SOME FEATURES OF RHYOLITE PETROGENESIS

by

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ABSTRACT

The problem of rhyolite petrogenesis is related to the problem of the origin of granite because of the chemical similarities of these rocks. Both igneous (magmatic) and metamorphic (granitization) processes have been suggested for the mode of origin of rocks of granitic composition.

A field and laboratory study was undertaken to determine the genesis of certain rhyolitic rocks exposed in Nogal Canyon, Socorro County, New Mexico. These volcanic rocks form a ridge upfaulted against late Santa Fe conglomerate. The area is cut by many north-south trending faults generally of small displacements. Minor folding in the eastern half of the area is masked by later faulting.

The outcrops reveal a complex sequence of igneous rocks, including rhyolitic flow breccias and rhyolitic tuffs, as well as dikes, sills, and flows of rhyolite and quartz latite; later andesite dikes and late-Tertiary (?) basalt flows are exposed near the western margin of the area. The Santa Fe conglomerate contains inclusions of most of the observed volcanic units, and Quaternary basalt flows are interbedded with the Santa Fe in the eastern part of the area.

Correlations between units, and compositional variations, have been indicated by refractive-index measurements of natural volcanic glass, as well as of artificial glass derived from the laboratory fusion of several rock samples, and by the relative abundance of certain trace elements.

CONTENTS

ILLUSTRATIONS

SOME FEATURES OF RHYOLITE PETROGENIS

INTRODUCTION

Rhyolites are considered the fine-grained equivalents of granites.[1] Metamorphic (granitization) as well as igneous (magmatic) processes have been utilized to explain the origin of granitic bodies. Therefore, the problems of rhyolite petrogenesis are related to the origins of granitic rocks.

The simplest and most direct evidence of granitic fluid is rhyolite flows.[2] Nevertheless, the fine-grained (aphanitic) character of the rocks often makes mineralogic relationships not readily distinguishable and may conceal highly varied chemical relationships.

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1. "The name rhyolite was given by von Richthofen to the extrusive equivalent of granite on account of its streamlike appearance. The rocks are generally porphyritic and show phenocrysts of quartz and sanidine, less commonly oliogoclase or a dark mineral, in a groundmass of variable appearance. The microscope shows much glass which, in the older rocks, may be entirely devitrified" (Johannsen, A., A Descriptive Petrography of the Igneous Rocks, vol. 1, p. 278 (1939).

2. Walton, M. The Emplacement of "Granite", Am. Jour. Sci., vol. 253, p. 1 (1955).

TABLE I: AVERAGE RHYOLITE COMPOSITION[1]

SiO_2	72.87 %
TiO_2	0.29 %
Al_2O_3	13.28 %
Fe_2O_3	1.30 %
FeO	0.92 %
MnO	0.05 %
MgO	0.41 %
CaO	1.05 %
Na_2O	3.21 %
K_2O	4.34 %
P_2O_5	0.05 %
H_2O+	1.79 %
H_2O-	0.29 %
	99.85 %

1. Washington, H. S., Chem. Analysis of Igneous Rocks, U.S.G.S. Prof. Paper 99 (1917).

Table I lists the average chemical composition of 189 complete chemical analyses of rocks which have been referred to as rhyolites.

There is little agreement on the method by which granitization progresses. One hypothesis proposes a liquid, or "ichor,"[1] derived from and permeating through the rocks, removing the more basic materials, and adding a sufficient quantity of acidic material to create a rock which is chemically and petrologically a granite; opposed to this idea is the hypothesis of ionic diffusion in the solid state.[2] Variations in trace element composition may indicate fundamental differences in genetic history.

The igneous hypothesis derives granite from direct crystallization of a liquid melt, or magma. Several ideas have been proposed for the source of the granitic magma. Four main ideas, according to Bowen,[3] are:

1. Fusion of geosynclinal sediments.
2. Refusion of the base of the granitic layer of the earth.
3. Differentiation of a syntectic magma formed by the solution of granitic or other salic material in a basaltic magma.

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1. Perrin, R., Granitization, Metamorphism, and Volcanism, Am. Jour. Sci., vol. 252, pp. 449-465 (1954).

2. Ramberg, H., The Origin of Metamorphic and Metasomatic Rocks, Univ. of Chicago Press (1952).

3. Bowen, N. L., The Evolution of Igneous Rocks, Princeton Univ. Press (1928).

4. Differentiation of a basaltic magma as such. Bowen[1] proposes a "one magma" theory: basaltic magma which, through the process of fractional crystallization, differentiates into salic and ultramafic fractions.

In some cases, field evidence can be determinative for the magmatic origin of a particular granitic body.

Goodspeed[2] evaluates the field criteria, whether for granitization or magmatic origins, as follows:

> Whether a magma was a liquid silicate melt originally nearly free from crystals or a pastelike fluid with many crystals, it had the property of mass flowage and the ability to precipitate minerals as crystallization and cooling proceeded.

First, Goodspeed points out that the form of the body, whether intruded forcibly or passively (piecemeal or block stoping), must be compatible with mass flowage. For example, laccoliths will show deformation of the wall rocks, and dikes will have offsets due to dilation of wall rocks; the amount of offset is proportional to the width of the dike and the angle of intersection. Second, a magmatic body should exhibit a progressive increase in grain size from the outer cooling surface to the inner part of the mass. Third, the body may exhibit a distinct mineral uniformity, or may have mineral gradations with another part of the body or with the wall rock. Fourth, magmatic separation may

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1. Bowen, N. L., op. cit.

2. Goodspeed, G. E., Origin of Granites, Geol. Soc. Am. Mem. 28, pp. 58-78 (1948).

not go to completion, causing gradations or forming rocks of intermediate character. Fifth, the presence of water in the magma[1] in specified zones, such as near the top or sides of the chamber may cause rocks of the same chemical composition, having a common origin, to appear quite different in the field. The correlation of these evidences should indicate the petrogenetic relationships.

On the basis of other field evidence, Goodspeed[2] has suggested what he believes is a third method - rheomorphism - (the first being magmatic crystallization, the second granitization) for the origin of granites. Rheomorphism has been described as the mobilization of metamorphosed material, which forms a new rock mass (neomagma) that did not pass through the state of a liquid silicate melt (magma or migma). It is obvious that rhyolite flows cannot be derived from rheomorphism.

Thus it is clear that rhyolite petrogenesis is related to either igneous or metamorphic processes; i.e., derivation from a granitic magma or rhyolitization. Rhyolitization can be defined as a process which produces rhyolites, whether they be flows, dikes, or sills, from previously existing rocks by deuteric alteration or metamorphism.

LOCATION OF AREA

The area mapped extends approximately 1 mile north and south of

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1. Kennedy, G. C., Some Aspects of the Role of Water in Rock Melts, in Crust of the Earth, Geol. Soc. Am. Spec. Paper 62, p. 489 (1955).

2. Goodspeed, G. E., op. cit.

Nogal Canyon, in the Chupadera Mountains, Socorro County, New Mexico. It includes portions of sections 31, 32, and 33, T. 4 S., R. 1 W., and sections 4, 5, 6, 7, and 8, T. 5 S., R. 1 W. (see Plate I). The area is accessible by automobile along an unimproved dirt road extending west from U. S. Highway 85, about 0.7 mile west of San Antonio and 10 miles south of Socorro (see Plate II). For the most part the road follows Nogal Canyon and is impassible during and immediately after heavy rains.

METHODS OF INVESTIGATION

The area was mapped on an aerial photograph enlarged to a scale of 1:10,000. The base map on which the geology is presented was enlarged to a scale of 1:10,000 from a 7 1/2-minute quadrangle map of San Antonio quadrangle (NW), prepared by the Army Map Service in 1948 (scale 1:25,000). Some areas were mapped at a scale of 1:3,000 (see Plate II) to provide more detailed information. A Focalmatic projector was used to project the geology onto the base map.

Contacts are shown as continuously exposed although some areas are covered with a thin layer of recent alluvium. Dips and strikes were measured with a Brunton compass on foliation or along fracture surfaces. The author spent approximately 50 days in the field.

Rock samples were collected from the map units and within each unit to note any variations. Sixty thinsections were studied. Semiquantitative spectrochemical analyses of certain trace elements were made for the purpose of correlating these rocks. In addition, approximately one-half of these specimens were fused to a homogeneous glass. The index of refraction was measured by immersion methods and plotted against silica and common oxide content to estimate bulk chemical composition[1] of the rocks. Finally, complete chemical analyses were obtained of two composite samples, selected as representative of (1) the major flow rhyolite unit and (2) the tuff sequence.

PREVIOUS WORK

The northern part of the area is included in an investigation of the Luis Lopez Manganese district by Alfred T. Miesch.[2] Miesch's mapping was on a small scale, of necessity omitting much of the detail included in this study. Formational units and terminology are taken from Miesch whenever possible.

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1. Callaghan, E. and Sun, M. S., Correlation of Some Igneous Rocks of New Mexico by the Fusion Method., Am. Geophys. Union, Trans. vol. 37 (1956).

2. Miesch, Alfred T., Geology of the Luis Lopez Manganese District, Socorro County, New Mexico, New Mexico Bureau of Mines and Mineral Resources, Circ. 38 (1955).

GEOLOGY

The Nogal Canyon area is composed of volcanic rocks of probable Tertiary and early-Quaternary age. The volcanic mass is faulted against late Santa Fe conglomerate (Plio-Pleistocene) which is capped in places with Quaternary basalt flows. The conglomerate contains fragments of most of the exposed volcanics. Except for the younger basalt flows the volcanic rocks are mainly rhyolite dikes, sills, and flows and rhyolitic tuff and agglomerate. The volcanic cycle was interrupted by intervals of erosion and weathering resulting in local uncomformities. The sequence of strata as determined from field data is as follows from top to bottom:

Quaternary basalt
Plio-Pleistocene Santa Fe conglomerate
Late-Tertiary (?) gray basalt
Late-Tertiary (?) andesite dike complex
Middle-Tertiary massive red rhyolite
Middle-Tertiary perlitic dike complex
Middle-Tertiary flow rhyolite and latite
Middle-Tertiary altered rhyolite flow breccia
Middle-Tertiary agglomerate-tuff sequence
Middle-Tertiary red-gray banded rhyolite
Middle-Tertiary basal flow breccia

Folding in the area has been masked by later faulting. Later intrusions have also caused much tilting of beds. There are two major en echelon fault systems: one ranging from N. 45° W. to N. 40° E., the other approximately N. 75° W. Displacements are generally less than 100 feet.

Igneous and Pyroclastic Rocks

Basal Flow Breccia

The basal flow breccia crops out only in the extreme southwest part of the area. It is the lowest unit recognized in the area. The outcrop is faulted against late-Tertiary (?) basalt to the west and is overlain conformably by red-gray banded rhyolite to the east. A thickness of less than 50 feet is exposed in the area but the actual thickness is indeterminate. The rock is characterized by a light-brown aphanitic groundmass with fragmental inclusions of older aphanitic rocks up to several inches in length. The inclusions have been stretched and flattened resulting in a ragged limeation and foliation which suggests flowage during or after deposition. Anhedral plagioclase and quartz are imbedded in the glassy groundmass. Euhedral phenocrysts of sanidine and hornblende (very rarely biotite) and subhedral phenocrysts of quartz, together with the glassy groundmass, make up approximately 50 percent of the rock; the remainder is the inclusions. Weathered surfaces are not clearly distinguishable from fresh surfaces.

In thinsection, the rock texture is aphanitic porphyritic, with euhedral to subhedral phenocrysts of sanidine, euhedral hornblende, and a small amount of anhedral quartz. Magnetite, locally altered to hematite, is sparse. The groundmass is composed of reddish-brown glass having a wavy flow banding which is distorted around the inclusions. There is a very slight amount of devitrification along some of the inclusion boundaries.

The mode (excluding inclusions) is estimated to be:

Sanidine	10 %
Quartz	3 %
Hornblende	1 %
Magnetite and hematite	1 %
Groundmass	85 %

The inclusions are pinkish red to dark brown igneous rocks, typically with subhedral to anhedral quartz phenocrysts. In some fragments the groundmass is tuffaceous. One inclusion contains much albite. Sanidine is present in some inclusions. Generally, the plagioclase feldspars have a cloudy appearance and some are kaolinized. Earlier volcanic rocks must underlie the flow breccia.

The index of refraction of the natural glass is 1.525. The partial composition derived from the determinations of W. O. George[1] is estimated to be:

SiO_2	59.0 %
FeO and Fe_2O_3	7.5 %
CaO	5.0 %
K_2O	3.5 %
MgO	2.5 %

The index of refraction of the fused rock sample is 1.501, indicating the following composition (after Callaghan and Sun[2]).

SiO_2	71.8 %
FeO and Fe_2O_3	2.7 %
CaO	1.7 %
MgO	0.6 %

1. George, W. O., The Relation of the Physical Properties of Natural Glasses to their Chemical Composition, Jour. Geol., vol. 32, p. 353 (1934).

2. Callaghan, E., and Sun, M. S., op. cit.

Because of its position below basalts which are included within the Santa Fe time interval, the basal flow breccia is considered middle-Tertiary or younger in age.

The presence of amygdules, flow banding, inclusions of earlier volcanics, and brecciation indicate that this rock is a flow breccia.

Red-Gray Banded Rhyolite

The red-gray banded rhyolite crops out in the extreme southwest part of the area, where it overlies the basal flow breccia conformably. It crops out also in the southeastern part of the area and along the road through the canyon in the eastern part of the area, where it is overlain conformably by the agglomerate-tuff sequence. The thickness is approximately 200-300 feet.

The rock is characterized by alternate red and gray near-parallel, and almost linear, flow bands ranging in thickness from 1/50 inch to 1/5 inch. The bands are distorted around phenocrysts and inclusions. Euhedral to subhedral phenocrysts of sanidine, hornblende, magnetite (very rarely biotite) make up approximately 10 percent of the rock and the remainder is the aphanitic groundmass.

In thinsection the rock texture is aphanitic prophyritic, with phenocrysts of euhedral to subhedral sanidine, subhedral to anhedral quartz, euhedral hornblende, and rarely, biotite. Magnetite grains and much hematite are present. The banding consists of alternate reddish gray and light gray bands which is sometimes extremely fine.

The reddish gray bands are composed of approximately 40 percent glass and 60 percent cryptocrystalline material and contain magnetite grains. The light gray bands are composed of orthoclase.

The mode is estimated as follows:

Quartz	15 %
Sanidine	10 %
Orthoclase	25 %
Magnetite and hematite	10 %
Albite	3 %
Hornblende and biotite	1 %
Groundmass	36 %

The index of refraction of the natural glass is 1.515, indicating the following composition:[1]

SiO_2	65.0 %
FeO and Fe_2O_3	5.2 %
CaO	3.0 %
MgO	1.5 %
K_2O	3.7 %

The index of refraction of the fused sample is 1.497, from which the following composition is derived:[2]

SiO_2	72.8 %
FeO and Fe_2O_3	2.5 %
CaO	1.5 %
MgO	0.5 %

The red-gray banded rhyolite is considered to be middle Tertiary in age because of its conformable position above the basal flow breccia.

Rapid cooling phenomena, e.g., glassy spherulitic groundmass, and flow banding are evidences that this was a flow.

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1. George, W. O., op. cit.

2. Callaghan, E., and Sun, M. S., op. cit.

Agglomerate-tuff sequence

The agglomerate-tuff sequence covers several square miles in and around the area. In the southwestern part of the area it overlies conformably the red-gray banded rhyolite. In the eastern part of the area, along the road, it overlies conformably the red-gray banded rhyolite and conformably underlies a rhyolite flow breccia. Further west, it underlies unconformably the main flow rhyolite. In the southwestern part of the area the agglomerate-tuff unit is faulted against late-Tertiary (?) basalt and andesite. In the northwestern section it is faulted against the red rhyolite. Thicknesses in the area vary from 0 to 500 feet.

The agglomerate-tuff sequence is gradational from a basal agglomerate with large fragments (up to 3 feet in diameter) through beds of volcanic ash overlain by a water-laid tuff (see Plate III, fig. 1) to a tuff containing little or no inclusions at the top. Euhedral phenocrysts of sanidine, plagioclase feldspar, quartz, hornblende, and biotite are found in most of the units. Throughout the formation, there are lenses of perlite which assume the spatial relations of the main mass. Parts of the formation are welded.

The basal agglomerate typically consists of approximately 50 percent inclusions and 50 percent tuffaceous groundmass with phenocrysts of sanidine, plagioclase feldspar, quartz, hornblende, magnetite, hematite, and (rarely) biotite. The color of the groundmass varies from cream to pinkish and greenish. The weathered surfaces appear orange to brown. Inclusions are mostly earlier volcanic rocks;

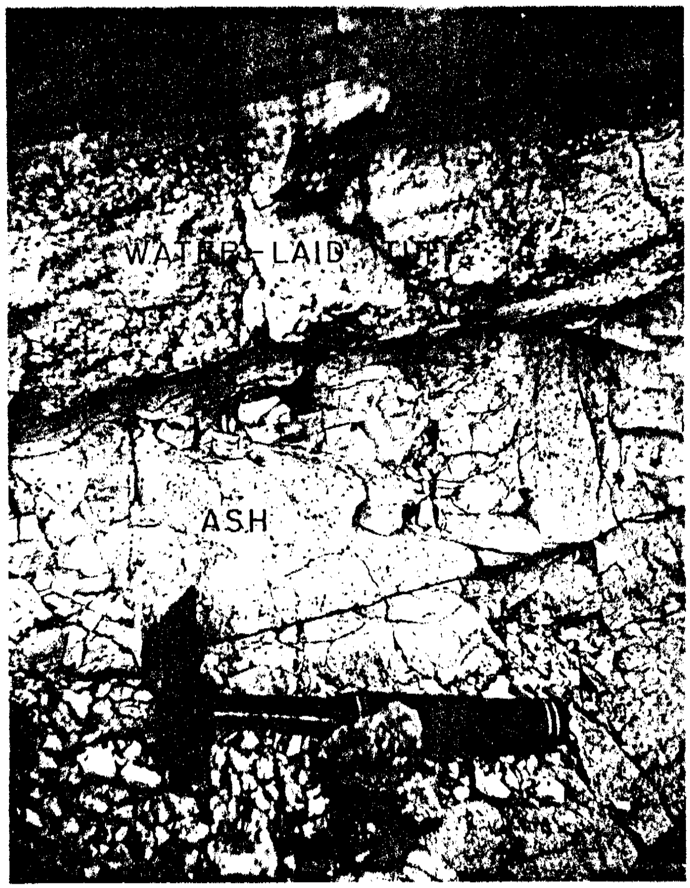

Figure I. Water-laid tuff over volcanic ash agglomerate-tuff sequence (Tat).

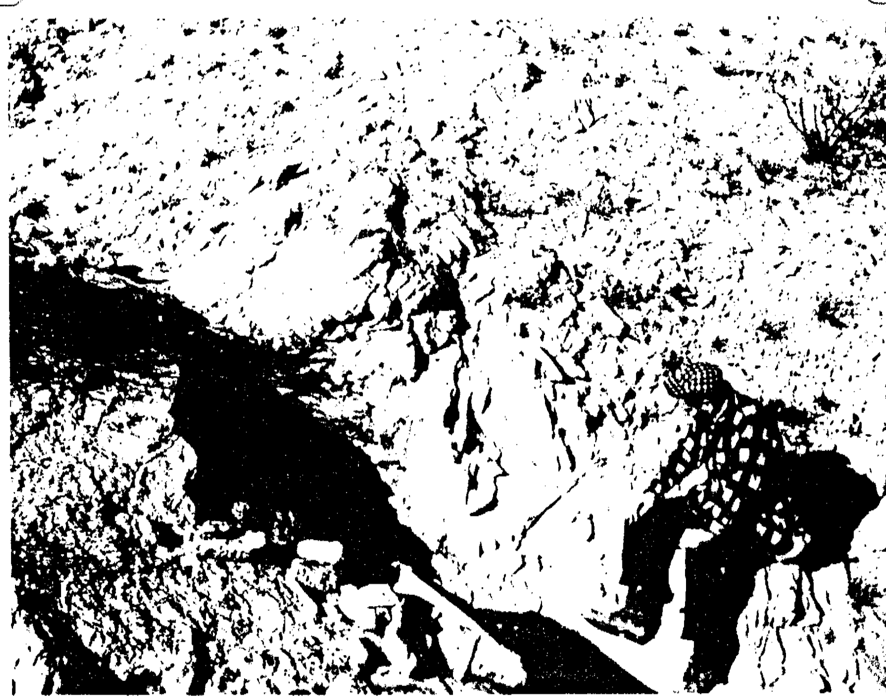

Figure 2. Water-laid tuff.

e.g., red-gray banded rhyolite. Some inclusions contain much albite in a glassy groundmass, the albite making up 75 percent of the rock. Others contain oligoclase in a glassy groundmass. In thinsection, the groundmass is composed of glass shards, many of which have devitrified, and spherulites. It is typically tuffaceous. Phenocrysts of euhedral to subhedral sanidine and plagioclase feldspar (some zoned and much oligoclase), hornblende, and subhedral to anhedral quartz are present. Some of the feldspars have been kaolinized and have minor amounts of biotite and magnetite, some of which is altered to hematite. The fragmental inclusions range from orange to dark reddish brown.

The mode of the rock is estimated to be:

Inclusions	50 %
Groundmass	30 %
Sanidine	10 %
Plagioclase feldspar	5 %
Quartz	2 %
Hornblende	1 %
Magnetite and hematite	1 %
Biotite	1 %

The index of refraction of the natural glass is approximately 1.495, indicating the following composition:[1]

SiO_2	73.0 %
FeO and Fe_2O_3	2.3 %

1. George, W. O., op. cit.

CaO	1.4 %
MgO	0.5 %
K_2O	4.2 %

The index of refraction of the fused sample (exclusive of inclusions) is 1.499, indicating the following composition:[1]

SiO_2	72.2 %
FeO and Fe_2O_3	2.6 %
CaO	1.6 %
MgO	0.6 %

The tuffaceous groundmass indicates the pyroclastic origin of this rock. Because of the amount of fragmental inclusions this rock is called an agglomerate. It is gradational into the tuff, and sharp boundaries exist only where there has been faulting of one unit against the other.

The consolidated ash bed is found near the top of the unit and within the tuff. It is overlain by the water-laid tuff and is extremely fine-grained and cream white. Minute phenocrysts are not recognizable in hand specimen. In thinsection, fragments of sanidine and oligoclase, and a little biotite, hematite, and magnetite make up approximately 10 percent of the rock, the remainder being groundmass. The groundmass is mostly glass, but some devitrification has occurred.

The mode of the rock is estimated to be:

Sanidine	5 %
Oligoclase	2 %
Biotite	1 %
Hornblende	1 %
Magnetite and hematite	1 %

1. Callaghan, E., and Sun, M. S., op. cit.

Groundmass	90 %

The index of refraction of the natural glass is 1.495. The estimated composition is:[1]

SiO_2	73.0 %
FeO and Fe_2O_3	2.3 %
CaO	1.4 %
MgO	0.5 %
K_2O	4.2 %

The water-laid tuff occurs above the ash and somewhat below the top of the unit. It consists of rounded grains of quartz, plagioclase feldspar, magnetite, hematite, and biotite.

The groundmass is tuffaceous. Crossbedding, stratification, and rounded grains indicate a water-laid pyroclastic (see Plate III, Fig. 2; Plate IV, Fig. 1). It is cream white, and hematite staining gives the appearance of banding.

In thinsection the groundmass is mostly devitrified glass, with many small spherulites. A few sanidine and quartz grains are euhedral to subhedral. Some epidotization is evident.

The mode of the rock is estimated to be:

Sanidine	40 %
Quartz	20 %
Oligoclase	10 %
Groundmass	30 %

The index of refraction of the natural glass is 1.495, indicating the following composition:[2]

1. George, W. O., op. cit.

2. George, W. O., op. cit.

Figure 1. Close-up of water-laid tuff. (Scale approximately 1:25)

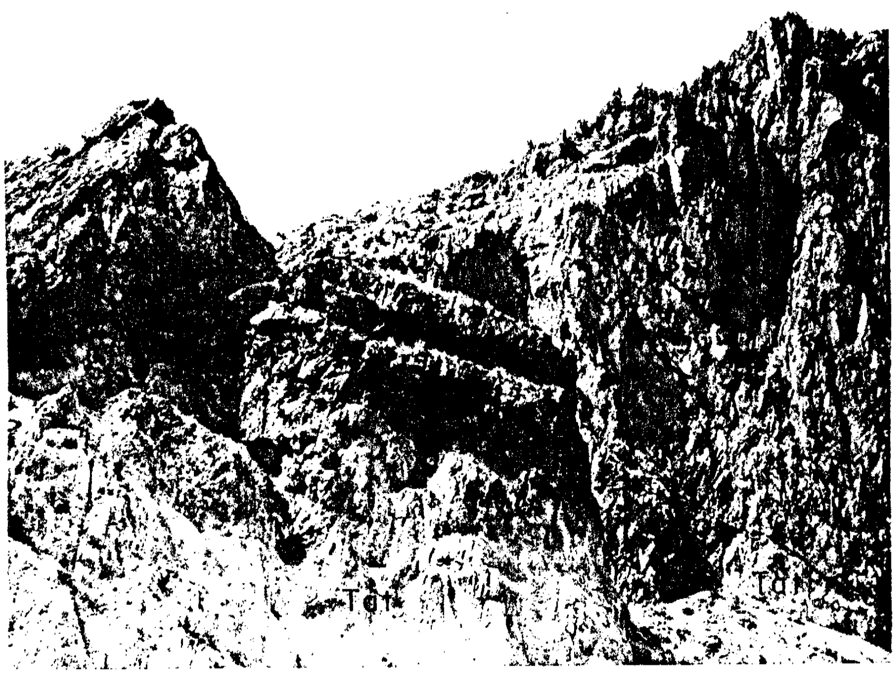

Figure 2. Flow rhyolite (Trs) unconformably over agglomerate-tuff sequence (Tat).

SiO_2	73.0 %
FeO and Fe_2O_3	2.3 %
CaO	1.4 %
MgO	0.5 %
K_2O	4.2 %

Neither the water-laid tuff nor the ash is a mappable unit. They represent phases of the pyroclastic unit and thereby are included in it. Lenses of black perlite have been deposited during the deposition of the tuff but likewise are not mappable.

The typical tuff at the top is cream white to greenish or pinkish white, with phenocrysts of sanidine, plagioclase feldspar, hornblende, and biotite in a tuffaceous groundmass. Inclusions vary and diminish toward the top, where the groundmass makes up approximately 90 percent of the rock. In places the tuff is somewhat pumiceous, and locally some welding has occurred. The weathered surfaces are cream to brown.

In thinsection the groundmass is colorless to orange brown and is tuffaceous. Part of it is glass, much of which has divitrified and is cryptocrystalline. Phenocrysts of euhedral to subhedral sanidine, oligoclase, hornblende, biotite, and magnetite, and subhedral to anhedral quartz make up about 35 percent of the rock, the remainder being groundmass.

The mode of the rock is estimated to be:

Sanidine	15 %
Oligoclase	8 %
Quartz	3 %
Hornblende	5 %

Biotite	2 %
Magnetite	2 %

The index of refraction of the natural glass is 1.495, indicating the following composition:[1]

SiO_2	73.0 %
FeO and Fe_2O_3	2.3 %
CaO	1.4 %
MgO	0.5 %
K_2O	4.2 %

The index of refraction of a fused composite sample is 1.493, indicating the following composition:[2]

SiO_2	73.8 %
FeO and Fe_2O_3	2.4 %
CaO	1.4 %
MgO	0.5 %

The tuffaceous fabric suggests the pyroclastic origin of the rock, which, because of its composition, may be called a rhyolitic tuff.

The chemical similarities of this rock indicate a common pyroclastic origin. The rock is gradational and is mapped therefore as a single unit called the agglomerate-tuff sequence. Table II shows a chemical analysis of a composite sample of the sequence.

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1. George, W. O., op. cit.

2. Callaghan, E., and Sun, M. S., op. cit.

TABLE II: CHEMICAL ANALYSIS[1] OF AGGLOMERATE-TUFF SEQUENCE (composite sample)[2]

	Percent[3]
SiO_2	75.36
TiO_2	0.23
Al_2O_3	13.89
Fe_2O_3	1.58
FeO	0.25
MnO	0.04
MgO	1.02
CaO	3.56
Na_2O	1.00
K_2O	3.02
P_2O_5	0.08
CO_2	0.00
	100.03%

1. Analysis by H. B. Wiik, Helsinki, Finland.
2. Two samples from different parts of the formation were mixed in equal proportions by weight.
3. The percentages are calculated as volatile-free.

Altered Rhyolite Flow Breccia

The altered rhyolite crops out in the east and southwest parts of the area. In the eastern part of the area, it overlies conformably the agglomerate-tuff sequence and is faulted against later Santa Fe conglomerate. In the southwest all contacts except one are fault contacts. The altered rhyolite has been faulted against the earlier silicified agglomerate-tuff sequence, and against late-Tertiary basalt, which also overlies it unconformably after an apparently long erosional period (evidenced by clastic debris of similar chemical and mineralogic composition and fabric). The east and southwest outcrops have been correlated on field and mineralogic similarities. Thicknesses up to 250 feet are exposed (including the clastic debris), but owing to erosion, the true thickness of the formation is indeterminate.

In the eastern section, the rhyolite ranges from a silicified and highly altered phase to a lesser altered phase showing distinct flow banding. The color varies from light pinkish gray, through red, to reddish purple. Weathered surfaces vary from purple to brown. The rounded and angular fragments make up more than 50 percent of the rock and consist of sanidine, quartz, plagioclase feldspar, hornblende, and some biotite.

In the southwest the formation grades from light pinkish to purplish gray, through orange, to a red similar to parts of the eastern formation. Weathered outcrop surfaces range from buff to reddish brown. The formation is typically aphanitic porphyritic, with inclusions making up more than 50 percent of the rock and consisting of quartz, sanidine, plagioclase feldspar, hornblende, and biotite.

In the southwest the altered rhyolite is gradational to clastic debris, which is partly weathered.

In thinsection the rounded and angular mineral fragments are seen in a cryptocrystalline and spherulitic groundmass, which in places is extremely altered (up to 75 percent of the groundmass has been noted to be kaolinized or sericitized). There is little or no remaining glass in the groundmass. Flow banding often is concealed by alteration but is observed in some sections. The mineral fragments are typically euhedral to subhedral sanidine and apatite, subhedral to anhedral quartz, oligoclase, zoned plagioclase, hornblende, biotite, and magnetite partially altered to hematite. Most grains are fractured, and fracture partings have been filled with replacement material.

The range of the mode of the rock is:

Sanidine	20-35 %
Quartz	5-10 %
Oligoclase and zoned plagioclase	5-15 %
Hornblende	0- 5 %
Biotite	2- 5 %
Magnetite and hematite	2-10 %
Inclusions	45-60 %

The feldspars are highly kaolinized in all samples. Many mineral grains show partial remelting along the boundaries.

The index of refraction of the fused samples ranges from 1.493 to 1.503, indicating the following range of composition:[1]

SiO_2	73.8 %	to	71.3 %
FeO and Fe_2O_3	2.4 %	to	2.8 %
CaO	1.4 %	to	1.7 %
MgO	0.5 %	to	0.6 %

This unit is presumed to be middle Tertiary in age because of its conformable relation over the agglomerate-tuff sequence. The fragmental inclusions indicate that it is a flow breccia. Some crystallization began before flowage. Sericitization and silicification are due to hydrothermal activity, possibly of late magmatic fluids. Kaolinization is due to weathering, which apparently occurred in two stages: one previous to the deposition of the late-Tertiary (?) basalt flows and one since this deposition.

Flow Rhyolite and Latite

Miesch's[2] rhyolite (Trs) and latite (Tls) is the main flow unit of the area, covering about 1 square mile in the center of the area. In the northeastern and southeastern parts of the area, it is silicified and faulted against the Santa Fe conglomerate and the agglomerate-tuff sequence. In the center of the area it overlies unconformably the agglomerate-tuff sequence. In places massive red rhyolite underlies the flow rhyolite as an intrusive sill. The upper part of the flow is a latite and is downfaulted

1. Callaghan, E., and Sun, M. S., op. cit.

2. Miesch, A. T., op. cit.

as a block in the center of the rhyolite mass (see Plate V, Fig. 2; Plate VI, Fig. 1). Thicknesses up to 200 feet are exposed.

The rhyolite shows typical flow banding with wavy bands (see Plate V, Fig. 1). Near the eastern edges it often contains a few fragments of chalcedony. Phenocrysts of sanidine and plagioclase feldspar are evident, along with altered hornblende and biotite (bronze biotite), which is believed to be a product of deuteric activity. The groundmass appears glassy, and ragged amygdules are present. The color varies from pinkish white to purple, the lighter areas having a bleached appearance. Weathered surfaces are light brown to reddish brown and purple. In some places there is heavy manganese stain.

In thinsection the rhyolite is aphanitic porphyritic, with euhedral to subhedral grains of oligoclase, much kaolin (probably as an alteration of plagioclase feldspar), some euhedral zoned plagioclase, subhedral to anhedral quartz grains, euhedral altered hornblende and biotite, and euhedral augite and ilmenite. Table III shows a chemical analysis of a composite sample of the flow rhyolite.

The mode of the rock is estimated as follows:

Sanidine	15 %
Plagioclase feldspar (oligoclase)	5 %
Quartz	5 %
Hornblende	2 %
Biotite	2 %

Figure 1. Flow banding in flow rhyolite (Trs).

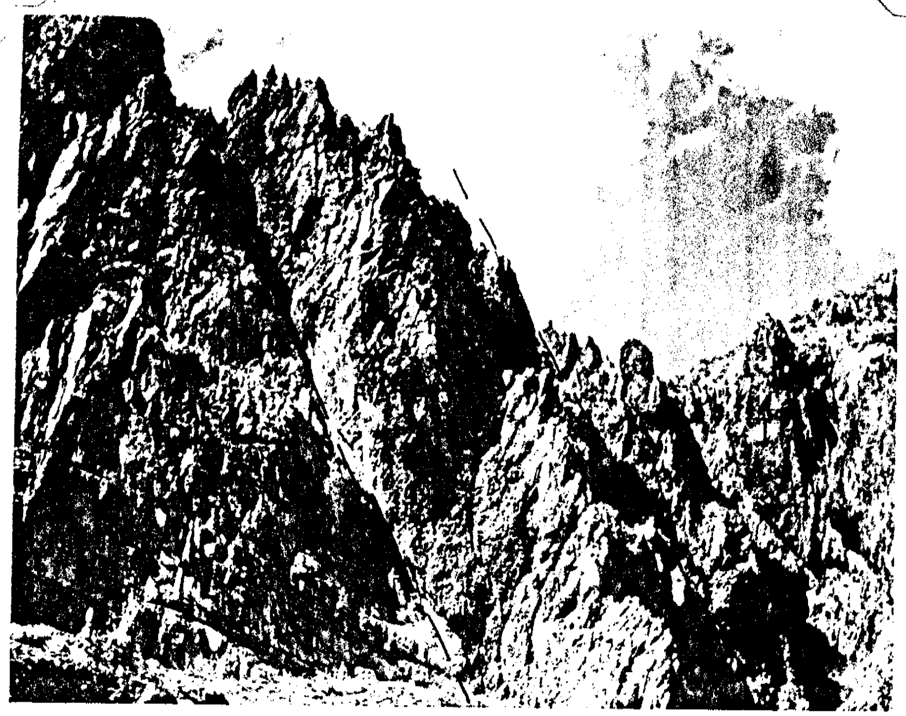

Figure 2. Flow latite (Tls) downfaulted against flow rhyolite (Trs), (Fault (12)). Note brecciated fault zone.

Augite	1 %
Ilmenite	2 %
Groundmass	68 %

The groundmass is cryptocrystalline and locally spherulitic, with minute laths of orthoclase. There is about 10 percent glass, the remainder having devitrified. The flow structure is intensified by alternating reddish-brown and colorless bands, which are very wavy and irregular.

The rhyolite is gradational to the latite, the amount of crystalline quartz decreasing as the amount of plagioclase feldspar and augite increases.

In thinsection the latite contains about 35 percent kaolinized feldspar. Quartz phenocrysts are absent; augite and ilmenite are more abundant. The rock texture is similar to the rhyolite, but good phenocrysts are rarer. Alteration has increased, and flow structures are not so evident in thinsection. The mode of the latite is estimated to be:

Sanidine	5 %
Oligoclase	5 %
Kaolinized feldspar	35 %
Hornblende	2 %
Biotite	1 %
Augite	2 %
Ilmenite	2 %
Groundmass	48 %

Figure 1. Exposure of flow rhyolite (Trs). Section 5, T.5S., R.1 W. Note faults (20) and (12) in background.

Figure 2. Exposure of part of perlite dike complex above flow rhyolite (Trs).
Tc - "contact" spherulitic gray perlite
Tp - perlite
Tsp - banded spherulitic perlite

TABLE III: CHEMICAL ANALYSIS[1] OF FLOW RHYOLITE (Trs) (composite sample)

SiO_2	73.69 %
TiO_2	0.23 %
Al_2O_3	12.94 %
Fe_2O_3	1.66 %
FeO	0.07 %
MnO	0.04 %
MgO	0.03 %
CaO	0.68 %
Na_2O	2.87 %
K_2O	6.08 %
P_2O_5	0.08 %
H_2O+	1.13 %
H_2O-	0.19 %
CO_2	0.00
	99.69 %

1. Analysis by H. B. Wiik, Helsinki, Finland.

The silicified rhyolite is correlated as part of the rhyolite flow because of its similarities both in petrological and field relations. The mode is estimated to be:

Sanidine	25 %
Oligoclase	15 %
Quartz	15 %
Hornblende	2 %
Biotite	1 %
Ilmenite	2 %
Groundmass	40 %

The groundmass is partly devitrified glass, about 5 percent glass remaining, and is spherulitic and cryptocrystalline, with some lithophysae. Flow banding is evident in many places both magascopically and microscopically.

A fused composite sample of the flow rhyolite gives an index of refraction of 1.503, indicating the following composition:[1]

SiO_2	71.3 %
FeO and Fe_2O_3	2.8 %
CaO	1.7 %
MgO	0.6 %

Other fused samples of the flow rhyolite have indices ranging from 1.493 to 1.503; the silicified portions have a lower index (1.493-1.495), indicating the following compositions:[2]

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1. Callaghan, E., and Sun, M. S., op. cit.

2. Callaghan, E., and Sun, M. S., op. cit.

	1.493	1.495
SiO_2	73.8 %	73.3 %
FeO and Fe_2O_3	2.4 %	2.4 %
CaO	1.4 %	1.4 %
MgO	0.5 %	0.5 %

The flow banding and amygdules indicate that this unit was a flow. The more silicic parts are called rhyolite (Miesch's Trs),[1] and the less silicic downfaulted blocks are called quartz latite (Miesch's Tls).[2]

Perlitic Dike Complex

The perlitic dike complex crops out above the flow rhyolite in the center of the area (see Plate VI, Fig. 2), and just north of the road in the eastern part of the area. The total width of the dike complex is approximately 2,000 feet. This complex is a later intrusion into the flow rhyolite. Xenoliths of the flow rhyolite are found in the complex, and beds of the flow rhyolite and the agglomerate-tuff sequence have been tilted by the intrusion. The perlite dike complex consists of the following units:

1. Perlite (Tp)
2. Banded spherulitic perlite (Tsp)
3. "Contact spherulitic gray perlite (Tc)
4. Spherulitic rhyolite (Ts)

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1. Miesch, A. T., op. cit.

2. Miesch, A. T., op. cit.

The perlite (Tp) is typically intergrown brown and black perlite, with phenocrysts of sanidine, hornblende, and plagioclase feldspar. The weathered surfaces are brown to black.

In thinsection the perlite contains euhedral to subhedral phenocrysts of sanidine and some microcline, subhedral phenocrysts of oligoclase, euhedral to subhedral hornblende and diopside, and biotite and magnetite in a glassy perlitic groundmass. The mode of the rock is estimated as follows:

Sanidine	15 %
Microcline	1 %
Oligoclase	3 %
Hornblende	3 %
Biotite	2 %
Magnetite	1 %
Diopside	1 %
Groundmass	74 %

The index of refraction of the natural glass is 1.495, indicating the following composition:[1]

SiO_2	73.0 %
FeO and Fe_2O_3	2.3 %
CaO	1.4 %
MgO	0.5 %
K_2O	4.2 %

1. George, W. O., op. cit.

The index of refraction of the fused sample is 1.497, indicating the following composition:[1]

SiO_2	72.8 %
FeO and Fe_2O_3	2.5 %
CaO	1.5 %
MgO	0.5 %

The banded spherulitic perlite (Tsp) is composed typically of series of bands of reddish-brown perlite and light-gray perlite, with reddish-brown spherulites within the bands; some bands have a greater percentage of spherulites, giving the impression of a peppermint stick.

Phenocrysts of sanidine, quartz, and hornblende are present. The hornblende is alined with the banding. The weathered surfaces are buff to dark brown.

In thinsection, phenocrysts of euhedral to subhedral sanidine, zoned plagioclase, apatite, biotite, hornblende, and magnetite, as well as subhedral to anhedral quartz, are observed in a spherulitic and perlitic groundmass. The spherulites range up to 1/8 in. in diameter and usually have potash feldspar centers. There is some devitrification around the perlitic cracks. The mode of the rock is estimated to be:

Sanidine	15 %
Plagioclase feldspar	10 %
Quartz	2 %
Apatite	2 %

1. Callaghan, E., and Sun, M. S., op. cit.

Hornblende	2 %
Biotite	2 %
Magnetite	1 %
Groundmass	66 %

(Spherulites make up approximately 30 percent of the groundmass.) The index of refraction of the natural glass is 1.495, indicating the following composition:[1]

SiO_2	73.0 %
FeO and Fe_2O_3	2.3 %
CaO	1.4 %
MgO	0.5 %
K_2O	4.2 %

The index of refraction of the fused sample is 1.497, indicating the following composition:[2]

SiO	72.8 %
FeO and Fe_2O_3	2.5 %
CaO	1.5 %
MgO	0.5 %

The contact spherulitic gray perlite (Tc) typically is found in the complex near the contacts with the agglomerate-tuff sequence and for that reason has been referred to as the contact perlite. It is typically light green to gray and contains abundant reddish-brown spherulites and felsitic patches. Phenocrysts of sanidine, plagioclase feldspar, hornblende, and a little biotite are present. The weathered surface appears light green to brown except for the dark-brown

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1. George, W. O., op. cit.

2. Callaghan, E., and Sun, M. S., op. cit.

In thinsection the groundmass is composed of light-gray to colorless perlitic glass, reddish-brown spherulites, and cryptocrystalline material of potash feldspar composition. The spherulites typically have potash feldspar centers. The mode of the rock is estimated to be:

Sanidine		2 %
Plagioclase feldspar (zoned, oligoclase)		12 %
Biotite		2 %
Hornblende		3 %
Magnetite		1 %
Groundmass:		80 %
Perlite	15 %	
Spherulites	50 %	
Cryptocrystalline	15 %	

The index of refraction of the fused sample is 1.495, indicating the following composition:[1]

SiO_2	73.3 %
FeO and Fe_2O_3	2.4 %
CaO	1.4 %
MgO	0.5 %

The spherulitic rhyolite is typically an aphanitic porphyritic rhyolite, with phenocrysts of sanidine, plagioclase feldspar, hornblende, and biotite in a pink to reddish-brown spherulitic groundmass. The weathered surfaces are dark brown to black.

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1. Callaghan, E., and Sun, M. S., op. cit.

In thinsection euhedral to subhedral phenocrysts of sanidine, oligoclase and zoned plagioclase, hornblende, biotite, and magnetite are present in a groundmass consisting of reddish-brown spherulites and lithophysae. The mode of the rock is:

Sanidine		5 %
Oligoclase		10 %
Zoned plagioclase		5 %
Biotite		4 %
Magnetite		1 %
Groundmass		75 %
Lithophysae	70 %	
Spherulites	5 %	

The index of refraction of the fused sample is 1.495, indicating the following composition:[1]

SiO_2	73.3 %
FeO and Fe_2O_3	2.4 %
CaO	1.4 %
MgO	0.5 %

The mineralogic, petrologic, and chemical properties indicate the similar rhyolitic composition of this formation. Though very similar petrographically, the units are well defined in the field, and contacts, though sometimes covered with recent alluvium, are recognized easily.

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1. Callaghan, E., and Sun, M. W., op. cit.

Massive Red Rhyolite

The massive red rhyolite (Tmr)[1] crops out in large areas throughout the mapped region. It is found in various relationships with the agglomerate tuff sequence and the flow rhyolite. In places it is in contact with the tuff as a dikelike intrusion (see Plate VII, Fig. 1); in other places it is within the tuff as a sill-like intrusion. It locally cuts through the tuff and the flow rhyolite. Xenoliths of the tuff (as well as xenoliths of the flow rhyolite) occur in the massive red rhyolite (see Plate VII, Fig. 2). Flow structure is typically absent from the massive rhyolite. The color in the southern part varies from dark red to brownish red. Weathered surfaces are red to brown. The massive rhyolite is typically spherulitic. Phenocrysts of sanidine, plagioclase feldspar, biotite, and (rarely) quartz make up about 40 percent of the rock, the remainder being spherulitic groundmass. Table IV shows a chemical analysis of the massive red rhyolite.[2]

In thinsection euhedral to subhedral phenocrysts of sanidine, zoned plagioclase, oligoclase, and biotite, and subhedral to anhedral quartz are in a reddish-brown spherulitic groundmass with some lithophysae. Flow structure is absent. There is little glass in the groundmass. The mode of the rock is estimated to be:

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1. Miesch, A. T., op. cit.

2. Miesch, A. T., op. cit.

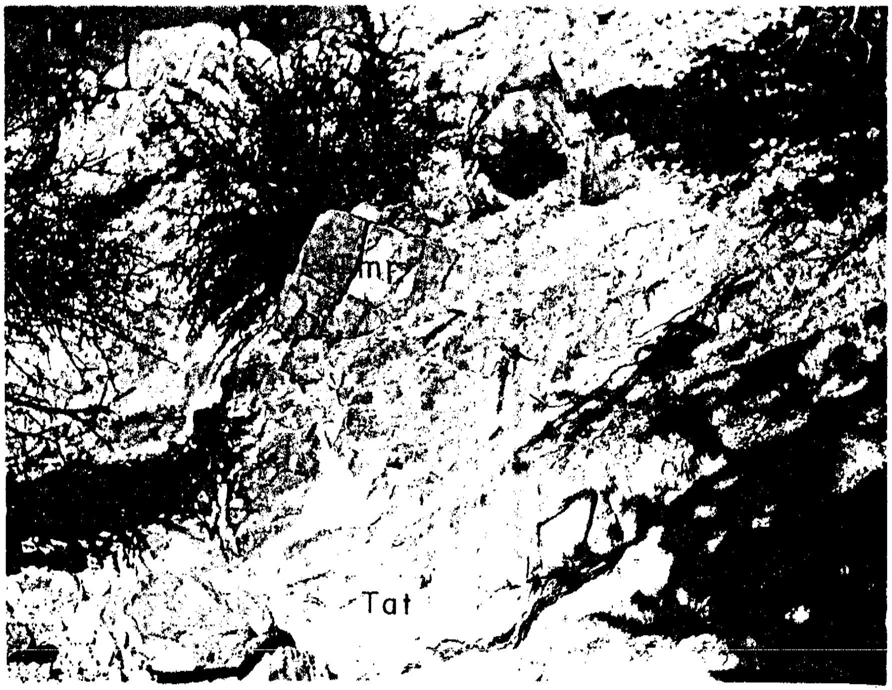

Figure 1 Intrusive contact of massive red rhyolite (Tmr) and agglomerate-tuff sequence (Tat).

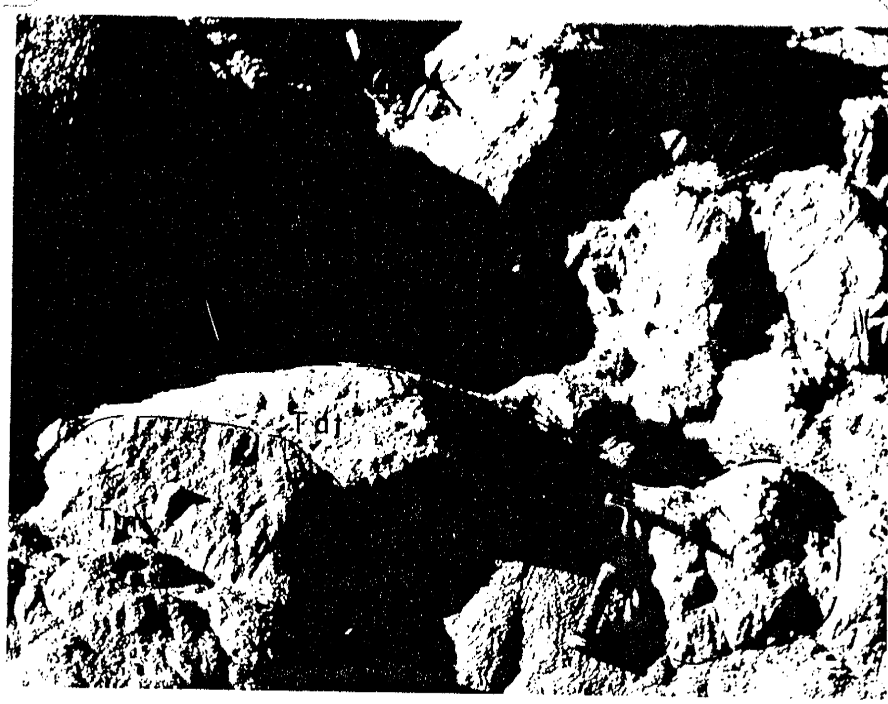

Figure 2. Xenolith of tuff (Tat) in massive red rhyolite (Tmr).

Sanidine	15 %
Plagioclase feldspar (zoned and oligoclase)	10 %
Quartz	5 %
Biotite	5 %
Spherulitic groundmass	65 %

The index of refraction of the fused sample ranges from 1.499 to 1.503, indicating the following range of composition:[1]

	1.499		1.503
SiO_2	72.2	to	71.3 %
FeO and Fe_2O_3	2.6	to	2.8 %
CaO	1.6	to	1.7 %
MgO	0.6	to	0.6 %

The contacts and included fragments of other rock units indicate that this rock is a shallow intrusive having dike and sill forms, and that it is younger than the agglomerate-tuff sequence, the flow rhyolite, and the perlitic dike complex. Owing to the intrusive nature of this formation, its actual thickness is indeterminate. Thicknesses up to 500 feet are exposed in the area.

The analysis and mineral content indicate that the unit is a rhyolite; it is the same as Miesch's[2] massive rhyolite (Tmr).

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1. Callaghan, E., and Sun, M. S., op. cit.

2. Miesch, A. T., op. cit.

TABLE IV: CHEMICAL ANALYSIS OF THE MASSIVE RED RHYOLITE[1] (Tmr):

SiO_2	71.09 %
TiO_2	0.25 %
Al_2O_3	14.07 %
Fe_2O_3	1.73 %
FeO	0.32 %
MnO	0.08 %
MgO	0.71 %
CaO	0.88 %
Na_2O	1.89 %
K_2O	6.19 %
P_2O_5	0.09 %
H_2O+	2.20 %
H_2O-	0.95 %
CO_2	0.00 %
	100.45 %

1. Miesch, A. T., op. cit.

Andesite Dike Complex (Ta)

The andesite dike complex crops out in the southwest part of the area as a series of dikes located in fault zones. It cuts the altered rhyolite flow breccia and is earlier than the late-Tertiary (?) basalt. It is found faulted against the agglomerate-tuff sequence and the late-Tertiary (?) basalt, which in turn are also in fault contact. The width varies from 10 feet (in the fault zones) to 500 feet.

The andesite is typically purple and contains grains of altered biotite, secondary calcite, and epidote. The weathered surfaces vary from dark purple to brown.

In thinsection the rock is holocrystalline, made up mostly of small andesine laths, with phenocrysts of biotite, magnetite altered in part to hematite, reddish altered hornblende, and (rarely) a pyroxene (usually augite). Secondary calcite is common.

The mode of the rock is estimated to be:

Andesine	70 %
Biotite	8 %
Magnetite	12 %
Hematite	1 %
Hornblende	5 %
Augite	2 %
Calcite (secondary)	2 %

The index of refraction of the fused sample is 1.539, indicating the following composition:[1]

SiO_2	62.2 %
FeO and Fe_2O_3	5.2 %
CaO	3.7 %
MgO	1.6 %

The andesite-dike complex is later in age than the altered rhyolite flow breccia. Fragments of the andesite (found in the clastic debris of the eroded altered rhyolite) indicate that the andesite intruded before the erosional cycle which represents the unconformity between the altered rhyolite and the late-Tertiary (?) basalt. The andesite, therefore, is considered to be late Tertiary (?) in age.

Gray Basalt

The late-Tertiary (?) gray basalt (Tb) crops out in the southwestern part of the area and is found as cap rock unconformably over the altered rhyolite flow breccia. It is also found downfaulted against the agglomerate-tuff sequence and the basal flow breccia. Much of the basalt has been eroded, but thicknesses up to 100 feet are exposed.

In hand specimen the rock appears dark gray. Weathered surfaces are brown to black. It is fine grained, and phenocrysts of augite and basic plagioclase feldspar are recognizable. Secondary quartz and calcite fill small vesicles.

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1. Callaghan, E., and Sun, M. S., op. cit.

In thinsection the rock is holocrystalline, with subhedral to anhedral plagioclase laths, augite, magnetite, and olivine altering to antigorite and iddingsite.

The mode of the rock is estimated to be:

Labradorite	34 %
Zoned plagioclase	25 %
Olivine	8 %
Iddingsite	15 %
Antigorite	4 %
Augite	8 %
Pigeonite	4 %
Magnetite	2 %

The fused sample has an index of refraction of 1.590, from which the following chemical composition is estimated:[1]

SiO_2	50.0 %
Fe_2O_3 and FeO	9.9 %
CaO	8.3 %
MgO	6.2 %

The evidence for flow is the vesicularity of this formation, along with its position above the clastic debris of the altered rhyolite flow breccia, which shows baking at the contact. Owing to its deposition after the erosion of a middle-Tertiary flow, the gray basalt is considered to be of late-Tertiary (?) age.

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1. Callaghan, E., and Sun, M. S., op. cit.

Basalt

The Quaternary basalt (Qb) crops out along the road just outside the eastern edge of the area, where it is found within the Santa Fe conglomerate, and crops out at the eastern edge of the area as a cap overlying the Santa Fe (see Plate VIII, Fig. 2). Exposed thicknesses vary from 10 to 150 feet. It is a series of flows (at least three have been identified), as is evidenced by alternating layers of massive and vesicular basalt. It is dark greenish black. Weathered surfaces vary from yellowish brown to dark green. In some places there is much epidotization (especially filling vesicles).

In thinsection the texture is ophitic, having euhedral to subhedral laths of labradorite in an augite matrix. There is much olivine in various stages of alteration to iddingsite and antigorite. The mode of the rock is estimated to be:

Labradorite	37 %
Augite	35 %
Olivine	10 %
Iddingsite	5 %
Antigorite	5 %
Chlorite	5 %
Magnetite	1 %
Secondary calcite	1 %
Secondary epidote	1 %

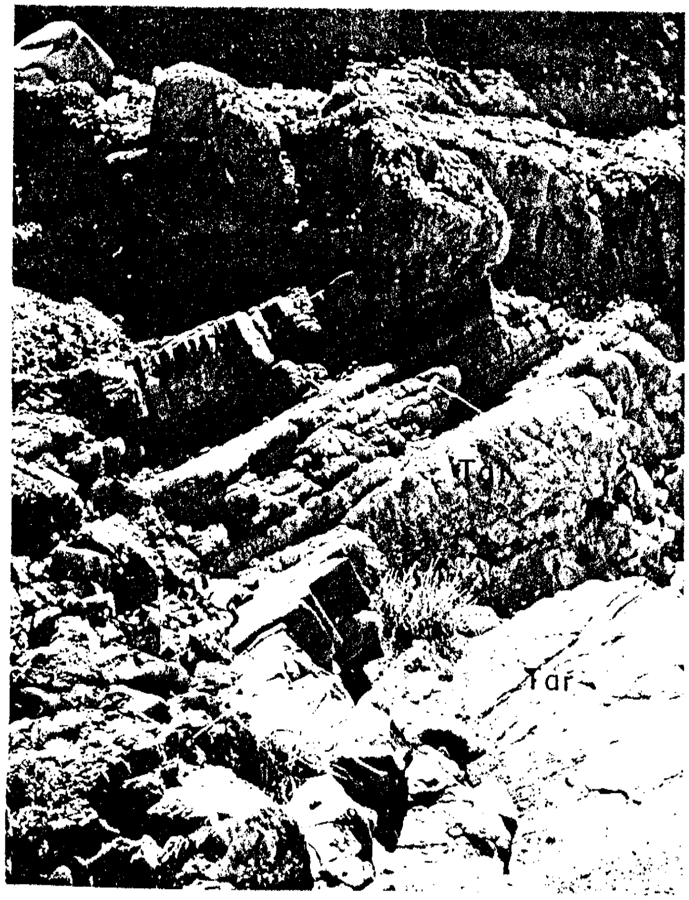

Figure I. Minor fault showing displacement of approximately three feet. Late Tertiary (?) basalt (Tb) unconformably overlying Middle Tertiary altered rhyolite flow breccia (Tar).

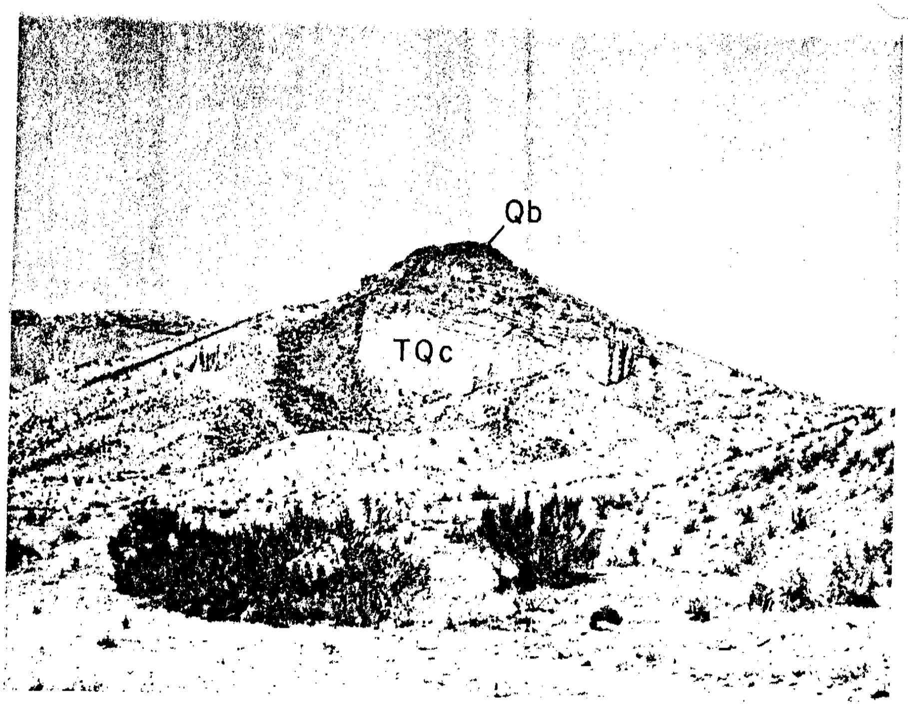

Figure 2. Quaternary basalt (Qb) overlying late Santa Fe conglomerate (TQc).

The index of refraction of the fused sample is 1.604, indicating the following composition:[1]

SiO_2	47.2 %
FeO and Fe_2O_3	11.5 %
CaO	9.6 %
MgO	7.8 %

The various zones of vesicularity indicate at least three separate flows of this basalt. Its position in the Santa Fe conglomerate sets its age as Quaternary. This basalt unit is the same as Miesch's[2] Quaternary basalt (Qb).

Sedimentary Rocks: Santa Fe Conglomerate

The Santa Fe conglomerate (TQc) crops out only in the eastern part of the area, where it is downfaulted against the Tertiary volcanic rocks. Near the fault, the Santa Fe formation has the appearance of a talus slope, containing large boulders (up to 3 feet in diameter) of some of the volcanics. The Santa Fe is typically composed of sand, gravel, and clay[3] in the Rio Grande Valley. The conglomerate is the only part of the Santa Fe which is seen in the Nogal Canyon area. The Santa Fe is upper Pliocene[4] in age.

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1. Callaghan, E., and Sun, M. S., op. cit.

2. Miesch, A. T., op. cit.

3. Miesch, A. T., op. cit.

4. Needham, C. E., Vertebrate Reamins From Cenozoic Rocks, Science, vol. 84, p. 537 (1936).

Structural Setting

The structure of the Nogal Canyon area has been influenced by two major factors:[1] (1) The intrusion of the massive red rhyolite, and (2) the formation of the Rio Grande trough. The intrusion of the massive red rhyolite caused local folding and faulting in the area. Earlier folding of beds from the initial stages of the intrusion is masked by later faulting. Evidence of folding in the eastern part of the area is from locally westward dipping beds; throughout most of the area the beds dip to the east.

The formation of the Rio Grande trough may account for the downfaulting of later Santa Fe conglomerate against the volcanic rocks and the displacement of the late-Tertiary (?) basalt. The faulting generally occurs in two major en echelon series; one system strikes from N. 45° E. to N. 40° W., and the other approximately N. 75° W. A third factor in the structural control of the area has been the intrusion of the perlitic dike complex, which can account for minor local faulting in the areas where this dike complex crops out.

Fault displacements throughout the area are difficult to measure, but the dip-slip components are generally less than 100 feet; there are a few extending up to 900 feet. In many cases the total displacement cannot be determined, owing to tilting, erosion, faulting within a single rock unit, and the irregularity of surface flows.

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1. Miesch, A. T., op. cit.

Attitude of Igneous Rocks

The strike and dip of volcanic rocks are not always measured easily. True bedding may be associated only with rocks of pyroclastic origin, such as the agglomerate-tuff sequence in this area. Other methods of measuring attitudes must be employed. Strike and dip measurements of flows and intrusives can be taken from either the foliation or jointing pattern.

The dip of the plane determined by flow banding and mineral alinement (foliation) is readily measurable. The strike then can be obtained from knowledge of the direction of dip. However, locally the foliation may not represent a true dip but rather an adjustment to the topography at the time of deposition. Also, uneven cooling in the magmatic mass can cause local irregularities in the foliation. Some local variations can be noted on Plate I.

The strike and dip of horizontal joints is used to determine the attitude of the formation if the jointing is related apparently to the last stages of emplacement of the rock mass.

The following strikes and dips are presented as general for the entire formation represented in the Nogal Canyon area:

The basal flow breccia strikes N. 15° W., and the foliation indicates a dip of approximately 38° E.

Foliation measurements in the red-gray banded rhyolite indicate an attitude of N. 30° W., 25° E.

Beds of the pyroclastic agglomerate-tuff sequence generally strike N. 10° W. and dip from 25° to 33° E.

The altered rhyolite flow breccia strikes N. 30° W. and dips 40° E. Measurements were made along foliation and bedding planes.

The main flow rhyolite and latite strike N. 30° W. The foliation dips approximately 30° E. Local variations in dip are due to flowage over an erosional surface.

Foliation within the units of the perlitic-dike complex indicates a variation in strike from N. 55° W. to N. 75° W. The units generally dip approximately 65° W.

Jointing in the massive red rhyolite indicates a variation in strike from N. 30° W. to N. 15° E., and in dip from 25° E. to 70° E.

The andesite dike complex generally strikes N. 30° W., and the foliation indicates a dip of 20° E.

The Quaternary basalt flows strike approximately N. 60° W. and dip approximately 10° NE.

Attitude of Sedimentary Rocks

For the most part, along the eastern margin of the area, beds of the Santa Fe conglomerate strike north-south and dip approximately 25° E.

Fault Descriptions

The numbers shown below (in parentheses) correspond to the numbers along the faults illustrated in Plate I. The numbers begin with (1) in the northeast corner of the map and run consecutively north and south, the higher numbers to the west.

(1) Late-Santa Fe conglomerate is downfaulted against silicified flow rhyolite. The fault strikes N. 5° E. and dips 45° E. The displacement is indeterminate. The fault is traceable by a small brecciated zone, the truncation of beds, and fault grooves preserved in the rhyolite.

(2) Late-Santa Fe conglomerate is downfaulted against the agglomerate tuff sequence. The strike of the fault is N. 48° W., and it dips 48° W. The displacement is indeterminate. The fault is traceable by a small brecciated zone.

(3) Altered rhyolite (silicified in this part) is upfaulted against the agglomerate-tuff sequence to the north and the flow rhyolite (silicified) to the south. It strikes N. 25° W. and dips 45° W. The displacement is indeterminate. The minimum stratigraphic throw is approximately 50 feet. Truncation of the formational units locates the fault position.

(4) The agglomerate-tuff sequence is faulted against massive red rhyolite. Locally, deep erosion on the upthrown side exposes the

underlying red-gray banded rhyolite. This is one of the major faults in the area, having a dip-slip displacement of approximately 400 feet. The attitude is N. 40° E., 60° SW. The only evidence for the fault is the truncation of beds.

(5) Faulting occurs within the altered rhyolite to the north, and within the agglomerate-tuff sequence and the underlying red-gray banded rhyolite to the south. The fault strikes N. 7° W. and dips 60° W. The dip-slip displacement is approximately 75 feet. Through breccia and slickensides on the scarp, the fault can be traced northward from dislocated units.

(6) Faulting occurs within beds of the agglomerate-tuff sequence, which are locally cut by the later perlitic dike complex. South of the road, the red-gray banded rhyolite is exposed because of faulting. The fault strikes N. 10° W. and dips 80° E. The dip-slip displacement is less than 50 feet and is evidence of the faulting.

(7) Massive red rhyolite is faulted against the agglomerate-tuff sequence. The fault strikes N. 20° E. and dips 30° E. The displacement is indeterminate. The fault is traceable by locally brecciated zones, and slickensides are preserved in the massive rhyolite.

(8) Faulting occurs within flow rhyolite and between the flow rhyolite and the perlitic dike complex. The attitude is N. 10° W., 80° E. The dip-slip displacement is less than 25 feet. The evidence for this fault is a brecciated zone.

(9) Faulting occurs within the agglomerate-tuff sequence, and, where exposed by the canyon, patches of the red-gray banded rhyolite crop out. The fault strikes N. 10° W. and dips 60° W. The dip-slip displacement is approximately 26 feet and is evidence of the faulting.

(10) Flow rhyolite and latite are downfaulted against the agglomerate-tuff sequence. To the east, beds of the agglomerate tuff sequence are in contact with the altered rhyolite, and the fault is extended through the altered rhyolite on the basis of irregular breccia zones. The strike and dip are N. 75° W. and 75° S. The dip-slip displacement is approximately 50 feet. The evidence for faulting is brecciation and the truncation of units.

(11-12) A block of flow latite is downfaulted against flow rhyolite. Fault (11) strikes due north and dips 83° E. Fault (12) strikes N. 10° W. and dips 75° E. (see Plate V., Fig. 2). The displacements are indeterminate. A brecciated zone, along with the truncation of the beds, is evidence of the fault.

(13) The fault occurs within the agglomerate-tuff sequence and the perlitic dike complex. It strikes N. 53° E. and dips 70° NW. A continuous brecciated zone indicates the fault position, although no displacement is noted at the contacts.

(14) Flow rhyolite is faulted against contact spherulitic gray perlite. The attitude is N. 53° E., 70° NW. The displacement is indeterminate. A brecciated zone and truncation of the flow banding indicate the fault.

(15) Faulting is suggested within the flow rhyolite by a narrow brecciated zone, although no displacement can be measured. The attitude of the zone is N. 20° E., 75° E.

(16) Faulting between flow latite and flow rhyolite extends southward from the contact between latite and massive red rhyolite. The attitude is N. 7° W., 80° E. The displacement is indeterminate. A brecciated zone and the truncation of beds are evidences of the faulting.

(17) Faulting of massive red rhyolite and the agglomerate-tuff sequence against flow latite extends northward within the banded spherulitic perlite and flow rhyolite, and within flow rhyolite. The fault strikes N. 20° W. and dips 87° W. The displacement is indeterminate. A fault breccia is evidence of faulting.

(18) Massive red rhyolite is faulted against beds of the agglomerate-tuff sequence. The strike and dip are N. 38° W., 83° E. The displacement is indeterminate. Slickensides, preserved in the massive red rhyolite, are evidence of the faulting.

(19) The agglomerate-tuff sequence and massive red rhyolite are faulted against andesite. The strike and dip are N. 12° W., 83° E. The displacement is indeterminate, but truncation and local brecciation are indicative of the faulting.

(20) The flow rhyolite is downfaulted against the agglomerate-tuff sequence and massive red rhyolite. The strike and dip are N. 70° W., 40° E. The dip-slip displacement is approximately 40 feet. The

truncation of beds is evidence of faulting (see Plate VI, Fig. 1).

(21) Massive red rhyolite is faulted against the agglomerate-tuff sequence. This is one of the larger faults in the area, having a dip-slip displacement in the northern part of the area of approximately 900 feet. It undoubtedly extends southward beyond the limits of the area through faults (22), (23), and parts of faults (25), (27), and (29). The strike and dip are N. 38° W. and 53° E. The juxtaposition of different beds in the sequence, along the trend of this zone, is evidence of the faulting.

(22) Faulting brings late-Tertiary (?) basalt into contact with the agglomerate-tuff sequence. The attitude is the same as fault (21), and it is considered the southern extension. The dip-slip displacement is approximately 800 feet, indicating a decrease southward.

(23) South of Nogal Canyon the fault zone described as faults (21) and (22) lies wholly within the altered rhyolite. The strike is the same as faults (21) and (22), but the dip has steepened to 80° E. The displacement decreases rapidly to the south. The dip-slip in section C-C' (see Plate I) is approximately 100 feet. The truncation of clastic beds and a weathered zone (associated with the upper part of the altered rhyolite flow breccia) marks the fault trace.

(24-25, 28) Andesite dikes apparently have been intruded into fault zones within the agglomerate-tuff sequence. It is probable that the walls of these fissures have been forced apart by the intrusion of these dikes. The walls are parallel and have an attitude of N. 10° E., 80° E., in fault (24); N. 42° W., 80° W., in fault (25); N. 12° W., 80° W., in fault (28). Displacements are indeterminate in faults (24) and (28). The dip-slip of fault (25) is estimated to be 25 feet.

(26) Late-Tertiary (?) basalt is faulted against the agglomerate-tuff sequence. Fault (26) represents an extension of the fault patterns initiated by faults (24) and (25). Extensions of the same andesite dikes also fill this fault zone. This fault strikes N. 30° E., and the dip is nearly vertical. Total displacement is unknown, but the basalt has been dropped into the same stratigraphic position as the agglomerate-tuff sequence. Renewal of movement along the fault after deposition of the basalt has placed the basalt in contact with the andesite.

(27) This fault bounds the late-Tertiary (?) basalt block on the south and brings it into contact with the agglomerate-tuff sequence. The attitude is N. 75° W., 87° N. The displacement is indeterminate. The minimum stratigraphic throw is 450 feet.

(29) Altered rhyolite flow breccia is downfaulted against the agglomerate-tuff sequence. The fault zone is filled by an andesite dike (apparently related to the faults previously described in this area) and may be an extension of the fault zone which includes faults (21), (22), and (23). The attitude is N. 12° W., 80° W. Some type of hinge movement is demonstrated here, since the displacement is reversed from that of faults (21), (22), and (23). A continuous

decrease in displacement southward has been noted in faults (21), (22), and (23). The displacement here cannot be measured. Another indication of the hinge movement is the change in direction of dip in the fault zone from east, in faults (21), (22), and (23), to west, in fault (29).

(30) This fault is the northerly extension of fault (18) and probably represents a renewal of movement along this fault line after deposition of the basalt. The attitude is N. 40° W., 75° E. Fault (30) is the northeastern boundary of the downfaulted basalt block and has a minimum stratigraphic throw of 450 feet. The contact relationships between the younger basalt and the older rocks surrounding it determine the fault pattern.

(31) This fault occurs within the altered rhyolite flow breccia and represents the northern and eastern boundaries of a downfaulted block. The strike and dip are variable, and the displacement cannot be measured. Well-preserved slickensides, as well as the displacement of layers in the altered rhyolite, indicate the fault trace.

(32) Silicification and brecciation mark the trace of this fault. It strikes N. 25° W. and dips 70° to the southwest, but gradually bends to the east in its southern extension (making up the western and southern boundaries of the fault block described in fault (31). The agglomerate tuff sequence is faulted against the altered rhyolite flow breccia. An andesite dike fills the fault zone along the southern two-thirds of its exposure and has created marked dilation of the walls. The displacement is indeterminate, but the stratigraphic throw cannot exceed 75 feet.

(33) Late-Tertiary (?) basalt is downfaulted against the agglomerate-tuff sequence. Fault (33) strikes east-west and dips approximately 80° N. The displacement is indeterminate. Evidence of the faulting is the juxtaposition of beds.

(34) Late-Tertiary (?) basalt is downfaulted against the basal flow breccia. The strike and dip are N. 55° W., 87° W. Exposures are poor, and evidence of faulting lies in the juxtaposition of the units. Displacement is not measurable but must be large.

(35) The agglomerate-tuff sequence is upfaulted against altered rhyolite flow breccia. The attitude of the fault is N. 20° W., 80° W. The dip-slip displacement is approximately 90 feet. Truncation of units is evidence of faulting.

SPECTROCHEMICAL INVESTIGATION

In order to determine the relative abundance of certain trace elements in the volcanic rocks, spectrochemical analyses were undertaken. The rock samples were crushed in a jaw-type rock crusher and ground in a pulverizer until the entire sample passed through a 150-mesh screen. 29 mg of sample were mixed with 1 mg lithium fluoride; carbon was added volumetrically to fill the electrode cavity. The electrodes were made from spectrographic carbon rods which had been soaked in aqua regia for a period of at least 10 days. Holes were drilled in the electrode, and it was necked, a standard tool being used, in order to obtain uniformity. The electrodes were arced in an Applied Research Laboratory Arc Spectrograph. The arc separation was 10 mm, and a current of 7 amp was used. The sample was arced for 80 sec (time for complete burning). The slit opening was 10 microns. The film was developed for 2 min. An attempt to read the film on a densitometer[1] was unsuccessful for the most part, because the arcing time was too long, therefore producing lines which were too dark; double lines were formed because of the extremely narrow slit width used. Also, arc wandering due to the wide electrode separation caused great variations in line intensities. Samples were run of all basic and acidic rocks described. A visual estimation of relative intensities proved inadequate.

The elements vanadium, titanium, gallium, barium, and chromium were found to be present in most samples. Miesch[2] reports the presence of barium, cobalt, chromium, copper, gallium, nickel, strontium, vanadium, yttrium, ytterbium, and zirconium in both acidic and basic rocks of the area. In the acidic rocks, the additional elements beryllium, lanthanum, molybdenum, and lead are reported;[2] in the basic rocks scandium is reported. Except for lanthanum in the acidic rocks, scandium in the basic rocks, and yttrium and

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1. The densitometer used was a Baird model at the Sandia Corporation laboratories, Albuquerque, New Mexico.

2. Miesch, A. T., op. cit.

3. Miesch, A. T., op. cit.

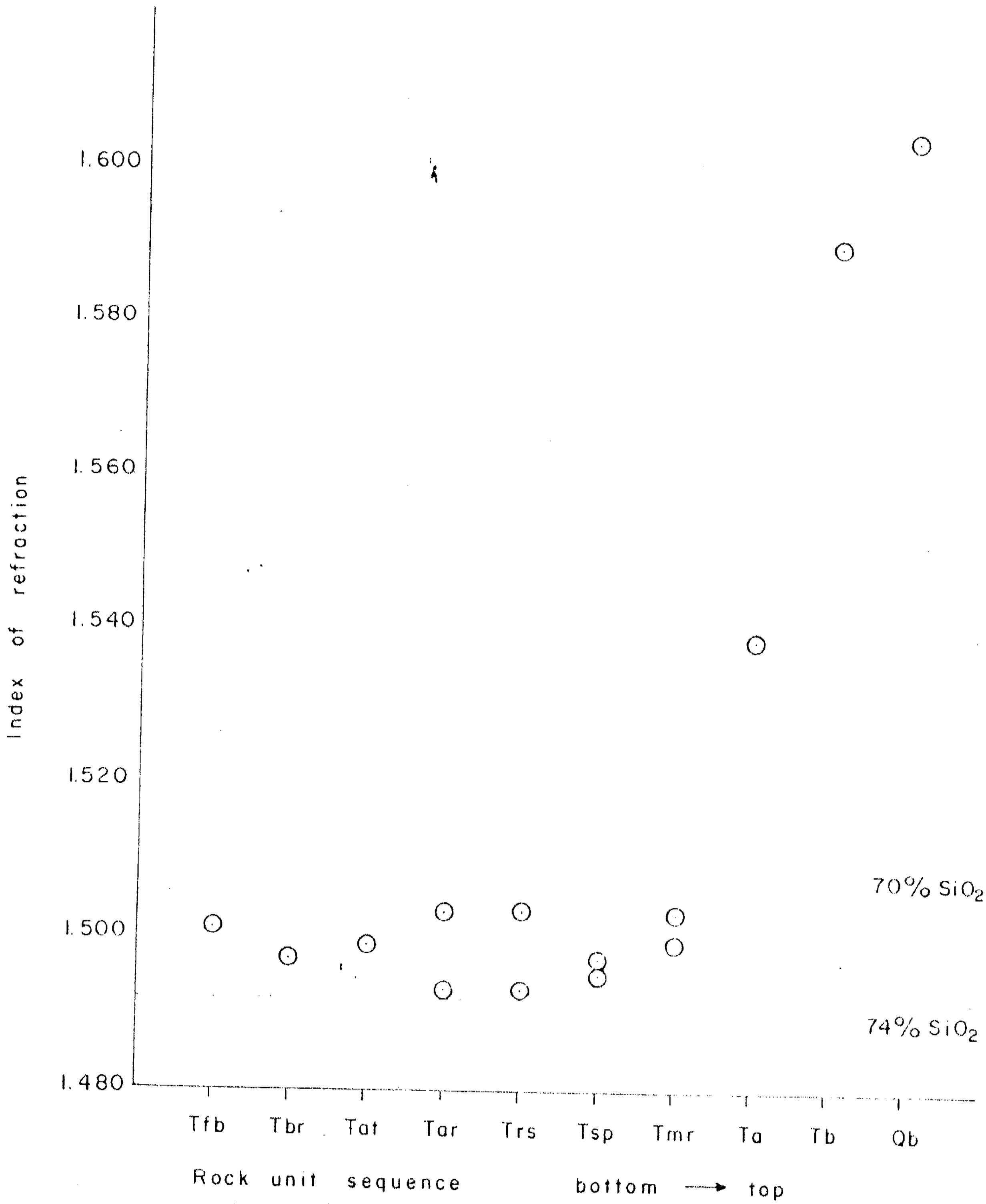
ytterbium in both, other rare-earth elements (including Ce, Nd, Dy, Er, Gd, and Sm) have not been detected in any of the samples by the spectrochemical investigation and likewise have not been reported by Miesch. Of the elements detected, cobalt, chromium, copper, nickel, and vanadium show an increase in abundance in the basic rocks, whereas strontium shows an increase in the acidic rocks. The elements barium, gallium, yttrium, ytterbium, and zirconium show the same relative abundance in both the basic and acidic rocks.

CONCLUSIONS

The results of the field and laboratory studies indicate that the rocks of Nogal Canyon consist of volcanic flows, dikes, sills, and pyroclastics and probably are derived from more than one magmatic source. Indications are that the acidic volcanics have had a different source than the basalts.

The rhyolites are similar mineralogically and chemically. Generally these rocks have the same accessory minerals and lack crystalline quartz (which may be accounted for in the highly silicious groundmass, as determined by the refractive-index measurements of the natural glass). Fusion results (see Plate IX) show a grouping of the rhyolites within the limits of 70 to 74 percent silica and indicate no important chemical changes in the sequence.

PLATE IX



FUSION RESULTS

VOLCANIC ROCKS OF NOGAL CANYON, SOCORRO COUNTY, NEW MEXICO

There is no evidence of any major alteration changing the fundamental chemical composition of the rocks. Locally, beds of the pyroclastic agglomerate-tuff sequence have been kaolinized, and potash has been removed, making the rock appear somewhat low in the percentage of that constituent (see Table II). Other rocks show approximately average rhyolite composition (see Tables I, III, and IV).

Spectrochemical investigation shows that the rhyolites of the area are somewhat unusual because of their lack of many of the rare earth elements (Ce, Nd, Dy, Er, Gd, and Sm). Yttrium and ytterbium are detected as having approximately the same abundance in the basic and igneous rocks in this area but generally show an increase in abundance in acidic igneous rocks.[1] As is expected, lanthanum shows an enrichment in the acidic rocks, and scandium an enrichment in the basic rocks. Calcium and zirconium both show approximately the same enrichment in basic and acidic rocks but generally show an increase in acidic rocks.[2] These trace-element concentrations indicate the chemical similarities of the rhyolites of Nogal Canyon and may be indicative of a single source of these rocks. The correlation of some of these rhyolitic units with those of Miesch[3] suggests that the source lies to the north of Nogal Canyon.

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1. Rankama, K., and Sahama, T. C., Geochemistry, p. 517, Univ. of Chicago Press (1950).

2. Rankama, K., and Sahama, T. G., op. cit.

3. Miesch, A. T., op. cit.

There is no evidence of any magmatic separation either in the chemical or mineralogical data. No gravitative separation of any of the elements is apparent. The basalts also appear to have a single source separate from that of the rhyolites. The relative abundance of basaltic outcrops in the southwestern part of the area suggests that their source lies to the west of Nogal Canyon. They are apparently extrusions of a basaltic magma as such.[1] The acidic magma, because of its chemical composition as expressed in the rhyolites, is derived possibly from the refusion of the base of the granitic layer of the earth.[2]

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1. Bowen, N. L., op. cit.

2. Bowen, N. L., op. cit.

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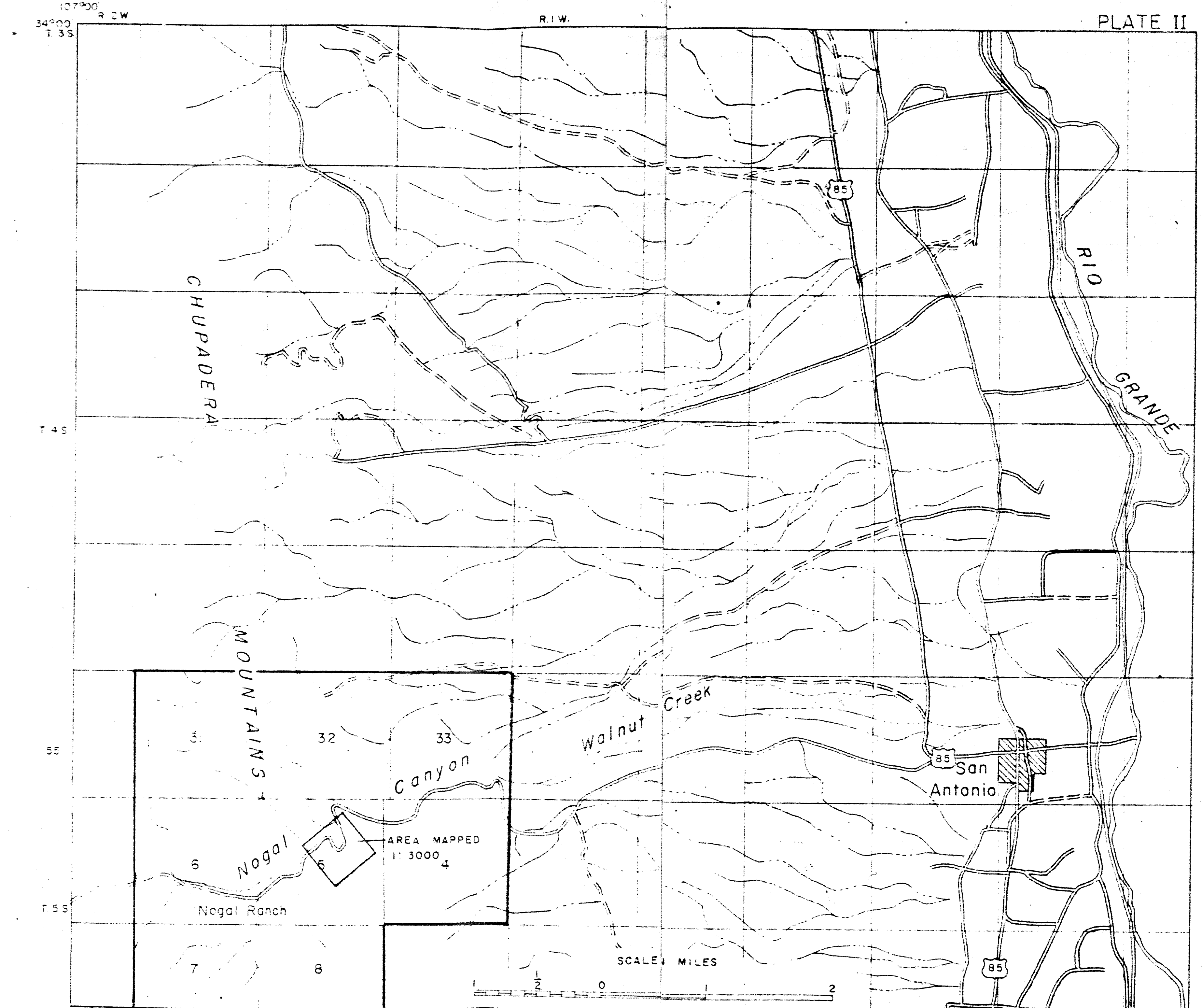

INDEX MAP OF NOGAL CANYON AREA, SOCORRO COUNTY, NEW MEXICO