), the writer feels that a secondary classification of tuffs and tuff-related rocks is needed. Further subdivision of the epiclastic volcanic rocks is also needed for the thick boulder conglomerate units in the older sequence.

CLASSIFICATION OF TUFFS

The majority of the rock units of the upper one-third of the stratigraphic sequence of the Peñas Azules area are ignimbrites, and thus fall under the heading of pyroclastic in Fisher's classification (Table 4). Cook (1965, p. 3) defines ignimbrites as "...sheet-like deposits of relatively nonsorted and nonstratified pyroclastic material." When used in this context the term ignimbrite becomes a rock-unit term, and is not equivalent to welded tuff. Cook (1965, p. 3) further defines an ignimbrite as "...a mappable rock unit, more or less equivalent to the 'ash-flow cooling unit' of Smith (1960), except that an ignimbrite may be made up of material that is not tuff, and was only in part ash during emplacement." The largest majority of the ignimbrites of the Peñas Azules area are welded tuffs; a few, however, are nonwelded tuffs and lapillistones.

A modification of the Wentworth and Williams (1932) classification of tuffs by Cook (1965) has proven extremely useful in the study of the ignimbrites of the study area. Wentworth and Williams (1932) classified tuffs as vitric, crystal, or lithic, depending on the relative percentages of particles of glass, crystals, and rock fragments, respectively. While all three elements are undoubtedly important components of ignimbrites, it does not necessarily follow that a classification scheme should give equal weight to each. Used in this paper is Cook's (1965) modification of the Wentworth and Williams (1932) classification (Fig. 6) which takes into account the varying roles of importance of the lithic and vitric components of a tuff. For example, the crystal content of ignimbrites rarely exceeds 50 percent. Thus Cook (1965) proposes that the adjective crystal enter the rock name at 10 percent and that a rock containing more than 50 percent crystals be called crystal. Furthermore, accessory lithic fragments may be of more importance in the field correlation of ignimbrites than would be suggested by

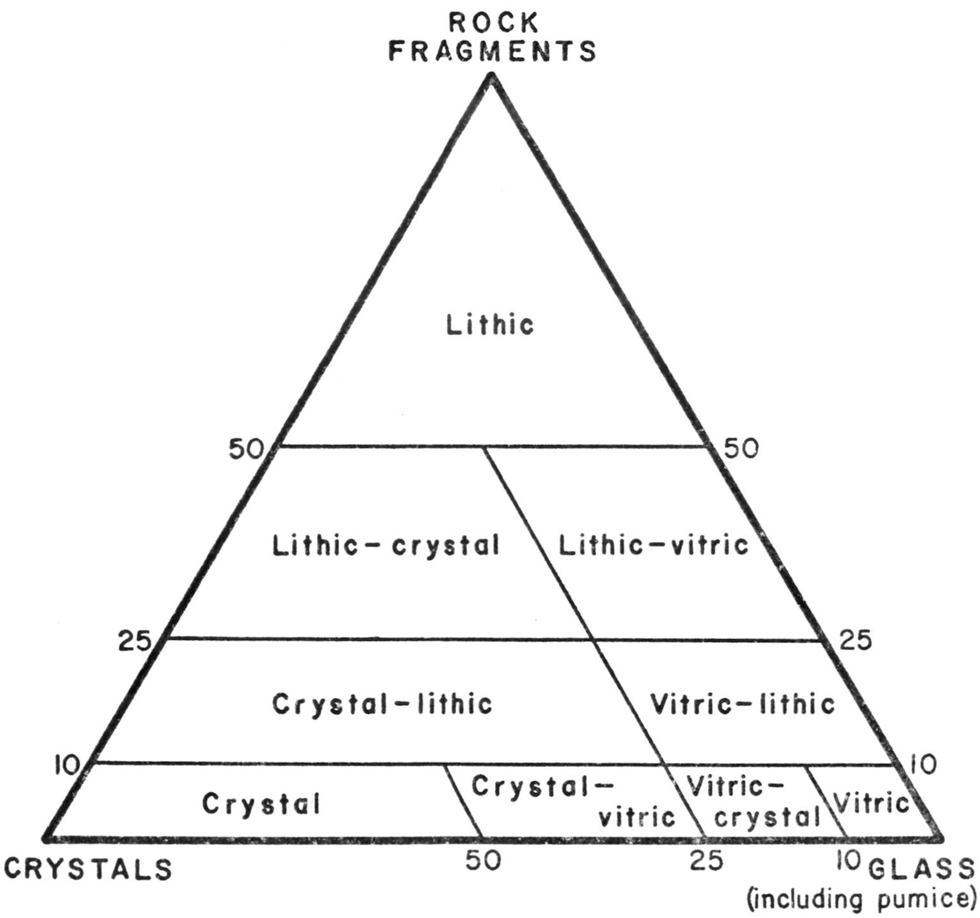


Figure 6. Mechanical composition triangle for ignimbrite rock types (After Cook, 1965).

their actual percentage. As a consequence, the lithic component is given greater emphasis than the other two components (Fig. 6). The lithic adjective enters the rock name whenever rock fragments account for more than 10 percent of the rock. Cook (1965, p. 5) points out that "...it is only possible to apply the 'lithic' adjective accurately if the pumice fragments, which may undergo a great change in volume vertically within an ignimbrite, are regarded as vitric rather than lithic." The vertical volume change is the result of pumice collapse due to compaction. In addition, the writer regards as lithic those fragments which are considered to be reworked but which have the same composition as the surrounding matrix.

In order to facilitate future correlation of the Peñas Azules ignimbrites in different localities, as well as to offer a convenient method for conveying petrographic data, a series of histograms has been prepared which show the phenocryst content of individual stratigraphic units of the study area (Fig. 7). This method, first described by Williams (1960) and employed extensively by Cook (1965), involves the identification of crystals with the aid of the binocular microscope on ground, etched, and cobaltinitrite-stained slabs. The relative percentages of quartz, sanidine, plagioclase, biotite, and hornblende are then plotted in histogram form. The present study utilized thin sections rather than ground slabs and a larger variety of phenocrystic crystals were counted and plotted. Williams (1960) points out that histograms based on the study of thin sections may display considerably higher percentages than those based on ground slabs, a point which should be taken into consideration when using the histograms for future correlation aids.

Both Williams (1960) and Cook (1965) point out that the relative proportions of the crystals generally tend to remain constant for a single

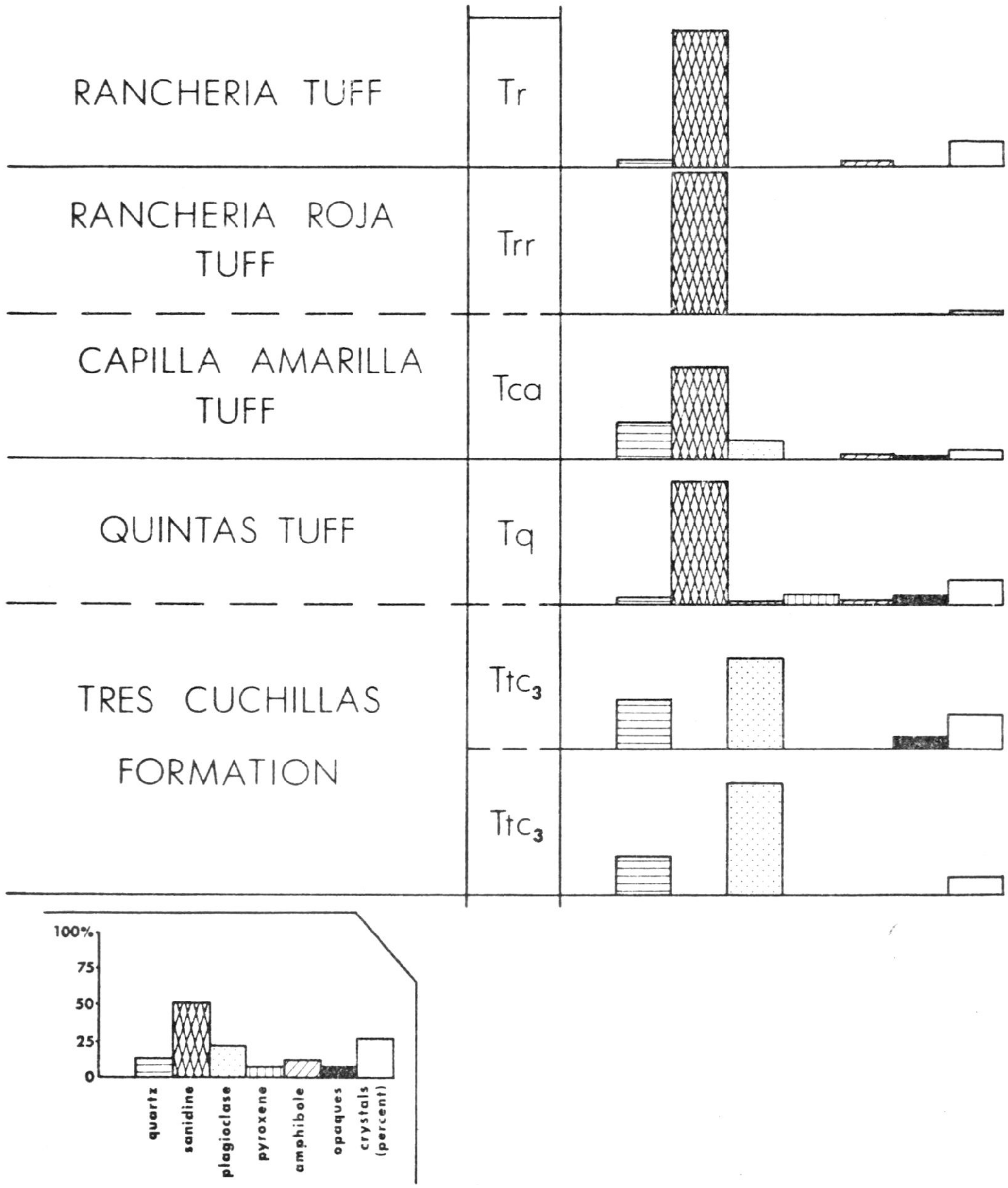


Figure 7. Histograms showing mineral composition of named ignimbrite units of the Rancho Peñas Azules area.

Six crystal components of each of the units were measured, as shown in the first six columns from the left. In each case, the first six columns total 100 percent. Column 7 indicates the percentage of the rock composed of these crystals, taken collectively. Histograms of Tq (4/82/1/6/2/5//15) and Tca (24/61/12/0/2/1//6), expressed in numbers, may be used to gain an idea of the histogram scale.

unit. This high degree of constancy of crystal proportions seems to be far more useful than color, pumice content, or degree of welding in the correlation of single units over large areas. Finally, it should be pointed out that two samples with very similar histograms do not necessarily represent the same ignimbrite, although two samples with distinctly different histograms may be assumed to represent different units (Cook, 1965). Thus, the method offers an extremely important aid in the correlation of ignimbrites, especially when used in conjunction with other lithologic criteria and sequential similarities.

CLASSIFICATION OF THE EPICLASTIC VOLCANIC ROCKS

Epiclastic volcanic rocks result from weathering and erosion of solidified or lithified volcanic rocks of various types. They are especially abundant in the older sequence of rocks in the Peñas Azules area. Fisher's classification (Table 4) of epiclastic volcanic rocks is used in this paper. The writer feels that the classification needs no further subdivision in the <2 mm range; however, standard terminology according to Folk (1974) will be used in some instances to adequately describe epiclastic volcanic sandstones. Epiclastic volcanic rocks composed of fragments larger than 2 mm are further subdivided on the basis of shape and percentage of constituent fragments and on mode of deposition.

A modification of Fisher's (1960a) classification of volcanic breccias is as follows:

- Epiclastic volcanic breccia and/or conglomerate
  - Laharic breccia and/or conglomerate
  - Water-laid volcanic breccia and/or conglomerate
  - Volcanic talus breccia and/or conglomerate

Epiclastic volcanic breccias contain angular fragments produced by any type of rock fragmentation and transported by geomorphic agents or by gravity transfer. Epiclastic volcanic conglomerates are composed of fragments which have been rounded by erosive processes. As might be expected, all transitions between the two types exist. Therefore, rocks that contain greater than 50 percent angular volcanic fragments will be called volcanic conglomerate-breccia; those that contain greater than 50 percent rounded volcanic fragments will be called volcanic breccia-conglomerate (Fisher, 1960b). Specific types of volcanic breccias or conglomerates, based on a knowledge of mode of deposition, may be named accordingly; an example is water-laid volcanic conglomerate-breccia.

The word lahar comes from the Indonesian word for materials of volcanic origin which have been transported by water. Van Bemmelen (1949, p. 191) defines lahar as "...a mudflow, containing debris and angular blocks of chiefly volcanic origin...." Lahar deposits are the result of mudflows which carry, disperse, and deposit various sizes of volcanic particles with or without admixed nonvolcanic material. Because mudflows grade from extremely viscous to fluid, the distinction between lahars and water-laid volcanic breccias and/or conglomerates is vague. The writer believes that it is impossible to distinguish, without extensive outcrops and detailed study, between a very fluid laharic deposit and a stream channel or alluvial fan-type epiclastic volcanic deposit. Every gradation between angular and rounded fragments could be expected in either type of deposit, depending on length of transportation alone. It also seems likely that lahars, with increased reworking by stream activity, will grade into volcanic gravels, sands, etc.. The coarse grained epiclastic volcanic deposits of the study area are the result of lahars and of deposition by normal stream activity.

Most of the coarse grained epiclastic deposits in the mapped area are massive, unsorted, and well lithified. Although individual beds appear to be as much as 20 meters thick in single outcrops, close examination reveals a series of widely spaced disconformities throughout the units. The deposits are interbedded with andesite flows, epiclastic volcanic sandstones, and tuffs. The angular to rounded fragments of the rock range from sand size to 1.5 meters in diameter and consist of two to three textural varieties of andesite. Vesicular or amygdaloidal rocks are noticeably absent. Thin and laterally discontinuous lenses of volcanic sands are common throughout the coarse grained deposits. Characteristics such as these have been attributed to deposits of laharic origin by several authors, including Anderson (1933), Rouse (1937), Van Bemmelen (1949), Crandell and Waldron (1956), and Fisher (1960b). Faulting, tilting, and erosion prevent the delineation of the source area of these deposits. It is believed, however, that the rocks were deposited primarily as a result of quite rapid denudation of large andesitic flows, and possibly even volcanic cones, situated either to the east or to the west of the study area. This assumption is based on the presence and orientation of channel deposits and on the presence of poorly developed cross-bedding within the thicker mud-flow units. More work is needed, however, before the main direction of sediment transport can be delineated.

CLASSIFICATION OF FLOW ROCKS

Andesite lava flows of extremely variable thickness occur throughout the Rancho Peñas Azules area. The following discussion deals primarily with a classification system which the writer feels is necessary to define and classify andesites on the basis of petrographic data. Hyndman (1972) published a classification which is a modification of a system being developed by the International Union of Geological Sciences Commission of Petrology (IUGS Commission). The classification scheme consists of a double triangle which is based on the estimated mineralogical composition of volcanic rocks. The following minerals and mineral groups, considered most important in the classification scheme (Fig. 8), are used as the end members for the classification double triangle:

Q---Silica minerals (quartz, tridymite, cristobalite)
A---Alkali feldspars (orthoclase, microcline, sanidine, perthite, anorthoclase, albite An_0-An_5)
P---Plagioclase (An_5-An_{100})
F---Feldspathoids (leucite, pseudoleucite, nepheline, sodalite, etc.)

In the absence of a chemical analysis, fine grained volcanic rocks are named from recognizable minerals. If, as is the case with the andesitic volcanics of the study area, only the composition of the phenocryst minerals may be determined, the resultant rock name should be prefixed with "pheno-", for example, pheno-andesite. Such usage will be followed in this paper whenever possible, for it is obvious that the groundmass of the rocks might easily contain abundant quartz and potassium feldspar, which would result in the rock being termed a dacite rather than an andesite. The distinction between andesite and basalt, which is an important consideration when dealing primarily with petrographic data, is based on the criteria (in approximate order of reliability) listed in Table 5.

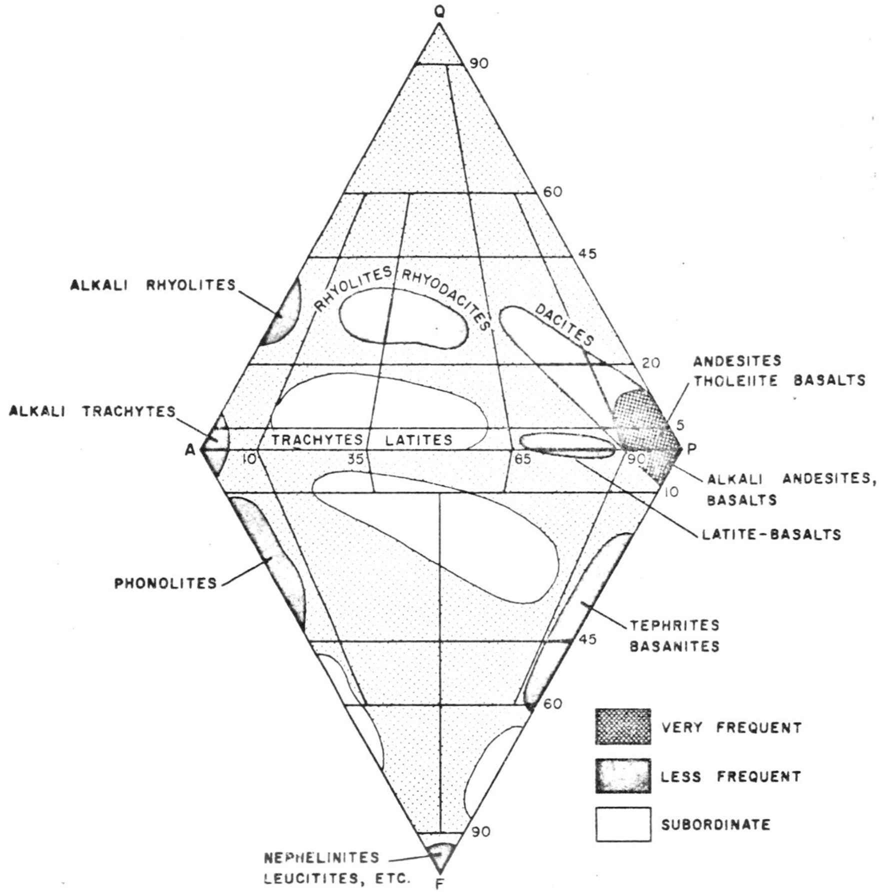


Figure 8. Double triangle relating estimated mineralogical distribution of volcanic rocks (After Hyndman, 1972). Q=silica minerals (mainly quartz); A=alkali feldspar (including albite An_{0-5}); P=plagioclase (An_{5-100}); F=feldspathoids.

CRITERION	BASALT	ANDESITE
Color index (% dark minerals may be reliably determined in thin section; corresponds to "black" basalts and intermediate-colored andesites in hand specimen)	>40	<40
Plagioclase mineral composition (determined microscopically, but crystals commonly zoned; phenocryst composition may be determined but groundmass composition commonly different and indeterminate)	$An_{>50}$	$An_{<50}$
Plagioclase composition in the norm (by chemical analysis)	$An_{>50}$	$An_{<50}$
Silica percentage of the rock (by chemical analysis)	<52	>52
Mafic minerals	Pyroxene (augite or hypersthene) or olivine	Hornblende or hypersthene, $\pm$ augite

Table 5. Criteria for distinction between basalt and andesite (After Hyndman, 1972).

V O L C A N I C S T R A T I G R A P H Y

INTRODUCTION

The oldest group of rocks present in the Peñas Azules area is a massive grayish brown boulder breccia belonging to the Majalca Canyon Volcanic Group, as named and described by Mauger (1975). Because this unit lies at the extreme western edge of the study area and is in fault contact with the younger rocks within the area, it is not described in detail in this report.

The exposed stratigraphic section in the Rancho Peñas Azules area above the Majalca Canyon Volcanic Group has a maximum thickness of 4,700 meters (14,400 feet). The section consists of andesite flows, ignimbrites, and mud-flow deposits, with minor amounts of fault-related talus accumulation (Fig. 9). Age dating of selected units by K-Ar analysis of sanidine is scheduled for completion in early spring of 1976. Until age dating has been completed, the writer can only speculate that the entire stratigraphic section is of early Tertiary age, most likely middle Eocene to early Oligocene. This assumption is based primarily on K-Ar dates by Alba and Chavez (1974) of rhyolite lavas and ash flows from the central Sierra Peña Blanca (Fig. 1). Their data indicates that the lower Tertiary volcanic activity took place from 44 to 37 million years ago. The proximity of the study area to Sierra Peña Blanca along with the gross similarities between the described rock units suggests contemporaniety of volcanic activity.

The stratigraphic section of the Peñas Azules area is divided into eight formations which are, from oldest to youngest (Fig. 9): Tres

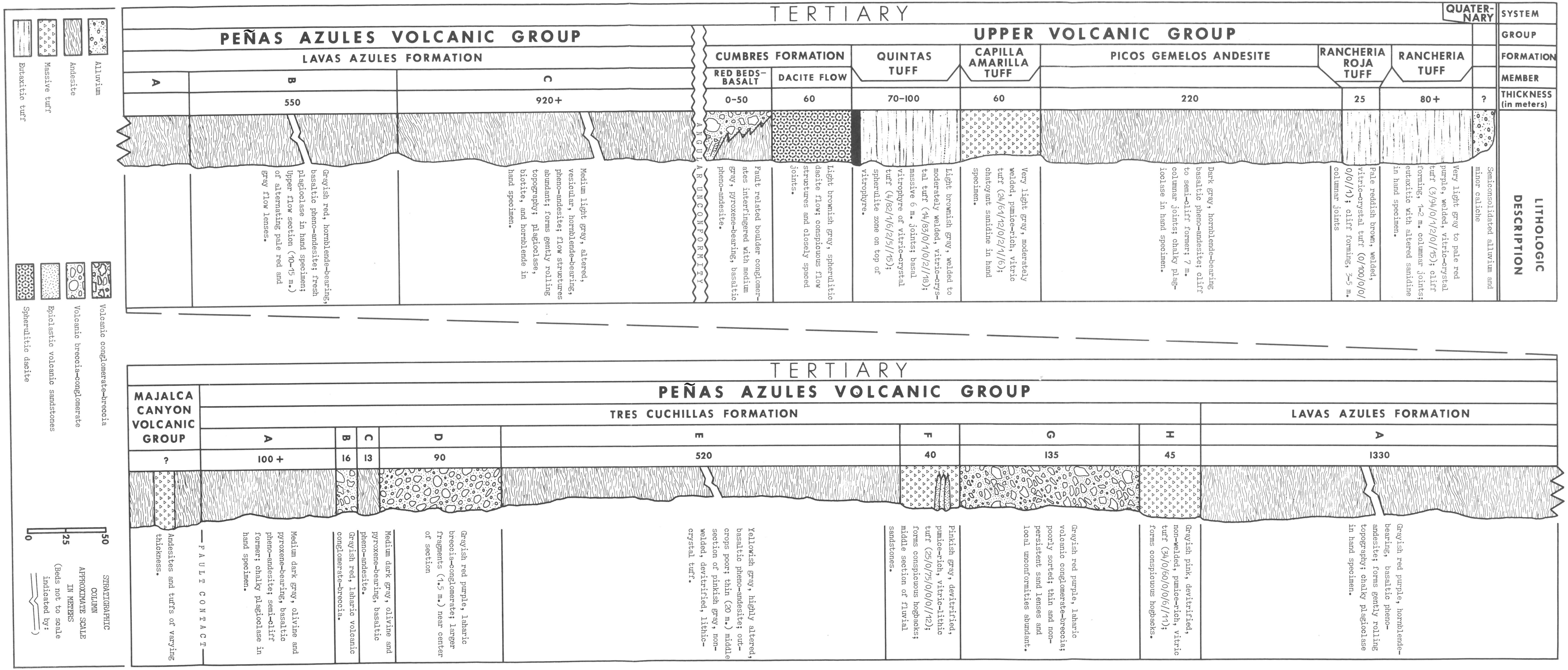


Figure 9. Generalized stratigraphic column of the Rancho Peñas Azules area, Chihuahua, Mexico.

Cuchillas, Lavas Azules, Cumbres, Quintas Tuff, Capilla Amarilla Tuff, Picos Gemelos Andesite, Rancheria Roja Tuff, and Rancheria Tuff. The two older formations, Tres Cuchillas and Lavas Azules, are combined to form the Peñas Azules Volcanic Group (4000+ meters), whereas the upper six formations constitute the Upper Volcanic Group (700+ meters). The formation and group names are used in this report for the sake of clarity; however, each formation is a distinct lithic unit that has been mapped throughout the Peñas Azules area and can be mapped over much of the surrounding area. The writer feels, therefore, that the formation names presented are valid and that they should become part of the future stratigraphic nomenclature in the area. The term "Upper Volcanic Group" is used informally in this paper and additional work is needed before a formal group name can be applied.

Good exposures of all formations occur throughout the study area. The formations of the Peñas Azules Volcanic Group dip steeply to the east and are exposed as an inlier within the broad, relatively flat area surrounding Rancho Peñas Azules. The nearly flat-lying younger formations are cliff-formers and several impressive canyons have been cut into them. The areal distribution of the formations is shown on the geologic map (Fig. 2).

LITHOSTRATIGRAPHIC DESCRIPTION

PEÑAS AZULES VOLCANIC GROUP

TRES CUCHILLAS FORMATION

The oldest group of rocks in the mapped area is a sequence of interbedded basaltic pheno-andesite flows, mud-flow deposits, and tuffs, here called the Tres Cuchillas Formation. The name is derived from three prominent hogbacks (Fig. 10) in the immediate vicinity of Rancho Peñas Azules which are formed by massive and very resistant tuff members of the formation. The formation is divided into eight members, designated by the letters A-H. Each of the members is discussed below.

A Member:--The A Member is a medium dark gray (N - 4), olivine and pyroxene-bearing basaltic pheno-andesite flow that is exposed in the Arroyo Majalca valley. This andesite is the stratigraphically lowest unit that was mapped. It dips at nearly 30° to the northeast and is in fault contact with a massive grayish brown boulder breccia which dips at 30° to the west (Fig. 5). The fault contact marks the boundary between the Peñas Azules Volcanic Group and the older Majalca Canyon Volcanic Group. The flow is strongly jointed and fractured (15-20 cm apart), the openings being filled in most cases with calcite. The unit is not exposed for any distance away from the stream, but a thickness of 160 meters was measured along the arroyo.

The andesite flow displays classic pilotaxitic structure and contains a high percentage of reworked fragments of the flow. These clasts, which average 2 mm (none larger than 10 mm), display a characteristically darker red matrix resulting from increased oxidation. Euhedral plagioclase phenocrysts (19 percent) are not highly zoned and range in composition from An_{30}

Figure 10. Hogbacks formed by resistant tuff members of the Tres Cuchillas Formation, one kilometer northwest of Rancho Peñas Azules. View is toward the northwest.

to An_{38}. Cores of some zoned crystals are as calcic as An_{44}. Albite occurs as both a thin outer rim and as cleavage infillings in most plagioclase phenocrysts. Carlsbad twinning is present in less than 10 percent of the crystals. Mafic minerals have been highly altered and replaced, so that determination of original mineral composition is difficult. Criteria for recognition of original mafics will be discussed in a later section. Generally, both pyroxene and olivine occur as accessory minerals, accounting for less than 3 percent of the total rock. Olivine appears to be slightly more abundant than pyroxene. The fine grained matrix (72 percent) of microlithic andesine laths displays flow structure in the form of parallel alignment of the small crystals. Calcite (7 percent) is an abundant accessory mineral, occurring as a vein and cavity filling.

B Member:--The B Member, a grayish red (5 R 4/2) laharic conglomerate-breccia, unconformably overlies the dark gray andesite flow. The entire unit lacks visible bedding or lamination, is poorly sorted, and shows no preferred orientation of fragments. Fragments of the breccia are angular to subrounded and range from clay-sized particles to boulders as large as 45 cm in diameter. By far, the most dominant fragments are light gray, completely devitrified crystal-vitric tuffs that contain highly altered plagioclase feldspar grains. A few grains display remnant shard structure but the majority have undergone complete crystallization. R. L. Mauger (1975 , personal communication) has found similar rock types in an older group of volcanics immediately to the west of the mapped area. Andesite fragments make up less than 5 percent of the total lithic component. There is no distinction between the lithology of the larger fragments and that of the very small fragments in the matrix. Small (1 mm) subrounded quartz grains are disseminated throughout the matrix. The larger fragments are irregularly distributed throughout the unit and are enveloped in a matrix of sand-, silt-, and clay-sized particles. The dull red coloration of the matrix is the result of intense oxidation of the finer particle sizes adjacent to grain boundaries.

Like all members of the Peñas Azules Volcanic Group, the unit is well exposed in the stream bed of the Arroyo Majalca. This mud-flow unit and the overlying andesite flow and mud-flow units form resistant ridges or ledges immediately to the north of the river (Fig. 5). The entire lower sequence dips generally to the northeast at about 45°.

C Member:--The C Member of the Peñas Azules Volcanic Group is a medium dark gray (N - 4) olivine and pyroxene-bearing, basaltic pheno-andesite, with a measured thickness of 13 meters. This unit displays pilotaxitic structure (68 percent microlithic matrix), but lacks the obvious fragmental structure of the lower A Member. Plagioclase consists of euhedral, highly altered crystals of calcic andesine (An_{40}-An_{46}) that account for 22 percent of the rock. Zoning is not prominent, but some cores of An_{49} are present. Albite occurs as a selective replacement mineral of some zoned crystals, resulting in concentric bands that display higher birefringence than the andesine. Mafic minerals are completely replaced or altered to outer rims of opaque minerals, with granular silica replacing the interior. Chlorite, actinolite, and minor calcite are present as alteration products associated with mafic minerals and as vein fillings. Silica has, however, replaced calcite in importance as a secondary vein and/or cavity filling mineral, in contrast to the A Member. Original mafic minerals (4 percent) were predominantly olivine and pyroxene, with pyroxene being slightly more abundant. The distinction between the two minerals is based on external crystal shape and remnants of cleavage in pyroxenes <u>vs</u> random orientation of fractures in olivine. The opaques that formed as a result of breakdown of the ferromagnesians seem to have preserved the characteristic cleavage and fracture patterns that were present in the original grains. Preserved crystal habits characteristic of pyroxene are abundant.

The C Member, along with the two lower members, forms a prominent NW-SE trending ridge which marks the lower entrance to Majalca Canyon.

<u>D Member</u>:--The D Member, with a measured thickness of 90 meters, directly overlies the C Member. A gently undulating erosional surface developed on the top of the C Member is filled in by larger fragments of the

conglomerate. Similar erosional surfaces are present on many of the andesite and tuff units of the Peñas Azules Volcanic Group (Fig. 11). The massive grayish red purple (5 RP 4/2) volcanic breccia-conglomerate contains fragments from sand-sized to 1.5 meters in diameter. The larger blocks consist almost entirely of subrounded to rounded andesite boulders. Although the unit lacks any visible lamination of preferred orientation of fragments, there is an obvious concentration of the larger andesite blocks near the center of the flow (middle 40 meters) and a marked decrease in fragment size toward the top of the section. Thin section analysis indicates that the clasts display grain support and that sorting has eliminated the finer grain sizes of clasts.

Two distinct and variably altered lithologic types predominate. Basaltic andesite fragments, ranging in size from 2 mm to 1.5 meters, make up as much as 60 percent of the rock. The andesite fragments vary in mineral content and texture, varying from very fine grained and non-porphyrtic to fine grained porphyries. The remaining fragments are light gray, highly devitrified crystal-vitric and vitric tuffs similar to those found in the A Member. Intense crystallization has removed all evidence of shard structure. Several of the andesite fragments are cut by silica (granular) veinlets which are truncated at the fragment boundaries, indicating implacement before later transportation and deposition. Both calcite and sericite occur as secondary veinlet and cavity fillings. The larger intergranular cavities are filled with a laminated zeolite mineral (possibly Thomsonite). The cavity filling zeolite displays auto-brecciation and is veined by both calcite and sericite.

E Member:--Directly overlying the D Member is approximately 550 meters of a highly altered, yellowish gray (5 YR 7/2) andesite, the E Member. The unit is not well exposed in the stream bed of the Arroyo Majalca. North of the river it is covered by talus and alluvium being deposited downslope from the topographically higher area immediately to the west of the field area. The entire unit forms a very broad area that slopes gently to the east, down to the level of the flat area surrounding Rancho Peñas Azules. Complete alteration of the plagioclase to clays and carbonate minerals (primarily calcite) has rendered simple point counts of matrix vs phenocryst extremely difficult. The flow is highly fractured (10-20 cm apart), which might easily account for its low resistance to erosion. Chalky plagioclase phenocrysts become less abundant upward in the section. Conglomerate units appear to be present as channel fillings near the top of the section.

The E Member contains a thoroughly devitrified pinkish gray (5 YR 8/1) lithic-crystal tuff with a maximum measured thickness of 20 meters. The tuff thins rapidly to the north and probably wedges out beneath an alluvial cover in less than 100 meters. This unit is interpreted as a tuff flow with an ash and mud matrix, representing a channel filling. Vesicular fragments are conspicuously absent, yet cavities resembling vesicles are present. The presence of such vesicular cavities and of moderate ash content in the matrix suggests an origin involving explosive activity combined with moderately rapid fluvial reworking of the constituents. Lithic fragments of altered (most of the alteration took place before incorporation in this unit) and rounded andesites and completely crystallized vitric-crystal and crystal tuffs comprise 47 percent of the rock. Highly embayed quartz crystals (14 percent) and rounded plagioclase grains (11 percent) seem to indicate a moderate degree of transportation before deposition. Remnant shard structure is only faintly visible in larger matrix accumulations. Generally, the ash and mud comprising the matrix is altered to sericite and chlorite. Calcite (3 percent) is present as a secondary cavity and alteration mineral.

F Member.--The contact between the F Member and the underlying andesite is quite sharp and well exposed at a small concrete bridge over the Arroyo Majalca, approximately 1 kilometer southwest of Rancho Peñas Azules. The vitric-lithic tuff and interbedded epiclastic volcanic sandstones have a measured total thickness of 43 meters, and the rocks of the entire unit dip steeply (52^{o}) to the northeast. This steep dip, combined with high resistivity to weathering, is responsible for the topographic prominence of the unit. Very large and conspicuous hogbacks (Fig. 10) are formed by this tuff and a lithologically similar tuff stratigraphically higher in the section (the H Member).

In outcrops at the bridge mentioned above, the member is composed of three lithologically distinct units: (1) a lower vitric-lithic tuff (28 meters); (2) a middle sequence of epiclastic volcanic sandstones (3 meters); and (3) an upper vitric-lithic tuff (12 meters). All three units are considered by the writer to be very closely related in terms of origin and petrology. However, the middle sequence of volcanic arenites cannot be traced along strike for any significant distance away from the Arroyo Majalca. It is not found in the thick vitric-lithic tuff of the large hogback only 0.8 kilometers north of the river. Thus, the middle sequence is interpreted as an extensive channel deposit developed during a brief (?) cessation of eruptive activity.

The lower section of the F Tuff Member is a pinkish gray (5 YR 8/1) vitric-lithic tuff showing very rough bedding in outcrop. Pumice clasts replaced by chalky-weathered calcite form conspicuous light colored cavities throughout. Variably colored lithic fragments are widely disseminated. Thin section analysis indicates a thoroughly devitrified and highly altered matrix (66 percent) which has been selectively altered to calcite, chlorite, clays, and sericite. Euhedral plagioclase phenocrysts (9 percent) range in diameter from 0.2 mm to 1.0 mm and range in composition from An_{30} to An_{34}. Quartz (3 percent) is in 0.1 mm to 1.2 mm (0.8 mm average), very highly embayed grains. A faint cleavage, visible only when the quartz grains are in the extinction position, probably represents cleavage inherited from β-quartz. Lithic fragments, comprising 21 percent of the rock, range in size from 0.2 mm to slightly over 7.0 mm, and are very highly altered. Two distinct lithologic types of clasts predominate; basaltic-andesite fragments (35 percent of total lithic fragments), and thoroughly devitrified crystal-vitric tuff fragments (60 percent of total lithic fragments). The later are conspicuously larger than the former. The remaining 5 percent of lithics are smaller (1.5 mm) clasts of microcrystalline silica. Intense crystallization has completely destroyed shard structure in both the matrix and the lithic fragments; however, faint eutaxitic structure remains visible in a few of the fragments.

A shift in position of the eruptive center or a short cessation of eruptive activity allowed the formation of a fluvial sequence of pale red purple (5 RP 6/2) to light brownish gray (5 YR 6/1) epiclastic volcanic sandstones and interbedded very thin (5 cm to 10 cm) air-fall tuffs. This middle section, totaling 3 meters in thickness, is characteristically well sorted. Cross-bedding is well developed and thin lenses of very fine sandstones occur at various horizons within the unit. Three distinct fluvial sections, listed below from oldest to youngest, outcrop at the bridge site; (1) granular, very coarse sandstone (1.2 meters): (2) slightly granular, coarse sandstone and interbedded tuffs (1.1 meters); and (3) slightly granular, very coarse sandstone (1.5 meters). As the textural terminology (Folk, 1974) indicates, the gravel-size fragments become less abundant near the top of the fluvial section. Devitrified tuff fragments (53 percent) and andesitic fragments (16 percent) are the dominant grains. Both are subangular to subrounded. Highly embayed quartz grains (13 percent) and rounded laths of andesine (16 percent) are generally smaller than the tuff and andesite rock fragments. Grain support is predominant and the matrix (8 percent) of original mud has been altered to calcite, chlorite, and clays.

The middle fluvial section grades almost imperceptibly upward into a moderately well bedded pinkish gray (5 YR 8/1) to pale brown (5 YR 5/2) vitric-lithic tuff. The upper part of this section is extremely massive, closely resembling the lower vitric-lithic tuff of this member. In outcrop, the upper and lower tuffs are indistinguishable, although pumice fragments are slightly more abundant in the upper unit. Quartz, as seen in thin section, is slightly less abundant in the upper tuff.

G Member.--More than 145 meters of grayish red purple (5 RP 4/2) volcanic conglomerate-breccia lies on the uneven erosional surface developed on top of the F Member (Fig. 11). The G Member is exposed in the stream bed of the Arroyo Majalca, and can be traced northwestward for nearly 2 kilometers, its thickness varying greatly along strike. It is also well exposed at the base of the hogback shown in Figure 10.

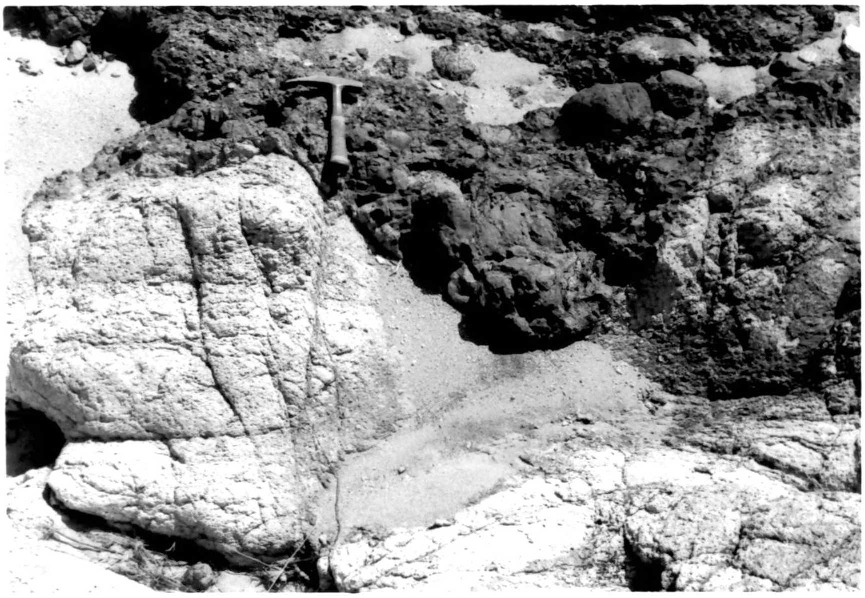


Figure 11. Uneven erosional surface developed on the F Member of the Tres Cuchillas Formation, exposed in stream bed of Arroyo Majalca, one kilometer southwest of Rancho Peñas Azules.

The beds are poorly sorted but do show a very general grading of fragment sizes. Largest fragments in the lower 35 meters are 45 cm to 50 cm in diameter. Fragment size increases in the middle 60 meters to a maximum of 90 cm and then decreases rapidly upward so that clasts of only 8 cm maximum diameter occur in the upper section. Thin and laterally non-persistent volcanic sand lenses, and repetitive, roughly parallel erosion surfaces are common throughout the unit. Because these water-laid and laharic volcanic conglomerate-breccias and other stratigraphically lower units of similar lithology are interbedded with the andesitic flows herein described, it is believed that the rocks are the result of rapid denudation of large andesite flows and/or cones.

Thin section petrography does not give a completely accurate account of such a unit simply because of the very large size of the fragments;

however, field evidence suggests no great discrepencies between the composition of the larger and smaller fragment sizes for this particular unit. The rock fragments (84 percent) are angular to subangular (a few of the smaller grains are rounded) andesites and devitrified tuffs in various stages of alteration, the former being twice as abundant as the latter. Plagioclase grains (An_{32} to An_{37}), which are angular to rounded and altered to clay, constitute 3 percent of the rock. Anhedral quartz comprises only 0.5 percent of the rock.

Grain support is predominant throughout the unit and secondary calcite and granular silica (13 percent) completely fill the pore spaces. In addition, every lithic fragment, regardless of size, displays a thin outer rim of iron oxide staining. Both these facts seem to indicate a high initial porosity of the grain supported unit. Oxidation of the fragments took place before cementation by calcite and silica.

H Member.--The uppermost member of the Tres Cuchillas Formation is the H Member, a grayish pink (5 R 8/2), moderately welded, vitric-lithic tuff. This tuff forms a series of conspicuous hogbacks a few kilometers northwest of Rancho Peñas Azules (Fig. 10). Thickness varies within the unit from 47 meters to 65 meters.

Elongate lapilli (up to 8 mm) of altered and chalky pumice are widely disseminated throughout a highly devitrified matrix. Very faint remnant shard structures attest to the moderately low degree of welding of the matrix. Lithic fragments, 15 percent, consist of highly welded vitric-crystal tuffs with quartz and plagioclase phenocrysts, and a very small percentage of andesite fragments, both of which are moderately altered and/or devitrified. Quartz is in very highly embayed, subhedral to anhedral grains averaging 0.6 mm. Some are as large as 2.2 mm. Plagioclase, as is true of quartz, occurs as both a matrix supported phenocryst and as primary phenocrysts in lithic fragments. Most of the plagioclase is under 1.8 mm in diameter, and the average composition is about An_{30}. Both completely untwinned and albite-twinned euhedral plagioclase are present. The untwinned variety is extremely altered to clay while the albite-twinned plagioclase is moderately fresh.

LAVAS AZULES FORMATION

The Lavas Azules Formation, with a thickness of over 3000 meters, directly overlies the H Member of the Tres Cuchillas Formation. The extraordinarily thick flow is well exposed in the stream bed of the Arroyo Majalca and in the broad, open area surrounding Rancho Peñas Azules. The bluish coloration of the andesite near the rancho is no doubt responsible for the colorful name Rancho Peñas Azules, literally "Ranch of the Blue Rocks." The flow is here divided into three major members based primarily on phenocryst composition and on physical appearance in outcrop. It should be pointed out that this subdivision is a very generalized one, and that there is field evidence for successive flows within each of the three members. The extreme thickness of the unit negated any attempt by the writer to thoroughly sample and study individual flows. Instead, samples deemed characteristic of gross lithologic types were studied in an attempt to accurately describe the general characteristics of the flow-unit. The great thickness of the flow-unit is attributed by the writer to infilling of a large graben structure, the eastern boundary of which is evidently not exposed in the study area. It is obvious, however, that large scale vertical displacements have occurred throughout the region; for example, Cretaceous carbonate rocks are exposed in Sierra Peña Blanca (Fig. 1) at elevations roughly equivalent to the elevations of the younger sequence of ignimbrites in the study area. Vertical displacements might have created a large sinking graben that was bounded on the east by carbonates. This depression could then have been filled with andesite flows and lahars. It should also be noted here that the top of the flow-unit was not located. The Lavas Azules Formation is covered unconformably by the younger sequence (Stratigraphic Column, Fig. 9) of ignimbrites and flows near the village of Majalca.

A Member:--The A Member, approximately 1450 meters thick, is a grayish red purple (5 RP 4/2), hornblende-bearing, basaltic pheno-andesite. In thin section the rock displays very pronounced pilotaxitic structure, with the groundmass plagioclase laths wrapping around phenocrysts of various types (Fig. 12). The groundmass, 74 percent, consists primarily of euhedral plagioclase , averaging 0.05 mm in diameter. Plagioclase phenocrysts comprise 18 percent of the total rock and show a moderate tendency for glomeroporphyritic development in the form of crystal clusters without visible intergrowth of the crystals. The euhedral to subhedral plagioclase is in 0.3 mm to 2.0 mm (1.2 mm average) crystals which exhibit both albite and albite-carlsbad twinning. Zoning is poorly developed and is of the normal variety in all observed cases. The phenocrysts range in composition from An_{42} to An_{51} (calcic andesine), with cores being only slightly more calcic. Alteration of the plagioclase is generally to clay and minor amounts of sericite. Hornblende, 4 percent, is euhedral and occurs as elongate grains

(1.2 mm maximum length) and cross-sectional crystals averaging 0.3 mm in diameter. Pyroxene comprises less than one percent of the total rock. The distinction between pyroxene and amphibole is here based on relic grain morphology and the presence of ghost cleavage. Both pyroxene and hornblende are completely altered and now consist of an iron oxide outer rim replacement and an inner crystal replacement of sericite. Both mafic minerals display a distinct tendency for glomeroporphyritic texture. As many as 10 to 12 crystals occur as crystal clusters in masses 3 mm to 5 mm in diameter, with no visible intergrowth; however, the largest percentage of mafic grains occur as disseminated crystals. Opaque minerals occur as reaction rims around mafic crystal borders and also as cavity or vesicle infillings. Quartz, 1 percent, as seen in thin section occurs as a secondary veinlet-filling mineral.

The percentages of plagioclase and mafic mineral phenocrysts are nearly constant throughout the unit. However, there is a distinct decrease in plagioclase crystal size toward the top of the unit, with average diameter decreasing from 1.2 mm to 0.5 mm. Combined with this upward size decrease, there is a shift upward toward more sodic (An_{33}) plagioclase. The groundmass (0.05 mm average diameter) throughout the unit is characteristically pilotaxitic, but in some zones the parallel arrangement of crystals around phenocrysts is at a minimum.

B Member:--The middle 600 meters of the Lavas Azules Formation, the B Member, is a grayish red (5 R 4/2), hornblende-bearing, basaltic-pheno-andesite. The contact with this unit and the underlying A Member is not sharp, although the B Member is conspicuously more resistant topographically. The subdivision is based on the higher percentage of both hornblende and plagioclase as phenocrysts and on the bright red coloration of the unit. In addition, the B Member marks the first occurrence of moderate zoning in the phenocryst plagioclase. In this unit also, quartz occurs as a granular veinlet-filling secondary mineral.

Plagioclase phenocrysts, comprising 26 percent, are euhedral and range from 0.3 mm to 3.5 mm (1.0 mm average) in diameter. The phenocrysts range in composition from An_{26} to An_{31} (calcic oligoclase) and are slightly more sodic than those in the upper part of the A Member. Normal, oscillatory, and reverse zoning listed in order of decreasing occurrence are characteristic of the plagioclase phenocrysts; however, great differences in composition do not occur from core to rim. Cores rarely exceed An_{40}. The plagioclase is not highly altered but is severely fractured. Alteration is confined to albite (?) replacement along fractures and selective alteration of zoned cores to clays. Bright red-orange iron oxide staining concentrated along fractures in the plagioclase gives the unit its characteristic grayish red coloration in outcrop.

Hornblende, 4 percent, is in euhedral grains ranging from 0.2 mm to 1.8 mm and averaging 0.8 mm in diameter. The hornblende displays two distinct periods of growth, a conclusion which is based on the presence of two distinct alteration rims of iron oxide within single crystals (Fig. 13). Also, intergrowth of crystals is illustrated by grain contacts of the inner crystals.

The upper 10-15 meters of the B Member is a pale red andesite flow with pronounced flow-banded structure. In hand specimen, the rock closely resembles an ignimbrite. However, in thin section

Explanation of Figure 12 and Figure 13

Figure 12. Lavas Azules Formation. Color photomicrograph (crossed nicols) illustrating pilotaxitic texture of the basaltic pheno-andesite. Plagioclase laths wrap around a large phenocryst of calcic andesine (upper left-hand corner).

Figure 13. Lavas Azules Formation. Color photomicrograph (crossed nicols) illustrating two distinct alteration rims of iron oxide within intergrown amphibole crystals. Intergrowth of crystals is shown by grain contact of the inner crystals. A zoned calcic andesine phenocryst which displays alteration to clay is present in the left-center of the figure.

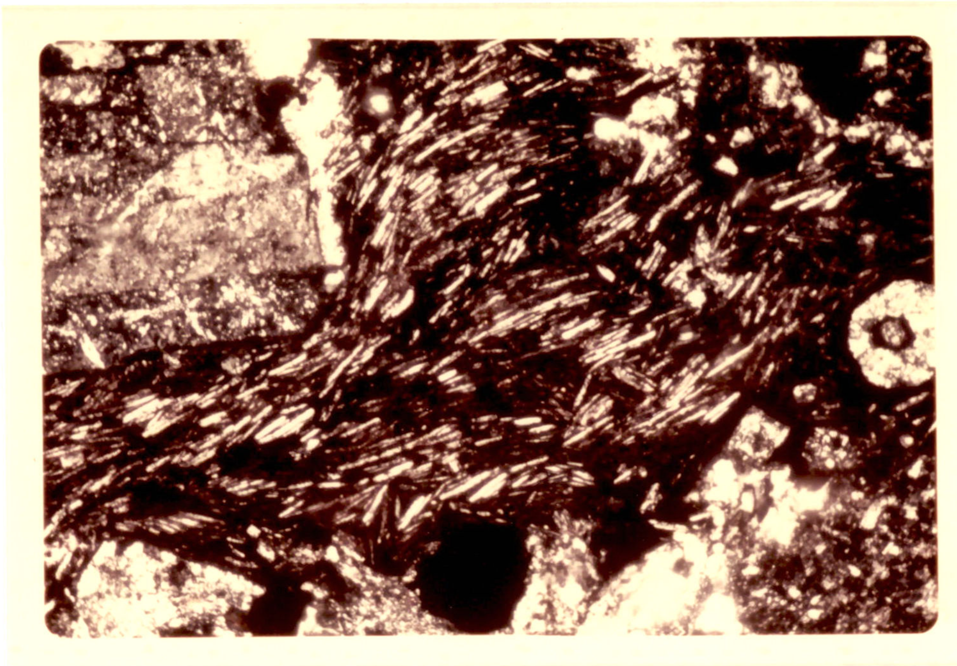


Figure 12.

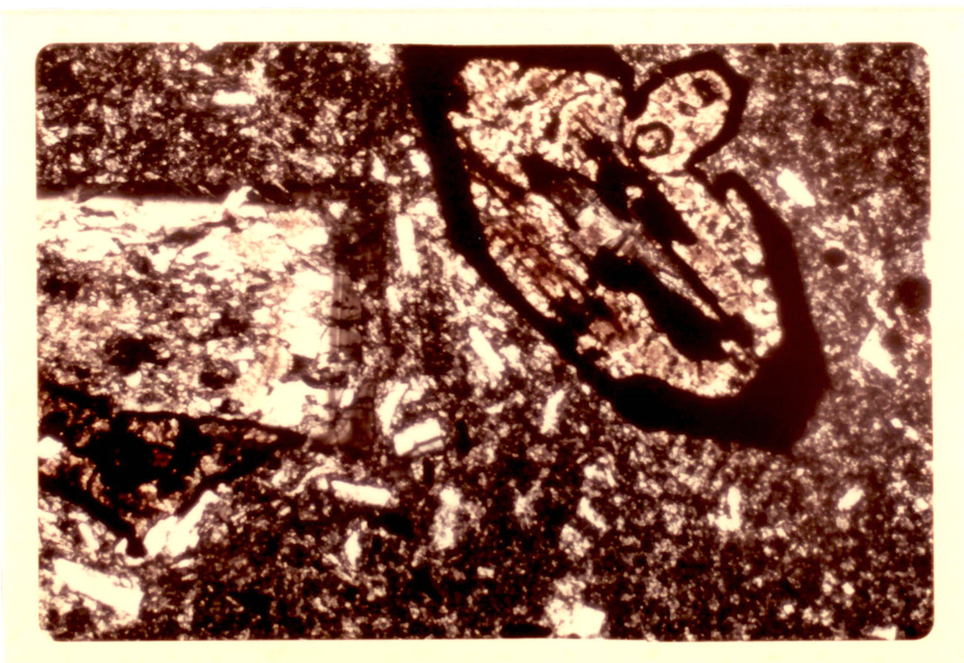


Figure 13.

hornblende and biotite-rich layers of pilotaxitic andesite alternate with light gray, fine grained, glassy zones (fiamme) that contain both equidimensional and elongate plagioclase grains and are low in phenocrysts (Fig. 14). Plagioclase is of the same size and composition as that in the lower section of the unit, but accounts for only 22 percent of the total rock. Attempted point counts of only the phenocryst-rich red layers yield considerably higher plagioclase percentages. Hornblende (4.5 percent) and biotite (0.5 percent) are also heavily concentrated in the same zones. Hornblende displays the iron oxide rim--sericite core--alteration pattern typical of the lower section. Ghost hornblende cleavage is especially well preserved. Red iron oxides are concentrated in the fractures of plagioclase crystals. The alternating red-gray color pattern is attributed to alteration of mafic minerals along zones in flow layers of high mafic mineral concentration.

The mechanism of formation of the flow-banded section is not clear; however, several authors (McCall, 1964; Vlodavetz, 1963; Keegai, 1966) have described similar lavas which they have termed "froth flows" and/or "tuff lavas." In them, clots of magma presumably richer in gas or silica than the surrounding magma have been drawn out into parallel lenses or fiamme by flowage and have developed a coarser crystallinity than their surroundings. The relics of angular and Y-shaped shards that are generally recognizable even in densely welded portions of ash flows are absent in the fiamme. According to McDonald (1972), the three-dimensional forms of the fiamme offer a clue to the mechanism of formation of the rock body that contains them. In true ash-flow deposits the fiamme are more or less equidimensional in horizontal section. They

Explanation of Figure 14

Figure 14a. Lavas Azules Formation. Color photomicrograph (plane polarized light) cut perpendicular to flow-banding, showing flow structures in 'froth flow' or 'tuff lava'. Light colored zones are silica-enriched lenses which have been flattened and elongated by flow. Darker zones contain plagioclase, hornblende, and biotite in a pilotaxitic groundmass.

Figure 14b. Same as Fig. 14a above, except nicols crossed.

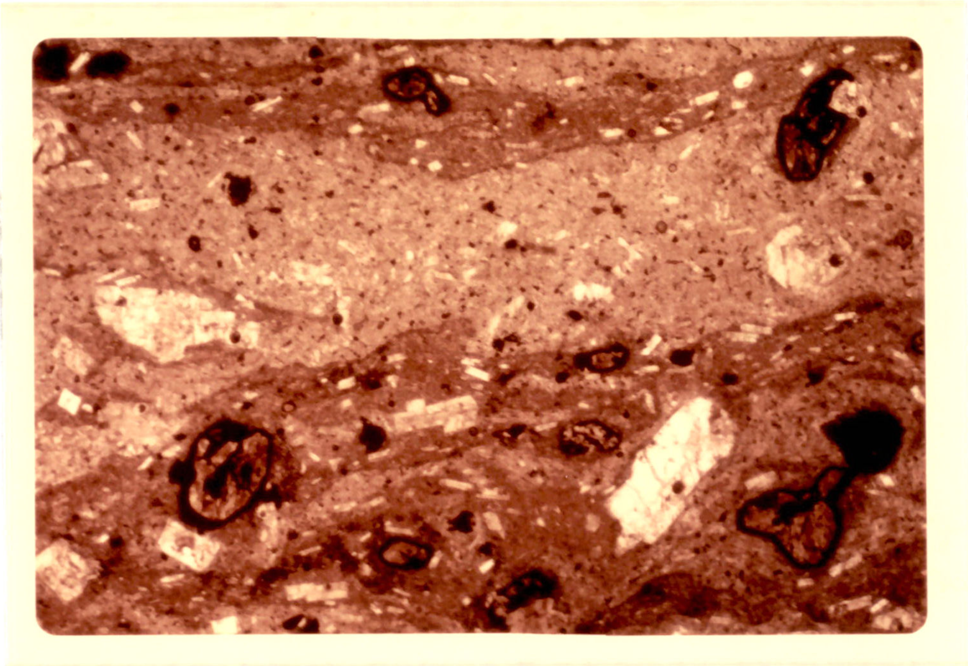


Figure 14a

1 mm

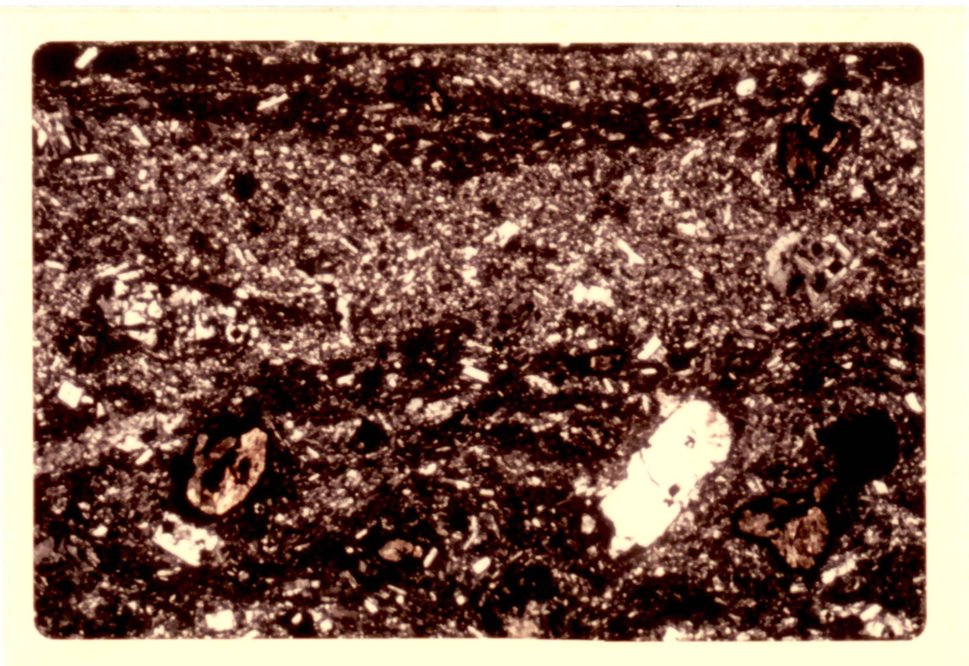


Figure 14b

1 mm

result from vertical compression and flattening of more or less equidimensional lumps of pumice after the flow had nearly or completely come to rest. As a consequence, they have suffered little or no stretching in the direction of flow. During initial movement of the ash flow, each lump of plastic pumice is discrete, and the viscosity of the surrounding material is too low to bring about deformation of the pumice by flowage. In contrast, the clots in froth flows or tuff-lavas that form the fiamme are not discrete and are drawn out by flowage of the relatively viscous enclosing mass. The resulting fiamme should be long and narrow in both horizontal and vertical section. This is indeed the case in the gray fiamme of the red-gray flow-banded section.

Vlodavetz (1963) described a tuff-lava from Kamchatka that contains fiamme of porphyritic rhyodacite in a matrix of dacite that has the texture of an ordinary flow. He believes that a body of differentiated magma in a shallow chamber consisted of fluid dacite with a cap of nearly solid but still plastic rhyodacite. Upward movement during eruption resulted in incorporation of rhyodacite into the rising liquid. The hot plastic fragments were then carried out in the liquid dacite where they were drawn out into thin streaks by flowage. The writer believes that this type of mechanism is responsible for the formation of the red-gray flow. Differentiation of an andesitic magma could produce a siliceous cap. Fragments or clots of this more siliceous cap could be incorporated into the andesite during extrusion and could be stretched by flowage. The resulting rock would consist of zones of pilotaxitic andesite that contain extensive silica-enriched fiamme.

C Member:--The contact between the red-gray flow of the B Member and the overlying medium light gray (N - 6) C Member is quite sharp in outcrop. The lower section of C Member displays none of the red coloration typical of the underlying flow. However, the contact is less distinct from a mineralogic and petrographic point of view. Mineralogically, the lower 650 meters of the C Member closely resemble the red flow layers described in the previous section. Plagioclase phenocrysts (15 percent) are considerably less abundant here than in other stratigraphically lower sections of the Lavas Azules Formation. The plagioclase, with a consistent composition of An_{25} (calcic oligoclase), is in 0.2 mm to 2.5 mm euhedral to subhedral grains, which are very highly altered to clay and calcite. The phenocrysts display a distinct alignment, and the rock contains calcite stringers which combine to give the rock an unmistakable flow structure in hand specimen. This feature is not characteristic of the lower two-thirds of the Lavas Azules Formation.

Both amphibole (3 percent) and pyroxene (0.5 percent) are present and average 0.4 mm in diameter. Ghost cleavage, again accentuated by iron oxide, is evident. Also, both mafic minerals display the high degree of alteration to iron oxide, sericite, and actinolite (?) which is characteristic of the entire sequence.

Biotite, comprising as much as 0.3 percent of the rock, is in 0.06 mm to 0.8 mm euhedral crystals that are only slightly altered. Chlorite and vermiculite pseudomorphs after very small (0.06 mm) original biotite crystals are well disseminated.

The upper 350 meters of the C Member is a medium light gray (N - 6), highly vesicular, hornblende-augite-bearing, pheno-andesite. Plagioclase and minor phenocrysts become increasingly more abundant upward throughout the entire C Member. Plagioclase phenocrysts (32 percent) average 2.5 mm in diameter. Larger crystals, up to 5.2 mm, are euhedral and moderately fractured while smaller crystals (0.2 mm) are generally subhedral to anhedral. Composition varies from An_{27} to An_{33} (calcic oligoclase). Alteration of the plagioclase is highly selective in that a small percentage of grains are highly altered to clay, while the majority are extremely fresh and unaltered.

Hornblende and augite (8 percent) display glomeroporphyritic development. Hornblende was present as 0.1 mm to 1.2 mm euhedral crystals but now consists of iron oxide rims that surround the interior areas of chlorite and actinolite. Augite is much less abundant than hornblende and is unaltered in some grains. However, alteration of large augite crystals to chlorite or replacement by calcite (?) is not uncommon.

Vesicles are quite common (11 percent) in the upper section of the C Member. Most vesicles reflect at least three major phases of infilling which are readily visible in hand specimen. A very thin rim of iron oxide completely lines the vesicle. Next the cavity is lined with a rim of silica, and both calcite and silica occur as the inner cavity filling. The siliceous amygdules commonly weather or break from the rock, leaving iron oxide-lined cavities (2 mm) which are easily visible in hand specimen.

UPPER VOLCANIC GROUP

CUMBRES FORMATION

The Cumbres Formation, informally named by Mauger (1975), was applied to a very complex unit of interfingered basalts, boulder conglomerates and boulder breccias, tuffs, and tuff breccias. These rocks make up most of the prominent east-facing erosional escarpment in the upper Arroyo Majalca drainage system, one kilometer east of the village of Cumbres de Majalca. Mauger divided the formation into two members, the Red Beds-Basalt Member and the Tuff-Tuff Breccia Member. The latter is not exposed in the study area. The Red Beds-Basalt Member is well exposed on the south slopes of the Arroyo Majalca valley, approximately 1 kilometer south of Rancho Peñas Azules. It should be pointed out here that Mauger named the Red Beds-Basalt Member for exposures farther west of the study area where the mafic rock of the member is highly altered and closely resembles basalt. Based on phenocryst composition, however, pheno-andesite is the dominant mafic rock of the formation within the study area.

A third unit, occupying approximately the same stratigraphic position as the two members mentioned above, is composed of a spherulitic rhyolite or dacite flow. The exact relationships of these three sections have not yet been completely worked out.

Red Beds-Basalt Member:--The Red Beds-Basalt Member immediately underlies the Quintas Tuff throughout the study area. A thick-bedded boulder conglomerate and boulder breccia unit is exposed along the south slopes of the Arroyo Majalca valley (Fig. 15). The massive bouldery unit grades rapidly eastward into a fluvial section of sandstones and bright red shales

Explanation of Figure 15 and Figure 16

Figure 15. Thick-bedded boulder conglomerate and boulder breccia of the Red Beds-Basalt Member of the Cumbres Formation. The exposure occurs along the south slopes of the Arroyo Majalca about 1.5 kilometers southwest of Rancho Peñas Azules. Largest boulders are approximately 1.5 meters in diameter. View is toward the south. Exposed thickness is 10 meters.

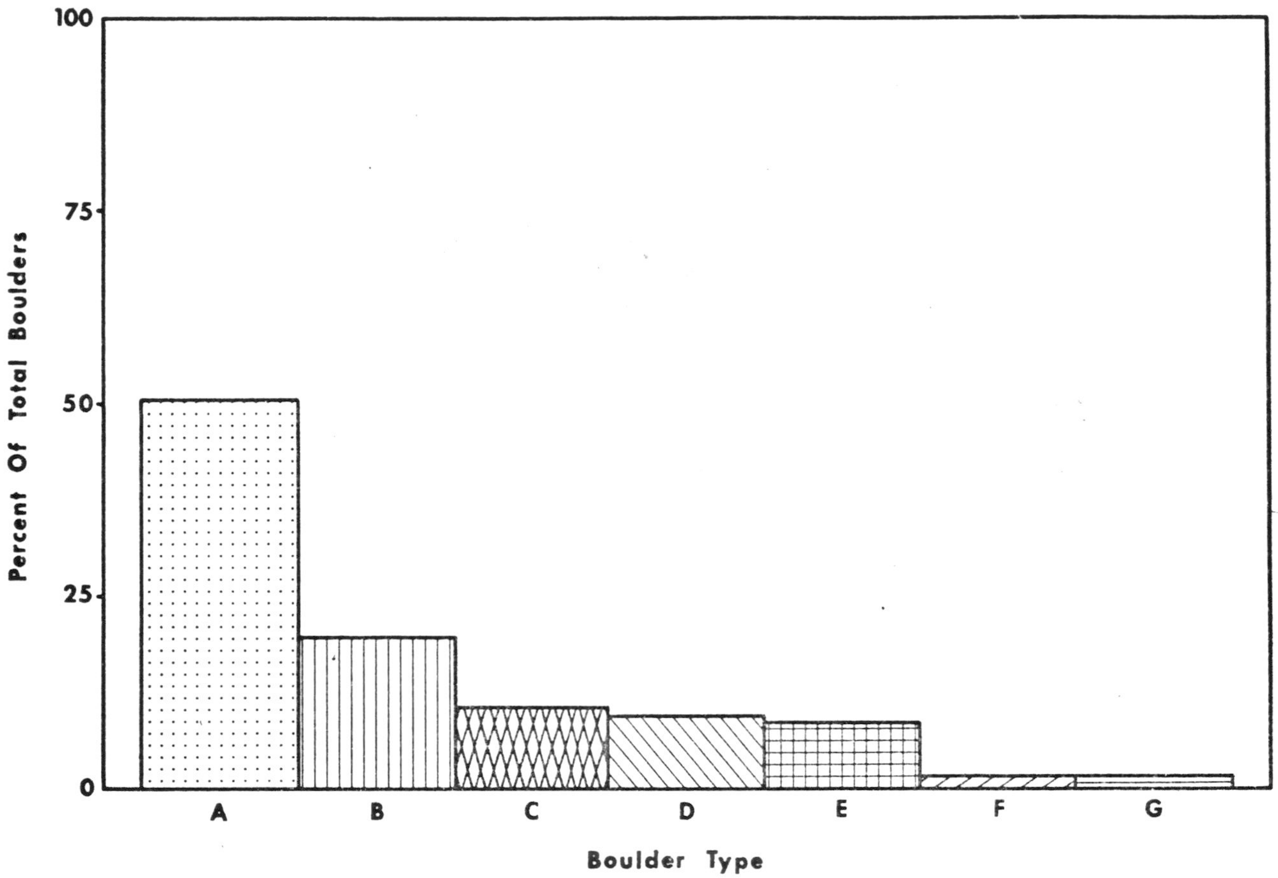
Figure 16. Bright red fluvial units of the Red Beds-Basalt Member of the Cumbres Formation. The exposure occurs along the south slopes of the Arroyo Majalca about 2 kilometers southeast of Rancho Peñas Azules. View is toward the southwest. Exposed thickness is about 3 meters.

Figure 15.

Figure 16.

(Fig. 16), the transition being observable along a strike length of less than two kilometers. The red clastic rocks dip gently east and, in angular unconformity, overlie the more steeply dipping basaltic andesite flows and light colored tuffs of the Peñas Azules Volcanic Group. Interbedded with the sandstones and shales along the south bank of the Arroyo Majalca is a grayish orange pink (5 YR 7/2), porous tuff about 1 meter thick. The tuff forms a small but persistent ledge within the red fluvial rocks. No basalt or andesite flows were recognized with the fluvial sequence on the southern slopes of the Arroyo Majalca valley.

The very massive bedded boulder unit thickens somewhat to the west, and is not recognized west of the roughly N-S trending fault in the southwestern corner of the study area (Fig. 2). Thus, the entire sequence of conglomerates and sandstones is considered by the writer to be a talus-type deposit that accumulated on the down side of a fault. Clasts range from angular slabs over 10 meters thick in the lower part of the section near the fault, to sand- and clay-sized particles in exposures farther east of the fault. Average fragment size near the fault is in the 0.5 to 1.0 meter range. Detailed petrographic analyses of the individual fragments comprising the section were not performed; instead, boulder counts of the predominant clast types were performed on the outcrop. The results of those counts are shown in histogram form in Figure 17. The descriptions of the major rock types listed in Figure 17 are field descriptions supplemented, in a few cases, by thin section study. Similar boulder counts performed by Mauger (1975) on units of the Red Beds-Basalt Member west of the study area yield quite similar histograms, suggesting contemporaniety of faulting and similarity of source rock.



ROCK DESCRIPTIONS:

A. Pale red (5 R 6/2), crudely eutaxitic, welded, crystal-vitric tuff; altered feldspar, moderately abundant quartz, and minor biotite in hand specimen.

B. Pale red (5 R 6/2). massive, moderately welded, vitric-lithic tuff; altered feldspar, dark rock fragments, and minor quartz in hand specimen.

C. Pinkish gray (5 YR 8/1), massive, vitric-crystal tuff; altered feldspar, and minor biotite and quartz in hand specimen.

D. Grayish red (10 R 4/2), highly altered, porphyritic andesite; phenocrysts of small (0.5 mm), altered plagioclase crystals.

E. Light gray (N - 7), massive, vitric-crystal tuff; large (4 mm) quartz phenocrysts in hand specimen.

F. Very light gray (N - 8), massive, vitric-crystal tuff; altered feldspar and minor quartz in hand specimen.

G. Light gray (N - 7), massive, moderately welded, vitric-lithic tuff; various rock fragments in hand specimen.

Figure 17. Composition of the most important boulder types of the Red Beds-Basalt Member of the Cumbres Formation, based on hand specimen description.

Red beds are much thinner on the north side of the Arroyo Majalca where basaltic andesite flows occupy the equivalent stratigraphic position. Such flows crop out along the southwestern foothills of Cerro Punta de Agua (Fig. 18). Based on phenocryst composition, the rock is a medium gray (N - 5), pyroxene-bearing, basaltic pheno-andesite. Abundant phenocrysts of euhedral to subhedral plagioclase (19 percent) and anhedral clinopyroxene (7 percent) are set in an orthophyric groundmass of plagioclase and iron oxides. The average plagioclase composition is An_{42} (andesine), and zoning is generally of the normal and normal-oscillatory type. Cores are as calcic as labradorite while the rims are usually composed of calcic oligoclase. Most plagioclase is very fresh and only moderately fractured. The dominant clinopyroxene is augite with extinction ($Z \wedge C$) of at least 40°. The augite is unaltered and occurs as both a groundmass constituent and as phenocrysts averaging about 0.3 mm in diameter. Most of the phenocrystic augite is associated with larger plagioclase crystals. Biotite and amphibole, both of which are completely altered to sericite and/or iron oxide, comprise 4 percent of the rock. Biotite was slightly more abundant than amphibole.

Dacite Flow Member:--An isolated hill less than 1 kilometer northeast of Rancho Peñas Azules consists of a short, but very thick, bulbous, spherulitic dacite (?) flow (Fig. 2). Thickness of the flow may exceed 65 meters. Color varies from light brownish gray (5 YR 6/1) to brownish gray (5 YR 4/1). The flow rests directly on the eroded and tilted lavas of the Peñas Azules Volcanic Group and is thus younger. However, its exact stratigraphic relationship with respect to the Red Beds-Basalt Member of the Cumbres Formation is not known.

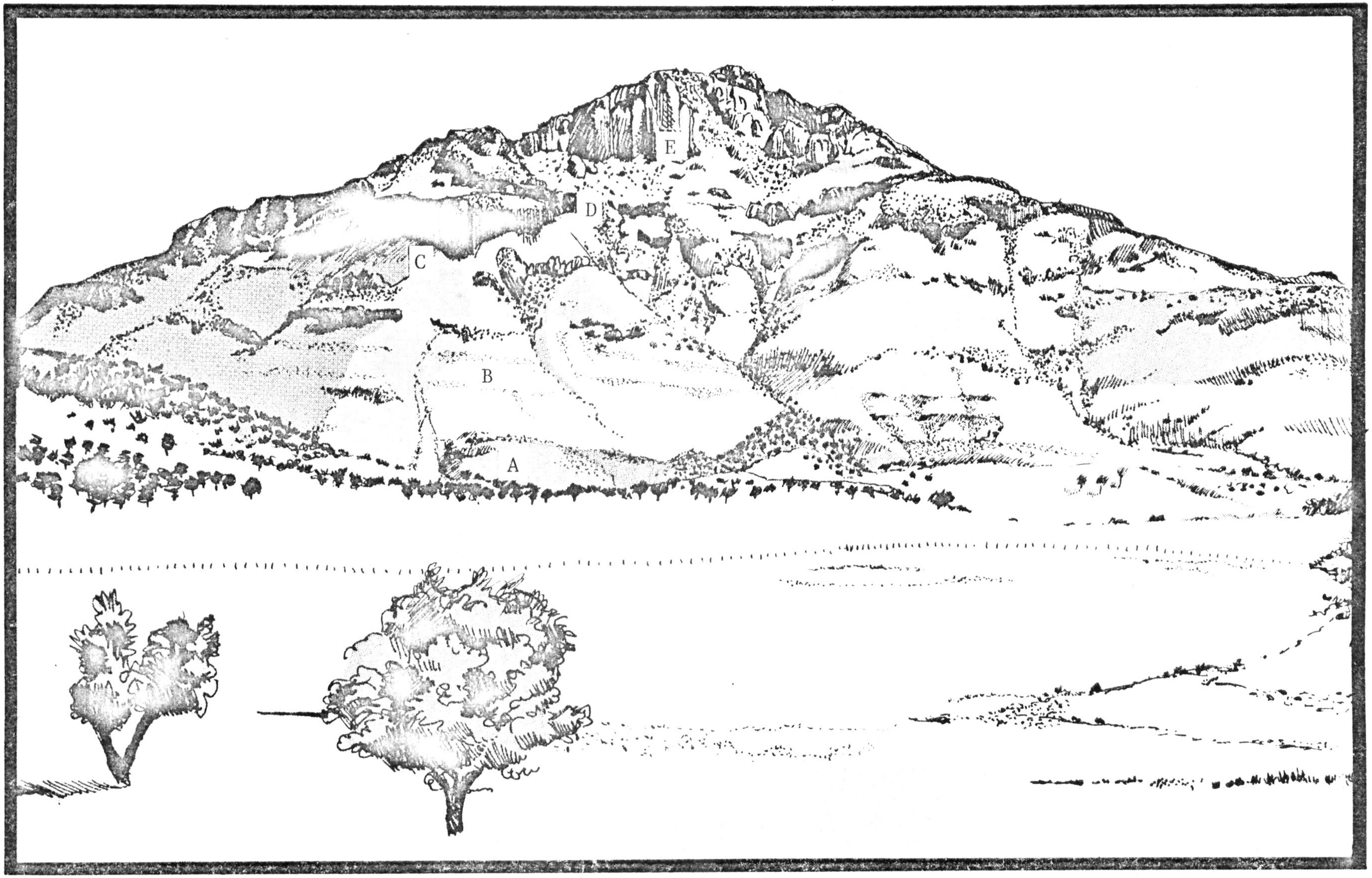


Figure 18. Cerro Punta de Agua as viewed from 1 kilometer southeast of Rancho Peñas Azules. View is toward the north. The stratigraphic section is as follows: A, Red Beds-Basalt Member of Cumbres Formation; B, Quintas Tuff overlain by Capilla Amarilla Tuff; C, Picos Gemelos Andesite; D, Rancheria Roja Tuff; E, Rancheria Tuff.

Flow structures characterize practically every outcrop of the dacite (Fig. 19), and silica veinlets (0.1 mm to 5 cm thickness) are extremely abundant. The veinlets are most likely the result of silica infilling of well developed cooling joints in the flow. The intersection of two or more veinlets has quite often resulted in the formation of geode-like cavities lined with quartz crystals and chalcedony.

In thin section the rock consists entirely of coarse ash to lapilli size spherulites (71 percent) and highly altered plagioclase (25 percent). The plagioclase, which averages about An_{33} (andesine) in composition, is typically altered to clay and almost completely replaced by granular silica. Most of the relatively unaltered plagioclase is spongy-looking, the result of micro-inclusions of glass or matrix material. Biotite is the only unaltered mafic mineral of importance, occurring as anhedral grains scattered throughout the flow.

The well developed spherulites are, by far, the most conspicuous features of the flow. Figure 20 illustrates the radially oriented crystalites and typical 120° triple junctions between adjacent spherulites. The process of development of triple junctions has been described by Stanton (1972) and others for aggregates of soap-froth bubbles and like grains in monomineralogic rocks and metals. Individual spherulites are composed of radially oriented crystalites with internal concentric banding, upon which are superimposed a very fine radial pattern of magnetite or hematite dendrites (Fig. 20). Ross and Smith (1961) attribute the presence of concentric bands within spherulites to variations in grain size of the aggregates of cristobalite and feldspar which make up the spherulite.

Explanation of Figure 19 and Figure 20

Figure 19. Conspicuous flow structures of the Dacite Flow Member of the Cumbres Formation, located 1 kilometer northwest of Rancho Peñas Azules. Similar exposures occur throughout the flow. Geologic hammer gives scale.

Figure 20. Dacite Flow Member of Cumbres Formation. Color photomicrograph (plane polarized light) of well developed spherulites. Notice the concentric banding within the two spherulites near the center of the figure. Numerous triple junctions (T) are evident throughout the photograph.

Figure 19.

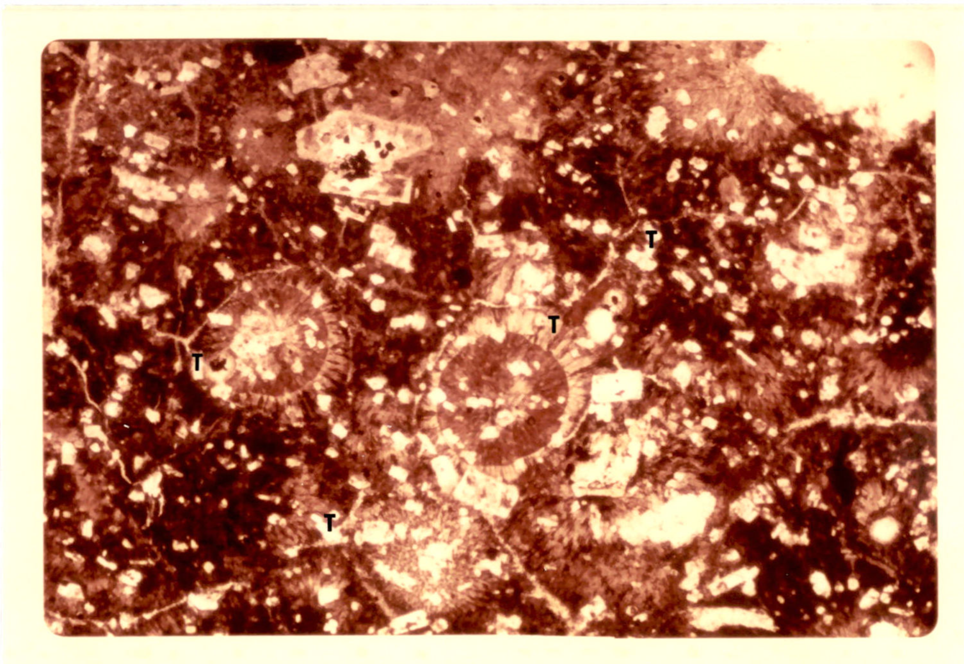


Figure 20. 1 mm

QUINTAS TUFF

The Quintas Tuff includes three members and is here named for excellent exposures of the massive tuff in the vicinity of Rancho Las Quintas (Fig. 2). The tuff forms moderately steep slopes at the base of Cerro Punta de Agua (Fig. 18), where the average dip of the formation is generally less than 5^{o}. To the south and east, the Arroyo Majalca has cut a spectacular canyon (Las Quintas Canyon) through the more steeply dipping formation (Fig. 21).

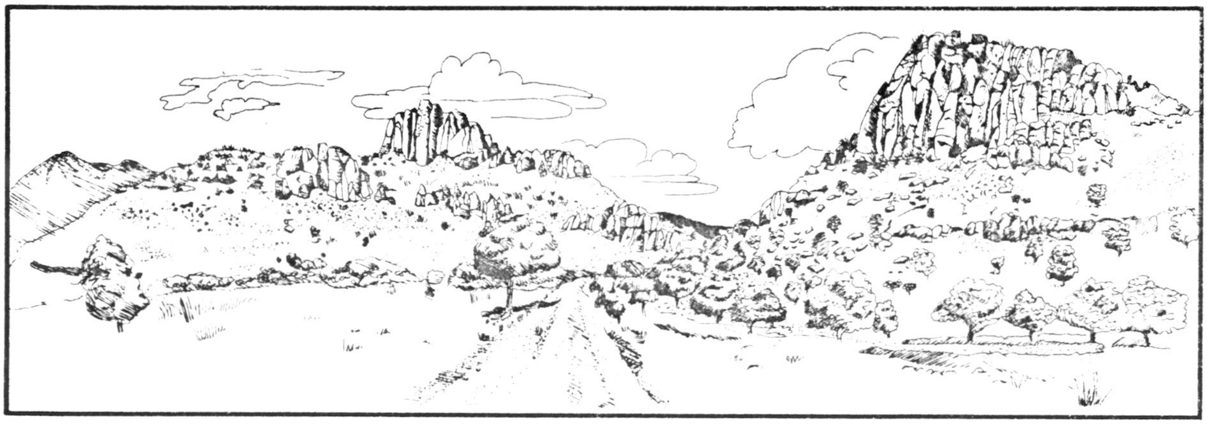


Figure 21. The Quintas Tuff as viewed from 0.5 kilometer southeast of Rancho Peñas Azules. View is toward the east. The basal vitrophyre forms a prominent ledge (right-center of photograph) below the columnar jointed upper section of the tuff. The gravel road in the foreground follows the Arroyo Majalca through Las Quintas Canyon.

The basal vitrophyre unit of the Quintas Tuff consists of a grayish black (N - 2), highly welded, vitric-crystal tuff (4/82/1/6/2/5//15), with a maximum thickness of 2 meters (Fig. 22). The unit forms a prominent ledge directly below the more massive and crudely jointed (3-5 meters) upper tuff (Fig. 21). This basal vitrophyre can be traced from the Arroyo Majalca northward for a maximum distance of 70 meters and southward for 150 meters where it abruptly pinches out.

Explanation of Figure 22 and Figure 23

Figure 22. Close-up of the basal vitrophyre unit of the Quintas Tuff. The vitrophyre forms a prominent ledge below the massive and crudely jointed upper tuff. The red unit below the vitrophyre is a fluvial unit of the Red Beds-Basalt Member of the Cumbres Formation. Notice the light colored lithic fragments throughout the vitrophyre. Geologic hammer gives scale.

Figure 23. Quintas Tuff. Photomicrograph (plane polarized light) of completely welded glass of the basal vitrophyre of the Quintas Tuff. Thorough welding and strong compression have only slightly impaired the shard structure. Subhedral sanidine crystals lie in the lower half of the photograph and a euhedral amphibole crystal lies in the upper-left.

Figure 22.

Figure 23.

The highly welded nature of the glassy matrix is illustrated in Figure 23. Sanidine is in generally subhedral, highly fractured, and moderately embayed crystals ranging in diameter from 0.1 mm to 2.5 mm (average 1.5 mm). Much of the quartz is in prominent subangular, highly embayed grains. Maximum size of the quartz is 2 mm; most is over 1 mm. Both pyroxene and amphibole occur as small (0.5 mm average), euhedral, slightly altered crystals. Light brown to yellow lithic fragments concentrated in the lower one meter of the unit account for an estimated 5-10 percent of the total rock mass. Thin section analysis indicates that the lithic fragments display approximately the same phenocryst composition and non-crystallized shard structure as the groundmass.

Classified by phenocryst composition, the basal vitrophyre is pheno-rhyolite. The index of refraction of the groundmass glass is approximately 1.51, very typical of rhyolites.

Directly overlying the basal vitrophyre at the entrance to Las Quintas Canyon is a 4 meter section of grayish red (5 R 4/2), highly welded, vitric-crystal tuff (8/75/0/11/3/3//15). The unit is characterized by well developed grayish red spherulites with an average diameter of 12 cm (Fig. 24). Sanidine is the most abundant phenocryst, occurring as subhedral crystals with slightly embayed edges, and ranging from 0.3 mm to 2.0 mm (1.2 mm average) in diameter. Quartz grains are 0.1 mm to 2.0 mm in size, are subangular to rounded, and are very highly embayed. Euhedral hornblende crystals displaying various shades of green and brown with marked pleochroism are speckled throughout the rock. Plagioclase is conspicuously absent. The spherulites are lying in a matrix of almost identical phenocryst composition. Upon weathering they are left on the floodplain of

Figure 24. Close-up of the grayish red spherulite unit of the Quintas Tuff. The spherulite overlies the basal vitrophyre shown in Fig. 22. Upon weathering the spherulites are left on the floodplain of the Arroyo Majalca as conspicuous accumulations of spherical welded tuff cobbles. Geologic hammer gives scale.

the Arroyo Majalca as conspicuous accumulations of spherical welded tuff cobbles. The spherulite unit is also of local extent and closely coincides with the maximum extent of the vitrophyre. The presence of these two highly welded and localized lower members of a very thick and massive tuff suggests that they were deposited over uneven terrain, most likely in a gentle valley or local depression. Ross and Smith (1961) have shown that the thickness of an ash flow depends on the volume of material that is erupted as well as on the type of topography over which it is emplaced.

Over gentle surfaces it will tend to spread laterally and form thin units. If confined to canyons or to topographic basins the ash flows will be thicker. When erupted upon uneven topography, the ash flows show evidence of having flowed around obstacles and down drainage channels. The greatest thickness of the flow would be expected where an ash flow has moved down and filled a pre-existing drainage channel or similar depression. The writer believes that this is the case in the formation of the Quintas Tuff. The basal vitrophyre and the overlying spherulite unit formed where the tuff deposit was very thick, and the position of the vitrophyre roughly delineates a pre-existing topographic basin or channel. Temperatures were higher near the basal section of the thicker part of the tuff deposit and slow cooling resulted in intense welding of the glass.

In outcrops surrounding Rancho Las Quintas, the upper unit is a massive light brownish gray (5 YR 6/1), crudely jointed (5 meters to 6 meters), highly welded, vitric-crystal tuff (14/83/0/1/0/2//18). Here the unit has large columnar joints which weather into prominent columns and pinnacles. The tuff is porous and in outcrop displays a slabby-weathering character which is probably related to removal of pumice by weathering processes. From a maximum thickness of 100 meters at Las Quintas Canyon, the tuff thins to the north and south, where average thickness is only 25 meters. This reduction in thickness of the unit is accompanied by a lateral change in gross appearance and composition. At the base of Cerro Punta de Agua, the Quintas Tuff is bedded, non-welded, and non-jointed (Fig. 18). It contains a high percentage of lithic fragments of andesite and abundant pumice lapilli.

Crystals comprise approximately 18 percent of the upper tuff unit at Rancho Las Quintas. The sanidine is in 0.3 mm to 3.0 mm subhedral, highly fractured, and moderately embayed grains. Quartz occurs as small (0.2 mm) well rounded grains and as larger (1.2 mm) angular to subangular highly embayed grains. Pyroxene is sparse, occurring as highly altered grains averaging less than 0.1 mm. Pumice fragments are not recognizable in thin sections of the highly welded tuff from Rancho Las Quintas. Thorough devitrification has obscured the actual shards; however, the unit displays well developed eutaxitic structure in thin section (Fig. 25).

The moderately welded section of the Quintas Tuff near the base of Punta de Agua contains abundant (9 percent) pumice lapilli. Axiolitic structure (Fig. 26) is extremely well developed throughout this part of the unit, yet the original forms of the shards are perfectly retained. According to Ross and Smith (1961), axiolitic structure is the result of the growth of crystals from the shard boundary inward, which are terminated at a dark central line of discontinuity. The major devitrification products are usually parallel intergrowths of feldspar and cristobalite, and the axiolitic structure is accentuated by the large difference in index of refraction of the devitrification products. As the numerically reduced histogram (41/58/0/0/0/1//19) indicates, quartz is much more abundant here than in the highly welded zone to the southeast. However, the relative crystal proportions and total crystal percentages remain moderately constant. Lithic fragments of andesite, more prominent near the base, comprise 1-2 percent of the unit.

Southern exposures of the tuff in the study area very closely resemble the section at Cerro Punta de Agua. Bedding is quite common and

Explanation of Figure 25 and Figure 26

Figure 25. Quintas Tuff. Photomicrograph (plane polarized light) of well developed eutaxitic structure of the upper section of the Quintas Tuff. Notice the distortion and molding of the glass shards around the larger phenocrysts, resulting in a marked simulation of flow structure. However, there is a distinct discontinuity of the stretched shards. Phenocrysts are sanidine except for highly embayed quartz grain in lower left-center of photograph.

Figure 26. Quintas Tuff. Photomicrograph (plane polarized light) of axiolitic structure developed in moderately welded tuff. Most of the photograph shows little distortion of the original shard structure. Dark central lines in the shards represent lines of discontinuity resulting from termination of crystal growths which began at the shard boundaries. The large phenocryst in the lower left is an altered sanidine crystal.

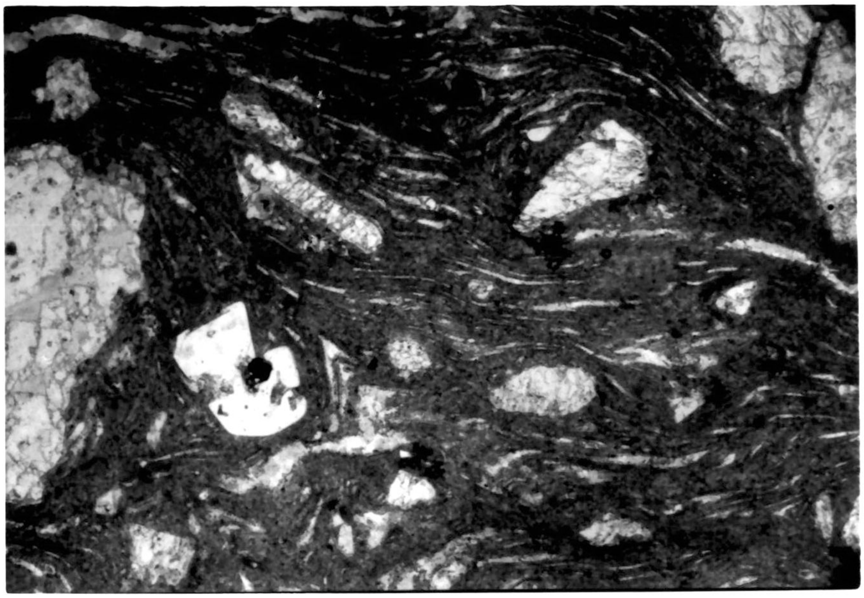


Figure 25. 1 mm

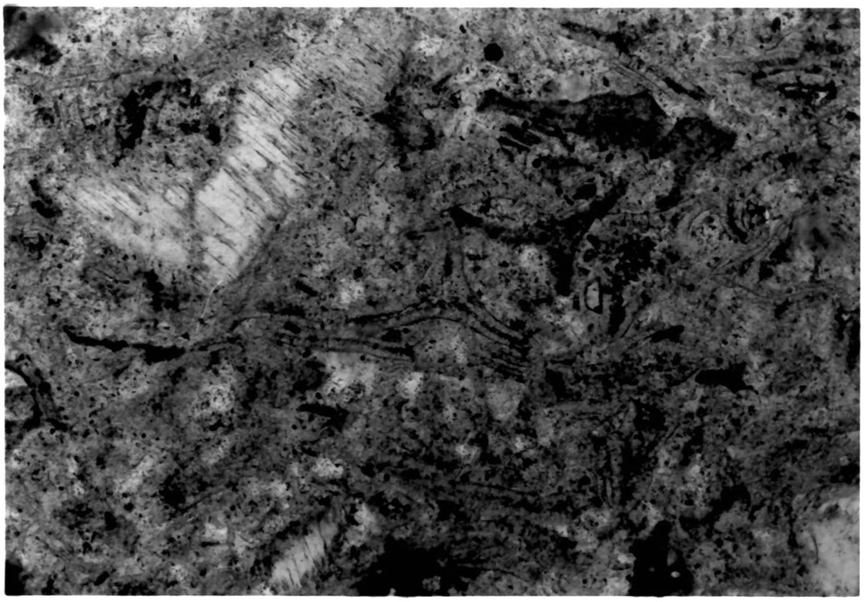


Figure 26. 0.5 mm

pumice lapilli are abundant. The percentage of lithic fragments varies considerably, from as low as 0.5 percent at Rancho Las Quintas to nearly 9 percent in exposures of the tuff that caps the dacitic flow in the center of the study area (Geologic Map, Fig. 2).

CAPILLA AMARILLA TUFF

Directly overlying the Quintas Tuff throughout the study area is approximately 60 meters of very light gray (N - 8), non-welded, pumice-rich, vitric tuff (24/61/12/0/2/1//6). The formation is here informally named the Capilla Amarilla Tuff, for exposures at a small yellow chapel in the village of Majalca. The tuff dips very gently (approximately 4°) to the east and characteristically forms recessive slopes. In marked contrast, the Quintas Tuff near the village of Majalca is quite resistant, forming impressive cliffs and steep slopes. The writer attributes the lower resistance of the Capilla Amarilla Tuff to the non-welded and pumice-rich nature of the rock. As previously mentioned, the Quintas Tuff is highly welded in cliff-forming outcrops near the Arroyo Majalca; however, at Cerro Punta de Agua the tuff is completely non-welded and forms quite recessive slopes. At this location the two tuffs are not readily distinguishable.

Glass shards that exhibit a faint axiolitic structure are clearly visible throughout the highly devitrified groundmass. Shards are generally non-compressed and only moderately distorted, and partially flattened bubbles are common. Lapilli-sized pumice from 3 mm to 2.5 cm in diameter comprises 8 percent of the rock and is now characteristically coarser grained than the surrounding devitrified matrix.

The total crystal percentage is quite low (6 percent). Slightly chatoyant sanidine is the most abundant primary mineral. The sanidine is in fresh subhedral to anhedral grains ranging in diameter from 0.2 mm to 6.0 mm; most are under 1.0 mm. Highly embayed anhedral quartz grains averaging about 0.8 mm in diameter comprise 2 percent of the total rock content. The Capilla Amarilla Tuff contains a higher percentage of plagioclase (1 percent) than the other tuffs of the younger section. The generally euhedral but highly altered plagioclase grains are widely disseminated throughout the unit. Alteration of the plagioclase is primarily to clay.

Sphene, biotite, and amphibole are the most abundant dark colored minerals. Sphene, which appears slightly more abundant than either of the other two, is quite fresh and often contains small zircon crystals. In contrast, both biotite and amphibole grains are completely altered and their distinction is based primarily on ghost cleavage and on crystal morphology.

PICOS GEMELOS ANDESITE

Two cone-like hills (Fig. 27) are very conspicuous features of the eastern section of the study area, especially when viewed from Mexico Highway 45, some 10 kilometers to the east. The twin hills are composed of a fine grained, dark gray (N - 3), hornblende basaltic andesite, here named the Picos Gemelos Andesite, literally, the "Twin Peaks Andesite." The flow is also present on Cerro Punta de Agua, where it reaches a maximum thickness of nearly 235 meters. At this locality, the flow forms three prominent cliffs, the upper being slightly more extensive than the

Figure 27. View of the cone-like hills of the Picos Gemelos Andesite from 3 kilometers west of Mexico Highway 45. View is toward the west. In the background is the erosional escarpment of Sierra Cumbres de Majalca. The village of Majalca is visible in the right-center of the photograph.

lower two (Fig. 18). Widely spaced (7 meters) columnar joints are present throughout the flow, but are especially prominent on outcrops at Cerro Punta de Agua. On fresh outcrops the rock is distinctly porphyritic, with phenocrysts of chalky plagioclase set in a very fine grained dark gray matrix.

The rock is classified mineralogically as a hornblende-bearing basaltic pheno-andesite. Primary mineral percentages differ by only a few percentage points from top to bottom of the flow, yet there are great differences in alteration and type of the mafic minerals. Generally, the flow can be divided into a lower zone in which the mafic minerals (oxyhornblende, augite, and biotite) are almost completely altered, a middle zone of very fresh mafic minerals, and an upper zone of moderate mafic mineral alteration.

The fine grained groundmass is composed essentially of subhedral to anhedral plagioclase, subhedral augite, and subhedral magnetite. The composition of the groundmass plagioclase is about An_{62} (labradorite). The plagioclase laths are larger (averaging 0.1 mm) in the middle section than in both the upper and lower sections, where average diameter is approximately 0.05 mm. Quite common throughout the groundmass is the parallel to subparallel arrangement of small oxyhornblende crystals representing flow structure.

Euhedral to subhedral plagioclase feldspar is the most abundant phenocryst, ranging from 14 percent in the lower and upper sections to 18 percent in the middle section. Crystals range in size from 0.2 mm to 6.0 mm, and average about 1.0 mm. Glomeroporphyritic texture is a commonly observed feature of the plagioclase phenocrysts. Some crystal clusters are as large as 6 cm and are composed of up to 20 intergrown crystals. Zoning is widespread and predominantly of the normal variety. The plagioclase is compositionally uniform throughout the flow. The phenocrysts possess highest An content in the cores, ranging from An_{40} to An_{52} and averaging approximately An_{43} (andesine). Normal zoning is often interrupted by the presence of a bubbly or cloudy zone near the outer crystal boundaries (Figs. 28 and 29). Similar bubbly or cloudy zones have been attributed by Stormer (1972), Lipman (1969), and Bentor (1951) to minute inclusions of groundmass material. At the inner edge of the cloudy rim zoning appears to be interrupted, but the composition changes are difficult to analyze optically. A clear rim developed outside the cloudy zone (Fig. 28) has about the same composition as the groundmass feldspar and is normally zoned. A process which could produce

Explanation of Figure 28 and Figure 29

Figure 28. Picos Gemelos Andesite. Color photomicrograph (crossed nicols) of basaltic andesite. A large embayed phenocryst of andesine in the left-center of the photograph is mantled by a dusty resorbed zone and a very thin clear rim of more calcic plagioclase. Notice the large clot of amphibole and plagioclase in the upper-left and the embayed and fractured quartz crystal in the lower-center of the photograph.

Figure 29. Picos Gemelos Andesite. Color photomicrograph (crossed nicols) of basaltic andesite. Large amphibole phenocryst in lower-center completely mantles biotite. Notice the corroded edges of the biotite. The amphibole crystal has a thin reaction rim of fine grained radiating clinopyroxene. Large andesine phenocryst (upper-right) has dusty resorbed zone and clear calcic rim. Quartz crystal in upper-left is moderately embayed. Notice the pilotaxitic nature of the groundmass.

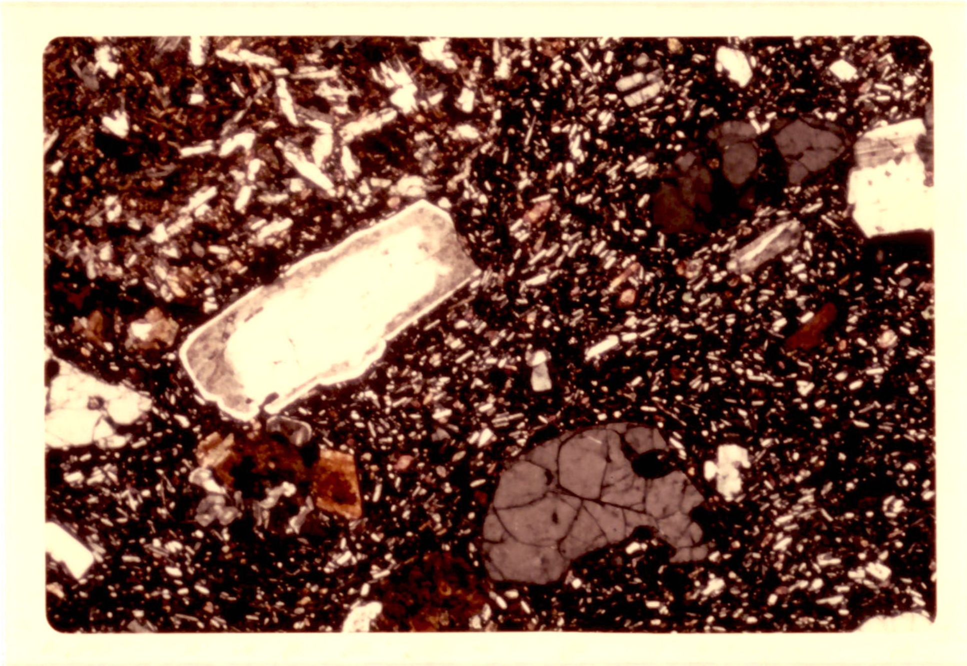


Figure 28. 1 mm

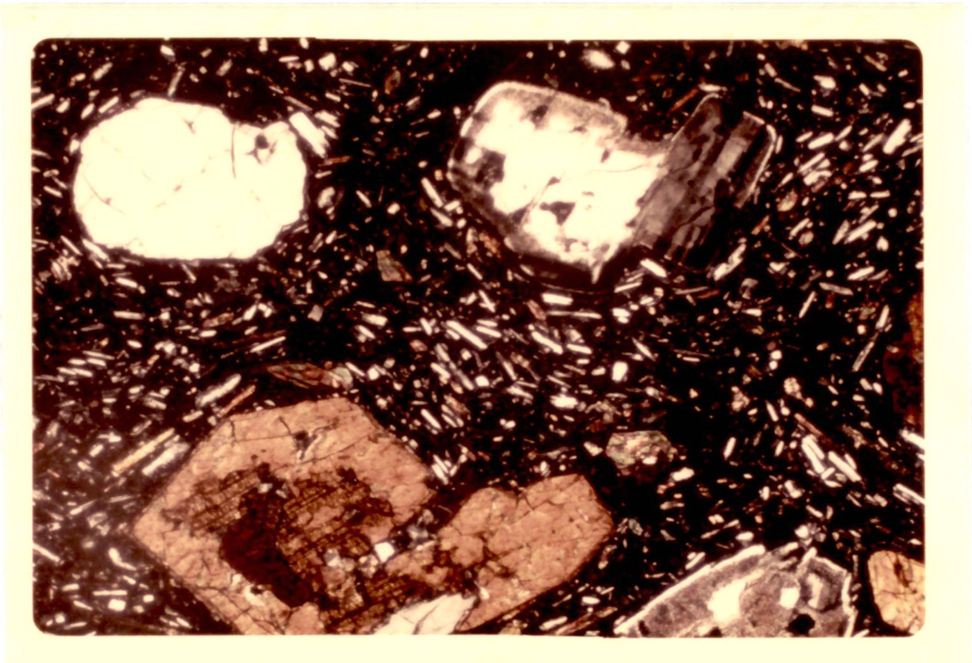


Figure 29. 0.5 mm

the same features in plagioclase phenocrysts has been suggested by some recent experimental work. Several authors, including Cohen, et al. (1967), and Green and Ringwood (1967), have shown that the plagioclase which crystallizes from basaltic magmas becomes more albite-rich with increasing pressure. The cores of these cloudy plagioclases may represent phenocrysts which crystallized at relatively high pressure, and the resorption and development of cloudy zones represents a readjustment of equilibrium with pressure release just prior to eruption. The crystallization of clear calcic rims under low pressure would be coincident with groundmass crystallization.

Oxyhornblende is the most abundant mafic phenocryst, ranging from 6 to 11 percent of the andesite and averaging approximately 10 percent. Size of the crystals ranges from 0.05 mm to 2.7 mm; most are under 0.5 mm. The mineral occurs predominently as euhedral to subhedral phenocrysts of various shades of green and brown. The lower section of the flow contains highly altered grains which have undergone either complete replacement by iron oxides or partial replacement of the central part of the crystal by iron oxides and of the margins by fine grained augite and magnetite. The oxyhornblende phenocrysts of the central part of the flow are usually fresh and display an outer reaction or alteration rim of fine grained radiating clinopyroxene crystals in a few isolated grains (Fig. 29). The upper section of the flow contains only partially altered oxyhornblende. Here the alteration is confined to outer rims of iron oxides, while the crystal cores are moderately fresh. The small crystals (less than 0.1 mm) of oxyhornblende are completely replaced by iron oxide throughout the flow.

Oxyhornblende usually occurs as isolated phenocrysts and as reaction rims on augite (Fig. 30). However, several of the larger euhedral crystals of the central section of the flow have cores of fresh biotite that display slightly corroded edges (Fig. 29). Such an occurrence suggests conditions of disequilibrium in the magma. A high pressure phenocryst assemblage formed at depth is composed of sodic plagioclase, clinopyroxene, quartz, hornblende, and biotite. The occurrence of the hydrous ferromagnesians indicates the presence of water in the system at high load pressures. A drop in water pressure brought about by upward movement of the magma reduced the stability of the hydrous ferromagnesian minerals. As the magma rose toward the surface, loss of hydrogen by diffusion increased the oxidation potential of the magma and was also accompanied by lower water pressure. The low pressure conditions then initiated the crystallization of pyroxene coronas about amphibole, the resorption of quartz phenocrysts, and the development of cloudy resorbed zones in plagioclase. The crystallization at low pressure of calcic rims on the plagioclase phenocrysts (Fig. 28) was coincident with crystallization of a calcic plagioclase matrix.

Clinopyroxene is an important groundmass constituent throughout the flow, but as a phenocryst mineral it comprises less than 2 percent of the total rock. The groundmass crystals are too small for detailed optical descriptions. The phenocryst clinopyroxene is augite, which occurs as subhedral grains ranging from 0.1 mm to 2.0 mm; most are under 1.0 mm. Augite phenocrysts are characteristically unaltered throughout the flow.

Biotite, averaging 1 percent, occurs in euhedral to subhedral crystals and commonly displays parallel arrangement around plagioclase and augite phenocrysts. Common inclusions in the biotite are zircons, magnetite, and apatite.

Highly embayed quartz grains up to 2 mm in diameter are found throughout the flow (Fig. 28). The quartz grains are characteristically clear and rounded single crystals. The origin (cognate vs xenocryst) of the grains is not certain, especially in view of the proposed cognate origin of the cloudy plagioclase. It has been suggested by Nicolls, et al. (1971), that quartz could be a cognate high pressure phase in some rather basic magmas. Olivine also occurs as a minor (less than 0.1 percent) accessory mineral. A few large xenocrysts of sanidine, often characterized by an outer rim of graphically intergrown quartz and feldspar, are scattered throughout the flow (Fig. 31). These crystals are believed by the writer to be the result of contamination of the magma during upward movement through sanidine-rich tuffs such as the Quintas Tuff.

Cognate xenoliths (up to 1.5 cm in diameter) composed of small augite, hornblende, and plagioclase crystals are an important constituent of the rock (Fig. 28). These clots represent fragments of crystal accumulations that are the result of crystal settling in the cooling magma body. During extrusion, fragments of the crystal accumulation were incorporated in the flow. The presence of these cognate xenoliths and of larger phenocrysts often characterized by glomeroporphyritic development suggests that the magma crystallized slowly at depth. Conditions of disequilibrium were initiated by pressure release during rapid rise of the magma to the surface. Cloudy resorbed zones in plagioclase (Fig. 28) and the reversal of the reaction series in pyroxene, amphibole, and biotite (Fig. 29) directly reflect the conditions of disequilibrium that existed in the magma during final stages of crystallization.

Explanation of Figure 30 and Figure 31

Figure 30. Picos Gemelos Andesite. Color photomicrograph (crossed nicols) of oxyhornblende corona around augite phenocryst in basaltic andesite. The phenocrysts to the left of the augite phenocryst are plagioclase. Notice the cloudy resorbed plagioclase in the upper-left of the photograph.

Figure 31. Picos Gemelos Andesite. Photomicrograph (plane polarized light) of sanidine xenocryst (lower-left) in basaltic andesite. Notice the outer rim of graphically intergrown quartz and feldspar. Euhedral biotite and hornblende crystals in upper-center are important phenocryst minerals. Embayed quartz grains and an anhedral olivine grain (just above the sanidine xenocryst) are also present.

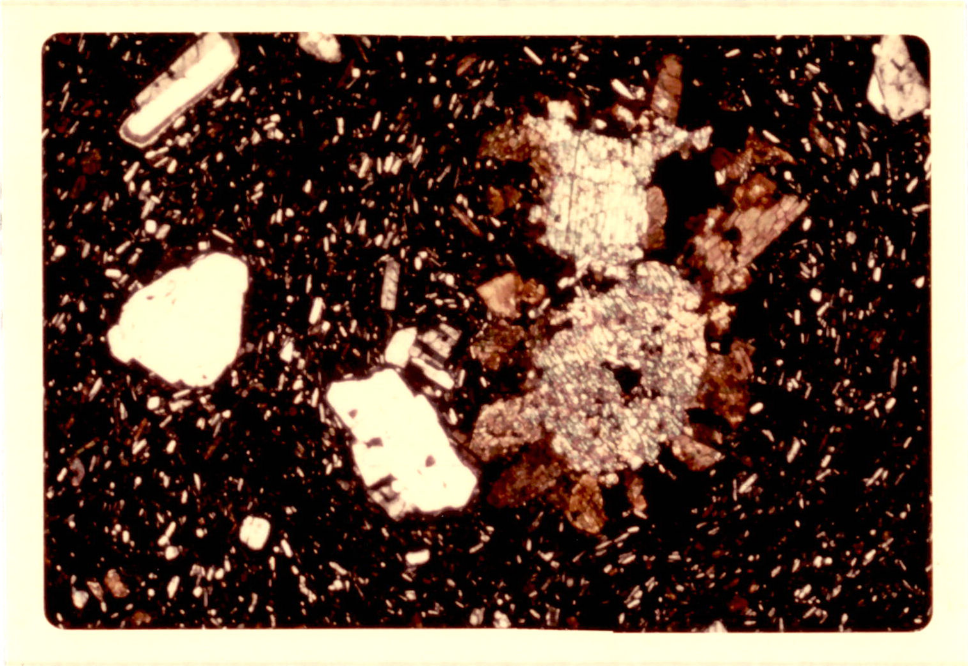


Figure 30.

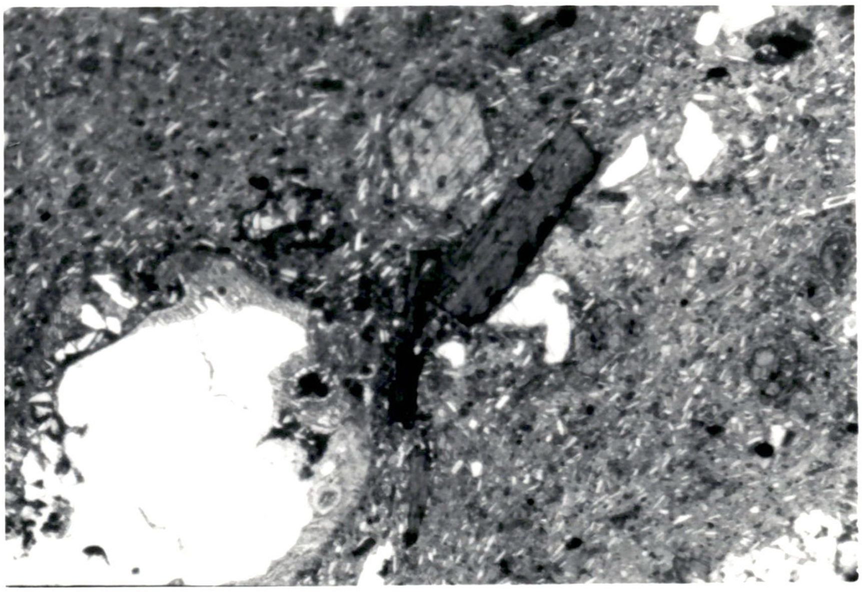


Figure 31.

RANCHERIA ROJA TUFF

The Rancheria Roja Tuff is a moderately well jointed, pale reddish brown (10 R 5/4), densely welded, vitric-crystal tuff (0/100/0/0/0/0//1). The tuff was named by Mauger (1975) for excellent exposures at the base of the prominent cliff near the top of Cerro Rancheria, a conspicuous north-south trending mountain located approximately 10 kilometers north of the study area. Thickness of the unit at the type locality may exceed 30 meters. The relatively flat-lying Rancheria Roja Tuff is well exposed in the north-central section of the study area, where it forms a prominent cliff nearly 20 meters in height near the top of Cerro Punta de Agua (Fig. 18). It is also present as a cap rock on a smaller east-west trending ridge approximately 2 kilometers north of the village of Majalca (Fig. 2).

The unit is distinctive in outcrop owing to its reddish coloration, pronounced eutaxitic structure, and massive joints (3 to 5 meters). The prominent eutaxitic structure is imparted by very thin white stringers of silica up to 5 cm in length; some stringers display open central cavities. Phenocrysts in hand specimen consist entirely of minor amounts of sanidine.

Thin section analysis indicates that there are two distinct phases of the tuff. The lower section consists of a densely welded, strongly eutaxitic tuff with a basal lithophysal zone. Overlying the tuff is a thin, non-persistent section of highly vesicular grayish red (10 R 4/2) glass.

At Cerro Punta de Agua, the lower 1 to 2 meters of the tuff is characterized by abundant lithophysal cavities which range in diameter from 2 cm to 6 cm and are partially to wholly filled with botryoidal chalcedony. Ross and Smith (1961) report a similar facies in a welded tuff that crops out near Idaho Falls, Idaho. They attribute such cavities to the release of volatiles during devitrification and suggest that ash flows containing such cavities had retained an unusually large proportion of volatiles in solution in the glass.

The overlying eutaxitic tuff consists of 86 percent pale reddish brown devitrified matrix. Although devitrification is complete, a distinct compaction foliation is imparted by silica stringers and parallel arrangement of elongate quartz grains (Fig. 32). Sanidine (1 percent), some of it embayed, occurs as highly fractured, subhedral grains ranging from 0.1 mm to 1.5 mm in diameter; most is under 0.5 mm. Quartz occurs in two different forms; widely disseminated subhedral to anhedral elongate grains (6 percent) less than 0.1 mm in diameter, and granular quartz (8 percent) in thin and non-persistent stringers up to 5 cm in length (Fig. 32). Both types probably represent vapor-phase mineralization or inversion of vapor-phase tridymite to quartz. The elongate stringers and the small grains are surrounded by a light colored and wispy glass that most likely represents original pumice; however, extreme compaction and complete devitrification render its identification difficult. Stringers of quartz may represent secondary mineral emplacement along vesicular zones of squashed pumice and the small quartz grains represent infilling of vesicles. Opaque iron oxides are concentrated along silica stringers but other mafic minerals are conspicuously absent.

A grayish red, highly vesicular glassy zone is present at a few isolated localities of the upper Rancheria Roja Tuff at Cerro Punta de Agua. This has not been observed at Cerro Rancheria, nor is it present in other outcrops of the unit within the study area. Vesicles (38 percent) in the unit are lined with tridymite crystals and partly infilled by a second generation of silica (Fig. 33). Sanidine (1 percent) and pyroxene (0.5 percent) are the only primary minerals.

Explanation of Figure 32 and Figure 33

Figure 32. Rancheria Roja Tuff. Photomicrograph (plane polarized light) of eutaxitic structure of the thoroughly welded tuff. Compaction and stretching have eliminated all clearly recognizable shard structure. Light colored discontinuous stringers represent completely flattened pumice. Secondary silica fills the central cavities of the stringers. The two larger phenocrysts are sanidine and the small slightly elongate grains are quartz infillings of vesicles.

Figure 33. Rancheria Roja Tuff. Color photomicrograph (plane polarized light) of vesicular glass of the vapor-phase unit which lies above the strongly eutaxitic tuff shown above (Fig. 32). Euhedral plate-like tridymite and/or sanidine crystals line the cavities. The tridymite crystals are completely enveloped by a thin layer of botryoidal silica and the inner cavities are filled by granular silica.

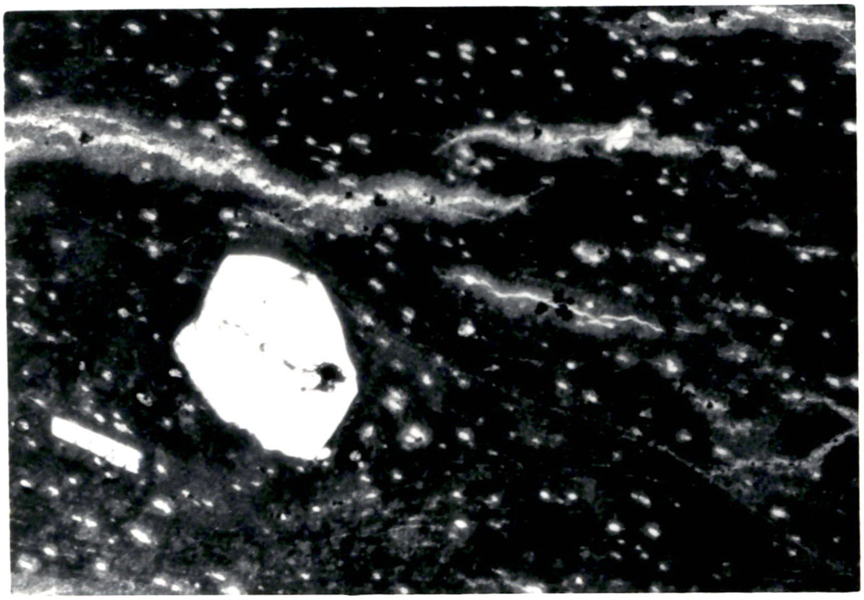


Figure 32.

1 mm

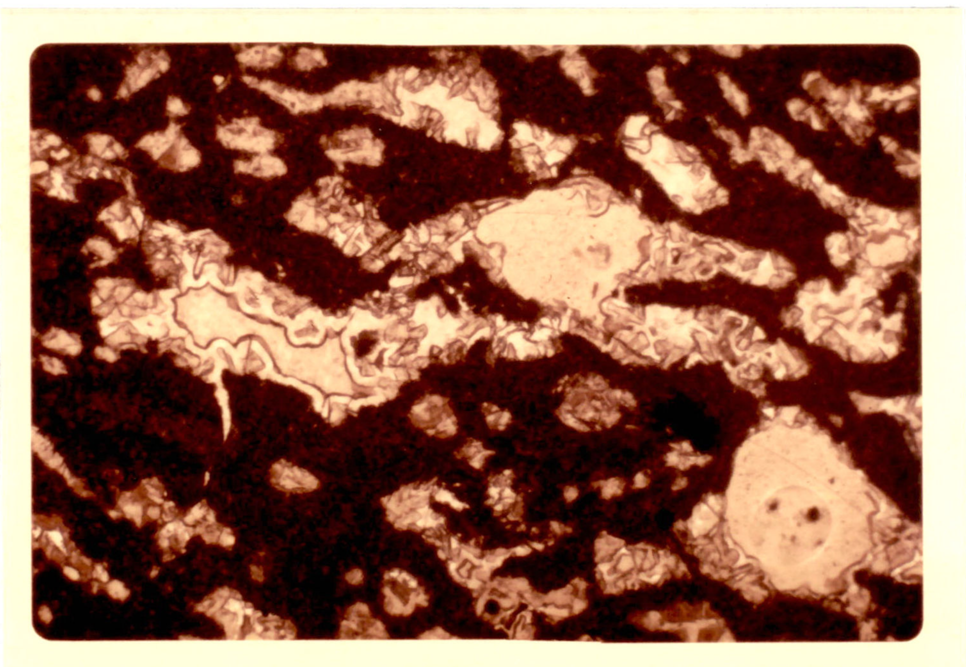


Figure 33.

0.5 mm

RANCHERIA TUFF

The Rancheria Tuff, named by Mauger (1975) for excellent exposures on Cerro Rancheria, is exposed in the north-central section of the study area where it forms a massive columnar jointed scarp at the top of Cerro Punta de Agua (Fig. 18). Actual thickness of the tuff is not known, but probably exceeds 85 meters at Cerro Punta de Agua.

The basal portion of the Rancheria Tuff appears moderately bedded, but exposures are poor owing to talus cover from the massive upper section. Exposures near the base of the columnar jointed upper section reveal a 3 to 5 meter thick unit of light brownish gray (5 YR 6/1), conspicuously eutaxitic tuff that is characterized by unmistakable flow structure (Fig. 34).

Primary minerals comprise only 4 percent of the flow-rock. Sanidine is the most abundant (3 percent) phenocryst, occurring as very fresh, euhedral, and moderately fractured grains averaging about 1 mm in diameter. Quartz phenocrysts (1 percent) display rounding and embayment and average about 1 mm in diameter. The only other primary mineral is highly altered, euhedral hornblende ranging in diameter from 0.5 mm to 1.5 mm; most is under 0.8 mm.

The distinctive flow structure in the lower Rancheria Tuff is imparted by continuous and undulating flow lines, as contrasted with the discontinuous foliation of simple welded tuffs. In thin section the flow lines show up as thin zones of completely devitrified glass with pronounced axiolitic structure. Rotation of crystals by the shearing motion of successive flow layers is a commonly observed feature (Fig. 34). Between the glassy layers are zones of devitrified glass containing vapor-phase tridymite and secondary

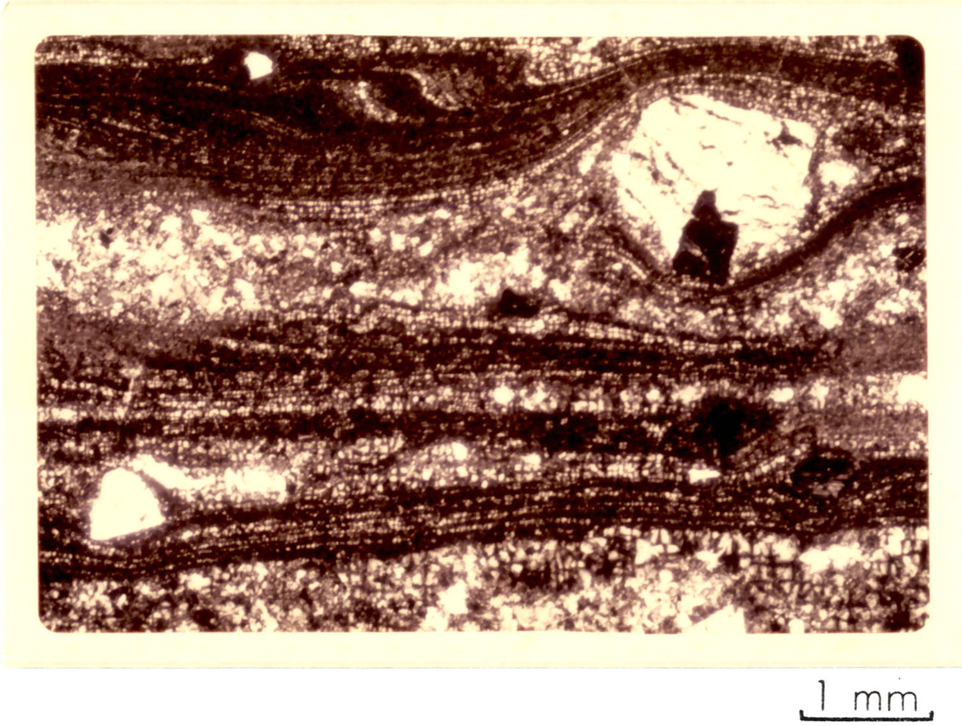


Figure 34. Rancheria Tuff. Color photomicrograph (crossed nicols) of the lower glassy flow zone of the tuff. The flow structure is imparted by continuous and undulating layers of completely devitrified glass. Crystal rotation of sanidine phenocryst by shearing motion of the flow layers is shown in the upper-right corner.

quartz. The pronounced 'flow-rock' appearance of the unit is attributed by the writer to incipient flow of welded but plastic glass particles in the lower section of a large ash flow. Solovev (1950) has described similar rocks from the Sikhote-alin volcanic region of eastern Russia. He believes that a mass of viscous glass highly charged with volatiles can acquire a very fluid character. The glass in some sections becomes displaced to the sides of topographic irregularities by the weight of the overlying accumulation of fragments. The displacement takes place in the form of flow involving a shearing or gliding motion of the glassy layers. Such movement is indicated in the flow unit of the Rancheria Tuff by rotation of the larger phenocrysts (Fig. 34). The flow also resembles the description by Rittmann (1962) of "flowing ignimbrites" or "rheoignimbrites" from Monte Amiata, Tuscany. According to Rittmann (1962), if ignimbrites are deposited on a steep slope they begin to flow and may closely resemble lavas. Most of the flow is confined to the lower part of the ignimbrite sheet where viscosity is lowest. The slow flow of the material completely destroys the textures characteristic of ignimbrites. Flow texture in the rheoignimbrites on a large scale is fairly common and can be recognized in thin vesiculated layers formed as a result of pressure release along shear planes in the laminar flowing mass. The flow unit of the Rancheria Tuff may represent a small scale rheoignimbrite formed by flow in response to deposition on topographic irregularities rather than on steep slopes on the flanks of volcanic cones.

The upper 65+ meters of the Rancheria Tuff is a pale red purple (5 RP 6/2) to very light gray (N - 8), thoroughly welded, vitric-crystal tuff (3/94/0/1/2/0//15). Stretching and compaction have eliminated all clearly recognizable shard structure, and in hand specimen the rock resembles a flow rock; however, the foliation lacks the continuity of typical flow rocks. Flattened pumice fragments comprise 29 percent of the rock. The pumice fragments are commonly made up of greatly elongated tubular pore spaces which contain quartz stringers in the central cavities. The devitrified shards are completely distorted and molded against feldspar grains. The pumice fragments are also devitrified, but display a much coarser grained intergrowth of quartz and feldspar than that which results from devitrification of shards.

Crystal content, determined in thin section, averages about 15 percent. Lithic fragments are not abundant in exposures at Cerro Punta de Agua. Sanidine is the most abundant phenocryst, averaging about 14 percent of the total rock. Most of the sanidine is in highly altered, subhedral to anhedral, highly embayed crystals ranging in diameter from 0.3 mm to 4.0 mm. Some clusters of sanidine are as large as 6 mm in diameter. Alteration of the sanidine throughout the unit is generally to clay. However, a thick zone near the lower flow section contains unusually fresh sanidine. This zone tends to be lighter colored and to contain a lower percentage of mafic minerals and pumice.

Quartz as a primary mineral accounts for less than 0.5 percent of the rock. Most of the crystals are moderately embayed anhedral grains generally less than 0.5 mm in diameter. Stringers of granular quartz are, however, extremely abundant as a secondary infilling of squashed and stretched pumice.

Both amphibole and pyroxene, comprising about 0.5 percent, are speckled throughout much of the groundmass. Crystals, usually under 0.5 mm in diameter, are completely replaced by iron oxide. Based on crystal morphology, amphibole appears twice as abundant as pyroxene.

SUMMARY AND CONCLUSIONS

1) The Rancho Peñas Azules area lies in a physiographic zone transitional between the internally drained system of desert basins and isolated fault-block ranges (the Basin and Range) to the east and the thick and relatively undeformed volcanics of the Sierra Madre Occidental to the west.

2) The exposed stratigraphic section in the Rancho Peñas Azules area has been divided by the writer into eight informally named formations. From oldest to youngest, the formations are the Tres Cuchillas, Lavas Azules, Cumbres, Quintas Tuff, Capilla Amarilla Tuff, Picos Gemelos Andesite, Rancheria Roja Tuff, and Rancheria Tuff. The Tres Cuchillas and Lavas Azules Formations comprise the Peñas Azules Volcanic Group, and the upper six formations constitute the Upper Volcanic Group.

3) Age dates by K-Ar analysis, which will not be available until the spring of 1976, will place the volcanic and volcanic-derived rocks of the Peñas Azules area in their proper stratigraphic position. At present it is postulated that the rocks represent a period of intense andesitic to rhyolitic volcanism which began during the early Tertiary.

4) The stratigraphic section is composed of an older sequence of steeply dipping, interbedded basaltic pheno-andesites, mud-flow deposits, and tuffs which is overlain, in angular unconformity, by a nearly flat-lying ignimbrite sequence. The older sequence is exposed as an inlier within the broad, relatively flat area surrounding Rancho Peñas Azules.

5) Thin section analysis indicates that the andesite flows are predominantly pyroxene and amphibole-bearing, basaltic pheno-andesites.

Plagioclase and hornblende, set in a characteristically pilotaxitic groundmass, are the most abundant phenocryst minerals.

6) Thick mud-flow deposits (lahars) in the Peñas Azules Volcanic Group are considered to be the result of rapid denudation of andesite flows and/or cones.

7) The duration of the hiatus between block-faulting and erosion of the older sequence of volcanics and extrusion of ignimbrites of the younger sequence is not known at present.

8) The interfingering of andesite flows and red beds of the Cumbres Formation is the result of talus-type accumulation of breccia and red beds from rapid erosion of fault scarps accompanied by extrusion of andesite flows.

9) The Quintas Tuff, Capilla Amarilla Tuff, Rancheria Roja Tuff, and Rancheria Tuff represent thick rhyolitic pyroclastic deposits of nuée ardente origin. The sequence of pyroclastic deposition was locally interrupted by outpourings of basaltic pheno-andesites such as the Picos Gemelos Andesite.

10) The exact time of cessation of volcanic activity will not be known until more stratigraphic work is completed and age dates are available. Normal faulting and dissection by stream erosion followed cessation of volcanic activity.

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