GEOLOGY AND MINERALOGY OF ALTERED ZONES IN THE RED RIVER AREA NEW MEXICO

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Master of Science
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by
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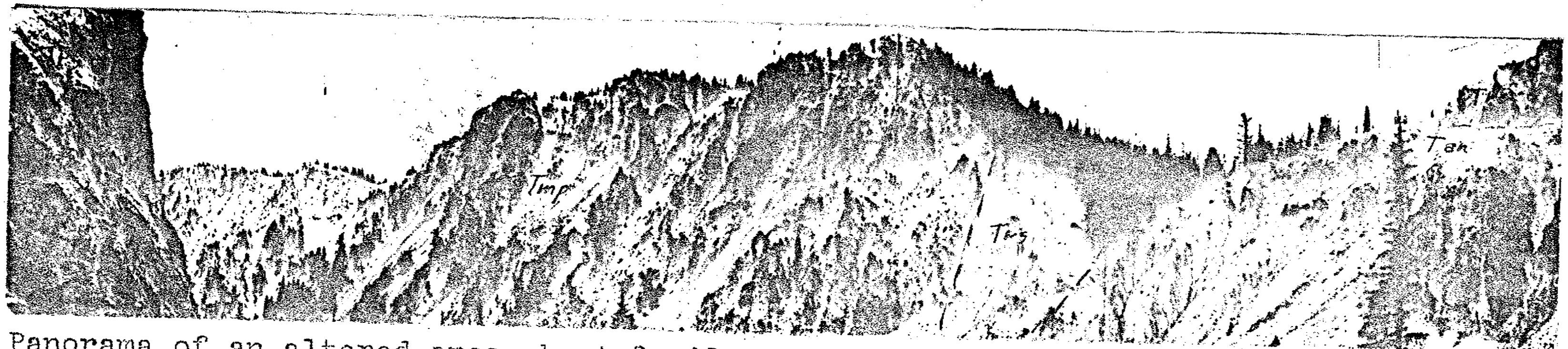
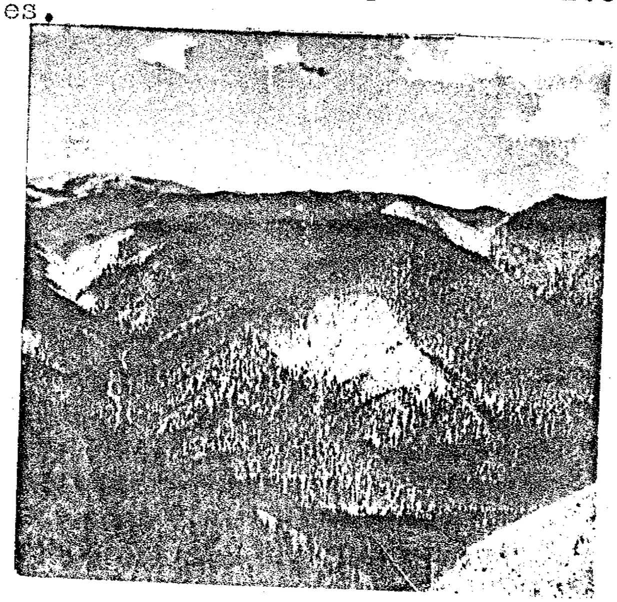


Panorama of an altered area about 3 miles N.W. of the town of Red River, Taos County, New Mexico, referred to as Area 2 in text. Tmp - Monzonite prophyry, Trs - Rhyolite series, Tan - Andesite series.



Taken from Area 3 looking north with Area 1 on the left and Area 2 on the right, with Red River below.

Frontispiece

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ABSTRACT

The altered areas of volcanic rocks discussed in this thesis are located 3 miles west of the town of Red River in the Taos Range of the Sangre de Cristo Mountains, Taos County, New Mexico.

The Taos Range is made up of Precambrian metamorphic rocks, which are overlain by Tertiary volcanics, and intruded by stocks, sills, and dikes. Tertiary igneous rocks and younger sediments are the only rock units exposed in the area investigated. They can be divided into three major rock types: (1) interlayered andesite and latite over 2000 feet in thickness; (2) rhyolite tuffs and flows over 500 feet in thickness that overlie the andesite and latite; and (3) intrusive monzonite and quartz monzonite porphyry, the youngest igneous rocks.

Faulting is an important structural feature throughout the Taos Range, whereas folding is not as conspicuous. Faulting has occurred intermittently since Precambrian time. Reactivated movement on old faults is reflected by offset of some of the youngest rock units.

Two major types of alteration are conspicuous in the Red River district: (1) deuteric alteration of the volcanic rocks throughout the district, during and immediately after volcanism; and (2) local, structurally-controlled

hydrothermal alteration, which was locally intense and later than the youngest volcanic and intrusive rocks.

Deuteric alteration had its greatest effect on the feldspar crystals and the groundmass in the extrusive rocks. It has been recognized in even the freshest appearing rocks.

A sericite-illite-quartz assemblage that is the end product of hydrothermal alteration succeeds chloritization and kaolinization. A kaolin-type clay mineral resembling dickite, associated with quartz and locally with iron oxide stains, is a major component of gouge in joints in siliceous volcanics; this association is thought to be exclusively cataclastic in origin.

Pyrite occurs in cubic, octahedral and pyritohedral habits, and composes about 3 to 4 percent of altered rocks. None of these habits has been positively associated with any particular mineral or environment, although there is a suggestion of a sphalerite-pyritohedral pyrite association. As much as 36 ppm molybdenum is contained in the pyrite.

Molybdenum is anomalously prevalent throughout the area studied, some rocks containing as much as 350 ppm. Gray quartz veins are the only recognized host of the visible hypogene molybdenum mineral, fine-grained, flaky molybdenite. The amount of molybdenum in the quartz veins is roughly indicated by the darkness or opacity of the quartz. The volcanic rocks are very poor hosts for disseminated molybdenite.

No primary copper minerals were identified, but copper contained in some of the pyrite may be the source of copper anomalies throughout the areas.

Surface waters draining areas of alteration were found to have a pH of about 2. Analyses of these waters revealed trace elements directly correlatable with minerals found in the respective drainage basins.

ACKNOWLEDGEMENTS

I should like to express appreciation to American Metal Climax, Inc. for generous technical and financial assistance provided during the period of this investigation, and to the New Mexico Geological Society for a grant to defray laboratory expenses. Many of the employees of the New Mexico Bureau of Mines and the faculty of the New Mexico Institute of Mining and Technology have provided patient assistance during the course of this investigation. The assistance and guidance of Dr. Robert Weber, Max Willard, and Dr. Carl Austin of the New Mexico Bureau of Mines, and John H. Schilling of the Nevada Bureau of Mines have been particularly appreciated. My wife Dorothy has been invaluable with her patient efforts in editing and typing this thesis.

INTRODUCTION

Purpose and Scope

Several large, bleached areas border Red River canyon and some of its tributaries east of the town of Questa (see frontispiece). These areas, variously referred to in the past as breccia zones, altered zones, and hydrothermal pipes, are generally barren of vegetation, conspicuously yellow to white in color, and are characterized by steep to precipitous, badland topography.

The purpose of this thesis is to describe the mineralogy, geology, and genesis of some of the features found in several of these bleached areas. Reconnaissance investigations were conducted throughout the district in order to make general comparisons on a broader scale. Local detailed study considered the relationship of mineralogy to alteration and physiographic features.

Red River district, particularly the altered breccia zones, has been of intermittent interest from an economic standpoint because of (1) the occurrence of the rich molybdenite deposit in the Questa molybdenum mine six miles west of the town of Red River; (2) the similarity between alteration in this district and alteration in the economically important San Juan district, Colorado; and (3) gold and silver prospects and mines that have been productive intermittently for the last century.

Methods of Investigation

A reconnaissance map of the altered area of primary interest was compiled from previous work by Schilling (personal communication) and McKinley (31), and field investigations conducted by the present writer during the latter part of 1960 through 1961. A district-wide trace element investigation of copper and molybdenum was conducted by random sampling for geochemical analysis.[1] A more detailed study included the use of emission spectrograph on quartz veins and the dissolved solids in drainage waters from some of the zones of alteration.

Studies of trace elements in pyrite included work with the emission spectrograph, X-ray fluorescence, and chemical methods.

The areas which were investigated are characterized by extreme relief, and by the prevalence of a mantle of talus and large slump blocks along the canyon walls (see frontispiece). Much of the prominent outcrop material on the canyon walls consists of either large slump blocks or older stream gravels cemented by iron oxides and silica.

Samples of unweathered rocks in place are quite limited, unfortunately, due to the nature of leaching and erosion characteristic of the area. Most of the samples were taken in the higher stream courses where active erosion has exposed relatively fresh rock, though many outcrops were

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1. Courtesy of American Metal Climax, Inc.

sampled in places other than at water courses. The frequent summer rains form strongly corrosive waters by leaching of oxidized pyrite, and thus, weathering and leaching products are unavoidably present in some of the samples. Minerals were identified by petrographic methods, X-ray diffraction, and differential thermal analysis. Paragenesis was determined from textural, structural, field, and compositional relationships. The results of these investigations are brought together in an over-all paragenetic picture (see Fig. 21).

Previous Work

The geologic setting and rock types of the Questa and Eagle Nest quadrangles are described by McKinlay (30), Schilling (37, 38), Larsen and Ross (26), Vanderwilt (49), and Carpenter (10, 11), whose investigations were primarily concerned with the Questa molybdenum mine at Sulphur Gulch. Maps and discussions heretofore published have described the altered zones of these quadrangles as altered rock and altered breccia without differentiating original rock types or stratigraphic position.

Location and Accessibility

The areas of alteration which were studied are located in the east-central part of Taos County, northern New Mexico (see Plates 1, 2). The areas can be reached from oiled road by following New Mexico State Highway 3 from Taos north 26 miles to Questa. At Questa turn east on New Mexico State Highway 38 for 10 miles. From this point two of the large altered areas (Areas #1 and #2, Plate 2) can be seen to the north (frontispiece) at the heads of two separate canyons; to the south another long, narrow canyon is headed by bare altered slopes (Area #3, Plate 2). These three areas contain the principal outcrops from which most of the information contained in this report was obtained.

The oiled road that connects the towns of Red River and Questa is on alluvial gravels. It is necessary to travel by foot or horseback for about a mile to inspect any outcrops of altered rocks in place.

PHYSIOGRAPHY AND CLIMATE

The Sangre de Cristo Mountains, in which the study area is located, are part of the southern Rocky Mountains physiographic province. The maximum relief in the Taos Range is 6000 feet, and that in the immediate area of the project is approximately 4000 feet. The terrain is composed of steep slopes and narrow V-shaped canyons with flat or rolling hilltops formed by resistant volcanic or sedimentary beds. Sheer cliffs supported by intrusive dikes, stocks, or resulting from rapid erosion along fault lines are especially characteristic of the areas of intense alteration. There are benches on some of the steepest slopes that result from landslide or toreva-block slumping.

The average precipitation is about 20 inches per year, in the form of moderate snows in the winter and frequent summer showers. Because of the lack of vegetation in the altered areas, and the poor induration of the rock, great quantities of material are carried down the canyons during even moderate showers. Flood conditions that are common after a summer shower have caused dangerous flash floods in the water courses. Frequently these floods deposit enough silt and rock to block the highway with as much as a foot of debris. The average daily maximum and minimum temperatures range from a high of 85° in July to a low of 10° in January.

VEGETATION

The vegetation on south-facing and north-facing slopes is markedly different. On south-facing slopes, the cover is scrub oak, juniper, pinon, and mountain mahogany at lower elevations, and spruce with scattered patches of aspen in the higher elevations. On the north-facing exposures, spruce, pine, fir, and aspen cover the lower as well as the higher slopes.

Altered zones are generally accompanied by acid soil conditions resulting from the oxidation of pyrite. The acid soil is conducive to the growth of pine. Where slopes are barren, rapid erosion and lack of soil have not allowed vegetation to stabilize the slopes.

GEOLOGY

The Taos Range of the Sangre de Cristo Mountains is made up of Precambrian amphibolite, schist, gneiss, metaquartzite, and intrusive igneous rocks, overlain by late Tertiary volcanics of andesitic, quartz latitic, and rhyolitic composition. These layers include flows, breccias, and tuffs interbedded with sediments. Permian and Pennsylvanian arkosic sandstones, conglomerate, shale, and limestone occur along the eastern edge of the range. The earlier rocks were intruded by late Tertiary granite, latite, and rhyolite stocks, dikes, and sills.

Almost all of the above rock types are represented in various altered areas, although those altered areas that are included in the main part of this study are restricted to the Tertiary volcanics and younger intrusives and sediments.

Stratigraphy

Precambrian Rocks

Amphibolite Complex

The lower-most Precambrian unit recognized is an amphibolite complex which is estimated to be several thousand feet thick, as the base of the unit is not exposed. This unit includes many varieties of amphibolite and quartz-biotite schist. Primary structure may be reflected in a few outcrops that contain alternating layers of quartz-biotite schist and amphibolite. The rocks grouped in the amphibolite complex range from black to dark green with specks or bands of white, and are massive to foliated. They can be separated into four general textural and structural types: massive coarse-grained, massive medium-grained, gneissoid, and coarse-grained schistose.

The massive coarse-grained amphibolites contain large, black hornblende metacrysts in a phaneritic groundmass of hornblende and andesine(?). The massive medium-grained amphibolites are equigranular aggregates of black hornblende and white plagioclase closely resembling a diorite in appearance. The amphibolite gneisses are similar to the massive medium-grained amphibolite except for the parallel orientation of the plagioclase and hornblende and coarse foliation of trains of black hornblende and white plagioclase. The amphibolite schist is a finer-grained variety of amphibolite gneiss and resembles the gneiss in thin-section. The amphibolite complex is probably the oldest rock unit exposed in the area, although its relationship to the overlying Cabresto metaquartzite is not clear.

Cabresto Metaquartzite

The Cabresto metaquartzite, named from exposures in Cabresto Creek (McKinlay, 31), is a coarsely crystalline gray to reddish-brown rock ranging from 200 to over 1000 feet thick. Streaks and thin bands of muscovite, magnetite, and biotite are characteristic. These bands divide the quartzite into units ranging from 1 to 10 feet in thickness. Local layers of graphite-mica gneiss and sillimanite-biotite gneiss are associated with massive quartzite, generally overlying the quartzite. The sillimanite and graphite gneisses included within the Cabresto metaquartzite sequence range from 10 to 200 feet in thickness.

Metaquartzite commonly forms small but prominent cliffs with smooth, vertical faces that appear gray to reddish-gray at a distance. The metaquartzite apparently overlies the Precambrian amphibolite complex, and is in turn overlain unconformably by the Pennsylvanian-Permian(?) sediments; it is tentatively dated as Precambrian because of its metamorphic character and similarity to other Precambrian quartzites of the Rocky Mountains.

Undifferentiated Metamorphic Rocks

A sequence of rocks designated by McKinlay (31) as undifferentiated metamorphic rocks consists predominantly of hornblende gneiss and schist, biotite schist, quartzite, amphibolite, migmatite, and mica schist.

The undifferentiated metamorphic rocks are for the most part a thick series of metamorphosed basaltic and rhyolitic flows and breccias interbedded with siltstone and sandstone. Basic sills, and bodies of diabase, gabbro, and peridotite that were intrusive into the volcanic and sedimentary rocks, have been locally metamorphosed along with the intruded rocks.

These rocks lie above the Cabresto quartzite, hence most of the rocks in the unit are believed to be younger than the quartzite, although the quartzite might be a unit within the metavolcanics. The undifferentiated metamorphic rocks are Precambrian also, since they are intruded by Precambrian granite.

<u>Hornblende Schist and Gneiss</u>. Hornblende schist forms high mountain ridges and peaks. The schist usually appears fresh. It has pronounced foliation, although lineation of hornblende crystals is rare. Hornblende, quartz, plagioclase, and biotite in decreasing amounts are the main constituent minerals.

Hornblende gneiss, as much as 500 feet thick, consists of coarse augen gneiss made up of hornblende, plagioclase, and quartz.

<u>Biotite-Muscovite Schist</u>. Thin layers of biotite-muscovite schist are intertongued with hornblende schist and gneiss. The micaceous schist is usually fine-grained and shows a well-developed foliation. Biotite up to 2 mm in diameter comprises approximately 25 percent of the rock. Quartz and feldspar are intergrown with, and enclosed in, biotite and muscovite flakes.

<u>Quartzite</u>. Fine-grained quartzite crops out on a few high ridges in layers ranging from a few inches to 20 feet in

thickness. This quartzite contains up to 45 percent hematite in places (McKinlay, 31).

Garnet-Tourmaline Schist and Garnet Schist. Thin bands of almandite-tourmaline schist and garnet schist are interlayered with some of the hornblende-biotite schists.

Amphibolite. Thick layers and bodies of amphibolite are commonly exposed within the undifferentiated metamorphic terranes in the Taos mountains. The hornblende schists and the amphibolites differ only slightly in mineral content, the difference being the low quartz content and the lack of well-developed lineation in the schists. The amphibolite is for the most part a dark green, fine-grained rock composed of intergrown hornblende and feldspar crystals.

Migmatite. The mixed rocks are best developed near outcrops of Precambrian microcline granite and granite gneiss. Migmatites in the western front of the Taos mountains, where they are well-developed, are made up of thin layers and lenses of gray orthoclase granite and hornblende schist. The relative amount of granite varies from place to place.

Muscovite Schist. The muscovite schist ranges from gray to green or pinkish in color, is usually fine-grained, and shows well-developed foliation with a matrix of fine mosaic quartz and feldspar.

Granite

Granite is exposed along the lower part of Red River where it forms pinnacles, knobs, and low cliffs separated by talus slopes and soil.

The granite varies in texture from a fine-grained aplitic to pegmatitic material, but the most characteristic phase is medium-grained, equigranular to slightly-foliated granite. In the vicinity of the Questa mine it has been divided into three varieties by Schilling (37): granite gneiss, gneissic granite, and massive granite. The difference is primarily the amount of biotite and the degree of alignment of constituent minerals. All three types are intergradational.

The granite is cream to pinkish in color and generally composed of pinkish microcline, glassy quartz, white albite, greenish-brown biotite, and muscovite, with accessory apatite, sphene, and magnetite. The relative proportions of these vary greatly from place to place.

The granite intruded the Cabresto metaquartzite and the undifferentiated metamorphic rocks. The granite is overlain by Pennsylvanian-Permian sediments, early Tertiary sedimentary and volcanic rock, Tertiary volcanics, and Tertiary gravels.

Pegmatite

A few scattered areas containing pegmatite dikes occur near the borders of the microcline granite. Most of the dikes are small and, in general, composed of orthoclase, quartz, and minor amounts of muscovite. The pegmatites trend north-south and range from a foot to 15 feet in width. The granites and Cabresto quartzite are cut by the pegmatites, but the Paleozoic and younger rocks are not.

Rio Hondo Granite

The Rio Hondo granite is a mottled pink to cream rock with pink orthoclase phenocrysts up to one inch in diameter, scattered phenocrysts of quartz and white albite as much as ½ inch across each, with scattered biotite flakes and shreds. The rock is approximately 35 percent orthoclase, 35 percent quartz, 25 percent albite, 4 percent biotite, and 1 percent combined magnetite, sphene, and apatite. The rock texture indicates considerable cataclastic deformation, with quartz granulated, fractured and crystallized, and the biotite broken and shredded.

The age of the Rio Hondo granite is obscure. It is definitely known to cut Precambrian rocks, but its relationship to the Tertiary volcanics is not known. The granite has the same composition as the soda or Questa granite dated late Tertiary by Schilling(37) but, although closely associated in many exposures, it does not appear to cut any of the volcanic rock. The Rio Hondo granite is cut by dikes of rhyolite porphyry that are believed to be Tertiary in age. The granulation and waxy quartz crystals are believed to indicate that the Rio Hondo granite is older than Tertiary in age (McKinlay, 31).

Paleozoic Rocks

Pennsylvanian-Permian(?) Sedimentary Rocks

The Pennsylvanian-Permian(?) rocks are well-silicified, interbedded conglomerates, grits and shales. Just south of Cabresto Creek the unit is made up of a basal conglomerate, succeeded upward by reddish arkosic sandstone, gray shale, thin beds of conglomerate and shale, and a coarse conglomerate. A section of the Pennsylvanian-Permian(?) sedimentary rocks on Cabresto Creek is as follows:

Conglomerate, coarse (pebbles mainly quartzite, some schist and gneiss) . . .	35 feet
Conglomerate and shale (layers 1 to 3 feet thick)	25 feet
Shale, siliceous, gray	200 feet
Sandstone, fine-grained, arkosic, reddish	60 feet
Basal conglomerate (quartzite boulders up to 3 feet in diameter)	50 feet
Total exposed thickness	370 feet

These sedimentary rocks locally overlie Cabresto metaquartzite and hornblende schists. Small bodies of albite granite of probable Tertiary age cut the conglomerate. No fossils have been found in this unit. It is, however, tentatively assigned to the Pennsylvanian-Permian Sangre de Cristo formation on the basis of lithology and structural relationships with other rock units.

Tertiary Rocks

Early Tertiary(?) Sedimentary Rocks

Gray to dark red thin-bedded sandstone, shale, and limestone, with numerous lenses and beds of conglomerate, crop out in the vicinity of Red River. These rocks occur in scattered small outcrops that are difficult to correlate. Thin, red shale and gray limestone beds are the principal rocks in most exposures. This sequence has been measured by McKinlay (30) to be approximately 160 feet thick.

A tentative age of late Cretaceous or early Tertiary is given to this unit because the outcrops are closely associated with overlying green and purple andesite tuffs and flows.

Foster Park Andesite

The Foster Park andesite, named after typical exposures at Foster Park 2 miles south of the town of Red River, is composed of a thick sequence of andesite flows, tuffs and coarse breccias, as well as intrusive rocks. This sequence is designated as andesitic, but it has been suggested by McKinlay (30) and Schilling (38) that the andesite flows have been mixed and interbedded in varying amounts with a latite sequence originating north of the district. The Foster Park volcanics represent a thick sequence best described as an extrusive complex. The composition and texture of this material in any one exposure varies greatly, and the over-all appearance and composition of the section differs markedly from one location to another. It has been estimated that the Foster Park volcanics have a maximum thickness of about 2000 feet. A coarse green to reddish tuff near the base, consisting mainly of andesite and latite fragments, is overlain by dark purple felsite flows. A thick purple breccia that overlies the tuff and felsite is the most persistent unit within the formation. The breccia, containing boulders of andesite more than three feet in diameter, is overlain by gray and purple flows and tuffs. Hornblende andesite is the main flow material in the upper part of the Foster Park sequence.

Foster Park andesite lies above, and in places may grade laterally into, the early Tertiary(?) conglomerate, shale, and limestone. The andesites and breccias were intruded by dikes and sills of latite porphyry, and locally the two rock types are not distinguishable.

The Foster Park andesite sequence is one of the predominant outcrop rocks in the area studied. The association with early Tertiary(?) sediments and overlying rhyolites is the basis upon which this unit is tentatively dated early Tertiary.

Latir Latite

The Latir latite occurs as flows, sills, and dikes. It is porphyritic with an aphanitic to glassy groundmass containing phenocrysts of plagioclase, quartz, biotite and hornblende. The texture and composition of the rock ranges from latitic to andesitic. The color in most outcrops is light gray.

The age relationships between the andesitic and latitic phases are not clear. As a rule, andesite underlies latite. However, latite layers occur in the upper part of the andesite, and andesite layers occur in the latite. Rhyolite volcanics overlie the Latir latite, and rhyolite dikes cut the latite, suggesting a tentative early Tertiary age.

Rhyolite Tuffs and Felsite

Gray to brown aphanitic and porphyritic rhyolite tuffs and felsites are exposed along the high ridges north of the Red River, and constitute one of the most important exposed rock types in the altered areas studied. Rhyolite tuff is the basal unit and lies below thin felsite flows. It forms prominent cliffs and extremely steep topographic features. The rhyolite tuff exceeds 500 feet in thickness.

Thick welded tuff forms a sheer cliff 450-500 feet high (see frontispiece). Cliff rock breaks in large blocks that have crept down over the slope-forming underlying rocks to give the false appearance of outcrops (Fig. 1). Fracturing from deformation of the rhyolite causes it to break in parallel slip joints from one to two inches apart (Figs. 2 and 3). Slip jointing is not controlled by internal structures, and is accompanied by open transverse joints at positions of deflection in the jointing.

Dark ferruginous aphanitic streaks that are characteristic of this rock accentuate its tuffaceous nature. The rock is composed of 3-5 percent clay pseudomorphs after plagioclase.

The felsite flows, light gray aphanitic rock with small phenocrysts of quartz and feldspar, strongly resemble intrusive aphanitic rhyolite. In the absence of diagnostic field relationships, the two may be indistinguishable from each other. The felsite flows are 100 feet or more thick.

The rhyolite tuffs and flows overlie the Foster Park andesite. The rhyolites are similar to the tuffs and flows in the Costilla and Latir Peak quadrangles where rhyolites are younger than andesite. On the basis of the above the rhyolitic volcanics are assigned a tentative age of Miocene (McKinlay, 30).

FIGURE 1

Slumped Welded Tuff

The cliff of rhyolite welded tuff, slumped over Foster Park andesite, is approximately 500 feet high. The inked line indicates the contact between the rhyolite and the andesite. Large open joints are seen on top of the cliff.

The cliff is located on the east wall of Area #2.

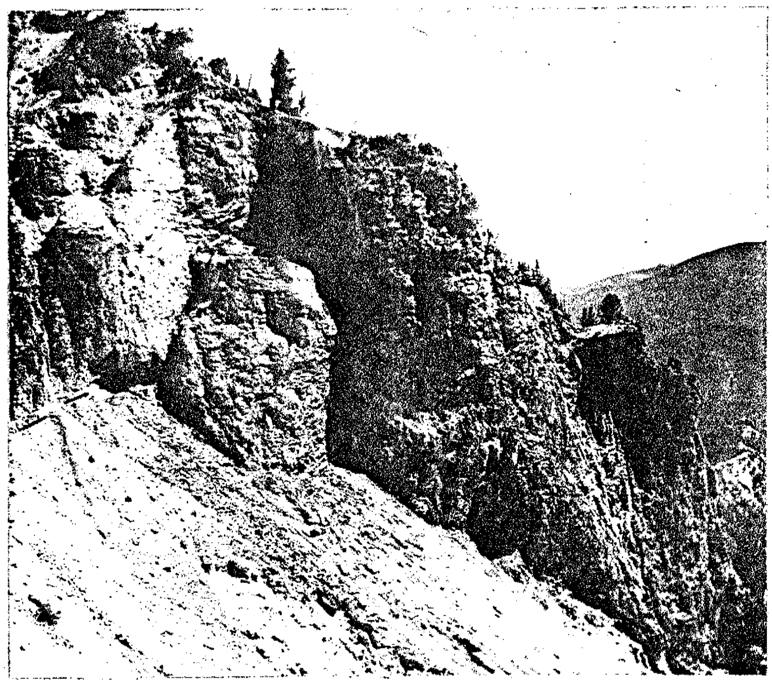


FIGURE 2

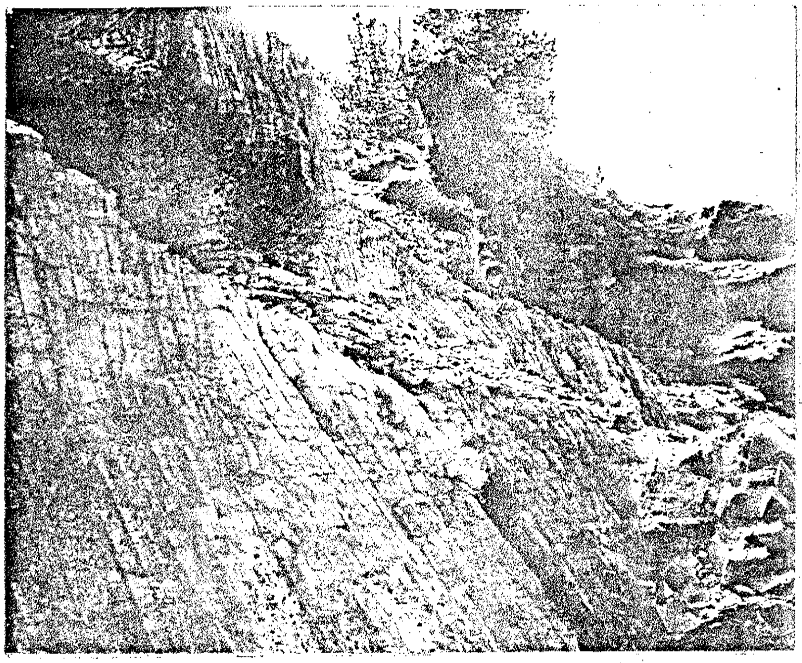
Jointed and Deformed Welded Tuff

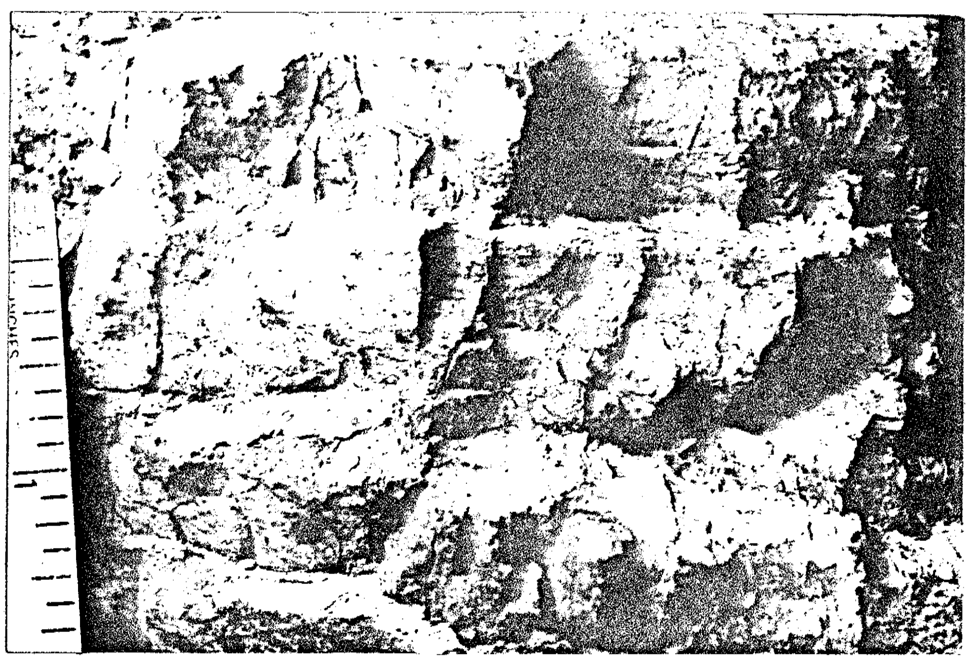
Rhyolite tuff with parallel slip joints from one to two inches apart. The jointing is unrelated to internal structure and bedding. Outcrop is near the head of Area #2 on the east wall of the canyon.

FIGURE 3

Rhyolite Tuff Jointing and Gouge
(Scale divisions equal 1/8 in.)

A close-up of the outcrop shown in Figure 2. The white gouge marking the slip joints is a dickite(?)-quartz assemblage formed by deformation. The transverse fractures are characteristic of the rock, but are much more prevalent where flexures in the major jointing pattern occur. (The flexures, probably the result of tectonic deformation, are permitted by the opening of these transverse fractures.)




INCHES

Questa Granite

The Questa granite is a fresh-appearing pinkish porphyritic granite with scattered, rounded quartz phenocrysts. The granite ranges in texture from aplitic to pegmatitic, but the main part of the rock has a porphyritic to inequigranular granitic texture and an approximate mode of 30-40 percent albite, 25-35 percent orthoclase, 25-35 percent quartz and 0-10 percent biotite, with minor magnetite, apatite, sphene and zircon.

Topographically the soda granite yields striking cliff outcrops interrupted at intervals by ledges, and cut by vertical crevasses.

The soda granite intruded the Precambrian rocks, and all but the uppermost part of the Miocene(?) volcanic complex. It was in turn intruded by later dikes that have not been dated. Eruption of the volcanic complex, hydrothermal alteration, and intrusion of the soda granite are thought to be relatively close in time (Schilling, 37). On the basis of dates assigned to the volcanics, the granite is tentatively dated late Tertiary (Schilling, 37).

Rhyolite Porphyry

Dikes ranging from 10 to 400 feet, but usually 30-50 feet in width, trend north 30 to 50 degrees west. The rocks are light pink porphyries with fine-grained holocrystalline groundmass. Rhyolite domes, plugs, and stocks are composed of aphanitic gray to white rock, locally containing phenocrysts of quartz and feldspar no larger than 1 mm in size.

The rhyolite intrusives are of questionable age, although they cut the Foster Park andesite. These rocks are similar to the felsite flows of the Tertiary rhyolite and tuff sequence, and may be eroded feeders of the extrusives (McKinlay, 31).

Monzonite and Quartz Monzonite Porphyry

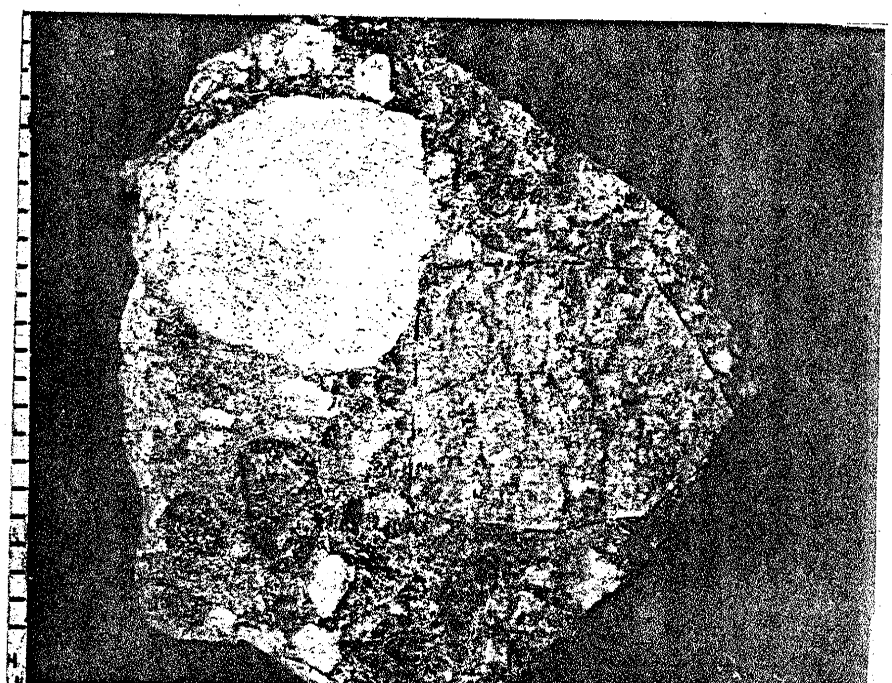
The monzonite and quartz monzonite porphyry ranges from light greenish-gray to dark green in color. Texture and mineral composition vary radically throughout the district. The principal minerals in the monzonite are sanidine, andesine, quartz, biotite, and hornblende. Sanidine forms white to pinkish phenocrysts that are in places 2 inches in length. White andesine phenocrysts up to 1/2 inch in size are common. Rounded quartz phenocrysts range up to 3/4 inch in diameter. Crystals in the groundmass, generally not over 1/8 inch in size, consist of quartz, feldspar, scattered biotite, and hornblende. Alteration and leaching of the country rock is most severe where it is cut by monzonite dikes (Fig. 4).

The monzonite dikes are thought to be the youngest dike rocks in the area, cutting most of the volcanic tuffs and flows, as well as the latite. A dark green monzonite dike that cuts the Questa granite suggests a Tertiary age for the dike (Schilling, 37).

FIGURE 4

Altered Monzonite Porphyry
(Scale divisions equal 1/8 in.)

Quartz monzonite porphyry with the end of a quartz-sericite pseudomorph after sanidine sticking out of the rock (large white crystal). Another relict sanidine crystal is faintly recognizable in the right side of the photograph. The dark, rounded grains are poikilitic quartz phenocrysts with clay inclusions. Sample came from the western crest at the head of Area #1, from the large peak in the center of the frontispiece.



Quaternary Rocks

Terrace Gravels

Several prominent terraces are present along Red River canyon. The well-rounded gravels covering all these terraces or benches, which are more than 30 feet above the river, have been grouped together by Schilling (37, 38) as terrace gravels. These gravels are distinguished easily from the angular soil and talus material of more recent age. Commonly the gravels contain rock types foreign to the bedrock of the benches or slopes above, making the separation even more positive.

McKinlay (30) reports that similar gravels form tops of many of the flat ridges 500-1500 feet above the canyon floor at the town of Red River (Fig. 5).

These gravels very likely range from late Tertiary to Pleistocene, or even Recent, in age.

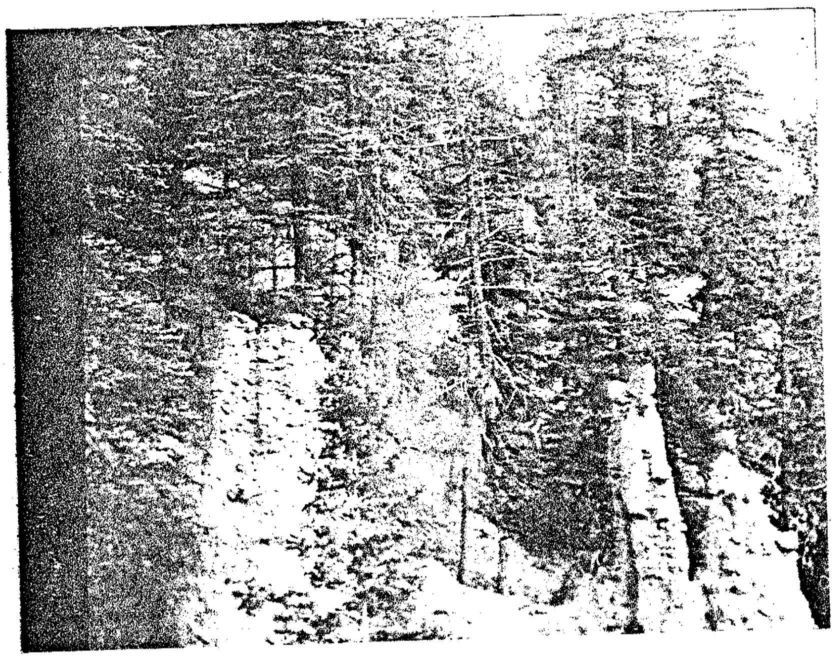
Cemented Gravels

Along the sides of Red River canyon and many of the side canyons are cemented gravels that form small ledges at levels less than 50 feet above the present water courses. These gravels are characteristically cemented with yellow to brown limonite, which comprises up to 20 percent of the rocks.

FIGURE 5

Residual Gravel Pinnacles

Bedded gravels high on the slopes east of Area #1. These gravels are several hundred feet above the present river course. The rocks are moderately rounded and the material is poorly indurated.



Alluvium and Mudflows

Reworked material in the valley bottoms and freshly-deposited gravels and muds from flood run off comprise the most recent unconsolidated material. This material is present where streams are reworking earlier gravels, or in alluvial fans at the mouths of side canyons.

Structure

Regional Structure

The Taos Range of the Sangre de Cristo Mountains has a very complex structure. The Precambrian rocks were deformed, metamorphosed, and intruded by granite, with subsequent deformation. Erosion was followed by late Paleozoic or early Mesozoic sedimentation, after which faulting recurred. The terminal stages of the tectonic history of the area are characterized by block faulting which has continued to Recent time.

Most of the structures of Precambrian age are obscured by later disturbances. The Pennsylvanian-Permian(?) rocks are too limited in exposure to determine their general structural characteristics. The Tertiary volcanics show no obvious folding, but their distribution does clearly reflect subsequent movement of fault blocks.

Three groups of faults are common in the Taos Range. One constitutes a prominent set of thrust faults, particularly well-developed along the east edge of the Taos Range, trending north and dipping gently to the west. These faults are dated late Cretaceous to early Tertiary by McKinlay (30). Another, north-trending, set of high angle faults delineates the western front of the Taos Range. The abrupt western mountain front at the mouth of Red River and easterly dipping beds reflect this faulting. The third group is an east-northeast trending set of high-angle faults traceable throughout the range. This set of faults largely displaces only Precambrian rocks. In a few places, however, the Tertiary volcanics also were found displaced by this set. Displacements along the east-northeast faults are small, and many parallel fractures occur along which no displacement could be recognized. In this system are included many of the faults and fractures that make up the downfaulted zone along Red River. Although the above are the three dominant recognizable sets of faults, there are other obvious but less extensive systems (Schilling, 37).

The most important feature in the area of immediate interest is faulting of the Miocene(?) volcanic complex and older rocks. This faulting was reactivated contemporaneous with or shortly preceding volcanism, and formed a graben-like area where no one fault can be traced for any great distance. This graben is well marked on aerial photographs.

Much of the younger faulting is thought to be a product of continued or renewed movement along older fault lines. Displacements range from practically zero up to an estimated

6000 feet. In places where brecciation has been intense a "piping system" was provided for altering solutions.

Local Structure

Features on aerial photographs, and correlation of rock types across Red River canyon, justify the conclusion that a major fault trending about EW resulted in a relative displacement of the southern side of the canyon upward several thousand feet. The Foster Park andesite complex crops out on the highest ridges between Pioneer Creek and the Red River whereas over five hundred feet of rhyolite overlie the andesite complex on the north side of the canyon.

In the water courses of the three canyons studied (see Plate 2), faulting is indicated by the abundance of gouge zones and slickensided surfaces. In the two canyons to the north (Areas #1 and #2) the water courses also follow a change in rock type as indicated on the geologic map (Plate 3.

North of Red River on the western slopes of Area #1 (see Plate 2) a block appears to have been uplifted in a fairly short period of time and/ or a rapid lowering of the base level, is suggested by pinnacles of poorly-cemented, rounded alluvial gravels that rise above the steep slopes of the canyon several hundred feet above the present water course (Fig. 5). Outcrops of iron- and silica-cemented gravel and breccia are present on the walls of the canyon. These reddish maroon well-indurated rocks are interpreted as older stream gravels that have been cemented by minerals deposited from iron- and silica-rich waters that leached pyritic alteration areas above. The cemented gravels were later attacked by erosion, and in places form resistant ledges along the stream banks.

Small fault blocks and landslips are encouraged by the extreme relief and the abundance of subsurface moisture. Shelves on the steep slopes commonly support large, leaning trees with distorted form induced by compensation for soil creep, and which are now tilted upslope as a result (Fig. 6). This phenomenon is conspicuous adjacent to the altered areas, and on other steep slopes in the district where there is either fault control or a plastic underlayer that encourages slumping. An example of a plastic layer that did not support the overlying rock is well illustrated by Fig. 1. This shows a 200-300 foot high welded tuff block slumped over the altere Foster Park sequence. Large, open joints on the top of the cliff outline other large blocks which have begun to creep down the slope.

Geomorphology

The structure is the dominant controlling feature in the development of the topography, particularly faults, breccia zones, and intrusive masses. Ridge-forming features are fault contacts, dikes, and zones of silicification. One large ridge of rhyolite tuff crops out in dike-like form in the canyon bottom of Area #1 (see Plate 2) near the head of the canyon. Welded tuff, surrounded by less resistant tuffs has apparently been silicified, making it more resistant to weathering and erosion processes.

Where the slopes are extremely steep and barren, radial or trellis drainage patterns have developed.

Summer floods sweep from the floors of these canyons a great amount of material, and promote a crude sorting of the debris over the alluvial fans, with largely only clays, silts, and fine sands reaching the Red River.

Intrusive dikes, plugs, and stocks are prevalent in and around the alteration zones, and there is a possible direct connection between intrusive activity and some of the brecciation. In places along the intrusive contacts the country rock has been altered to such an extent that thin slices of the altered rock bordering the contacts have been removed rapidly by erosion.

A generalized sequence up a stream channel from Red River is as follows: alluvial deposits containing boulders ranging up to five feet in diameter. Upon entering the canyon, talus slopes and rockslides are common; blocks up to 30 feet across have slumped into the water course (Fig. 7). Farther up, the water course is commonly cutting through cemented conglomerate from earlier alluvial deposits or material dammed behind a slide or slump block. Still higher, the stream is cutting into bedrock where, although the water

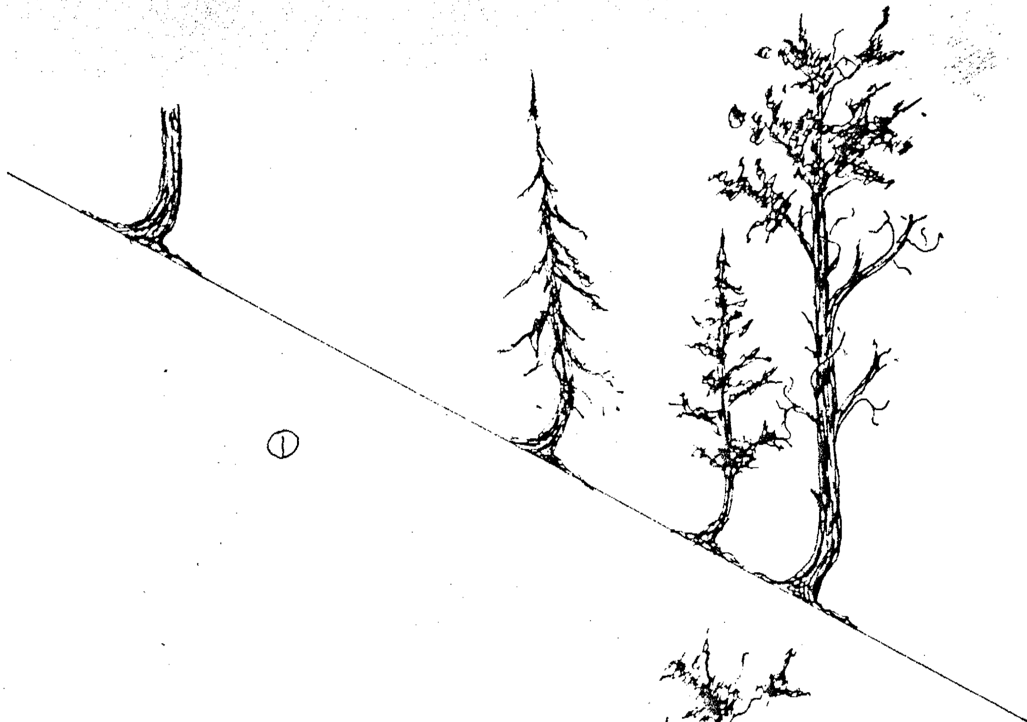
FIGURE 6

Evidence of Faulting and Slumping

The illustration represents observed physiographic and vegetative features that are interpreted as an expression of faulting and slumping.

(1) Pre-faulted surface. Tree trunks have compensated for soil creep.

(2) Configuration of trees after faulting and slumping.



①

②

is strongly acid and bleaching has penetrated up to ½ inch in the rock, fresh pyrite persists at or near the surface. Steep slopes of highly-altered brecciated material that erodes and decomposes rapidly are characteristic of the canyon heads.

IGNEOUS PETROGRAPHY

For the purpose of the petrographic study, thinsections were made representing most of the large outcrops of each rock unit. Studies with the petrographic microscope were made on thinsections and separate grains. The binocular microscope, X-ray diffraction unit, and polished section studies were also utilized for this investigation.

Foster Park Andesite

The Latir latite is included in the discussion of the Foster Park andesite inasmuch as the Foster Park andesite, the oldest unit exposed in the alteration areas studied, appears to grade from porphyritic quartz latite to nearly aphanitic andesite. This sequence is made up of a series of many small flows, none of which are distinctive and continuous enough to serve as a stratigraphic index.

Stony rhyolite, a coarser rhyolite porphyry, and a monzonite porphyry are present in the Foster Park sequence. In the writer's opinion most of these rocks are intrusive in nature and do not belong to the Foster Park andesite or Latir latite rock units, although it is possible that some rhyolites were extruded along with the multimodal intermediate andesite sequence.

The Foster Park and Latir rocks are dense and massive, and have a greenish gray to dark green color due to chloritization. Exposed surfaces are in many places bleached by acid groundwaters to grayish-white. In the examination of thinsections and hand specimens, no amphiboles or pyroxenes were identified. Thinsections show a few outlines which probably had been amphiboles. In one section, an amphibole cleavage pattern was suggested by oriented, unidentifiable needlelike crystals of possibly rutile or hornblende. Other workers in nearby localities have reported glass in the groundmass of these intermediate volcanics. However, due to alteration effects, the groundmass is mostly clay minerals, quartz, feldspars, micas, and chlorites; clay minerals and quartz are by far the most abundant minerals.

Quartz

Quartz has very likely been introduced during alteration and comprises from a few percent up to 20 percent of the groundmass in the Foster Park sequence. The quartz is anhedral, commonly showing undulatory extinction; it is clouded with opaque material, probably ferruginous, and gas bubbles. Saccharoidal texture is common, and no recognizable relict flow structure was recognized.

Most of the quartz phenocrysts are small and suggest an intratelluric origin; they appear to have been partially redissolved due to their unstable relationship with the environment, probably shortly before extrusion. They are well-rounded and irregular, showing embayments from corrosion, as well as overgrowths of varying degrees of prominence.

In the rocks included in the Foster Park series, quartz phenocrysts are generally absent, but were found locally to comprise up to 17 percent of the phenocryst fraction or about 3 percent of the rock.

Alkali Feldspar

Alkali feldspar, like quartz, is not uniformly distributed throughout the Foster Park sequence, varying from less than 10 percent to nearly 30 percent of the phenocryst fraction. All the alkali feldspars that were identified were sanidine. These crystals show euhedral to subrounded outlines of original sanidine, or pseudomorphs of alteration products after sanidine.

Plagioclase

Plagioclase comprises up to 85 percent of the phenocryst fraction and, where the alteration has not been too intense, up to 35 percent of the groundmass. The phenocrysts lack any preferential orientation and form a seriate porphyritic texture. The plagioclase, andesine, was found to have an average composition of An_{38} as determined from curves by Wahlstrom (50). Determinations were made both from maximum extinction angles from twinning planes measured in sections normal to (010) and (001) faces, and from grains oriented with (100) normal to the microscope stage. Zoning in the andesine has a composition ranging from about An_{30} to An_{48}.

The plagioclase is subhedral to euhedral, rarely rounded, and distinctly twinned according to the carlsbad and albite laws. In many cases plagioclase is moderately to intensely altered, and reaction rims are common. The complex magmatic history of these rocks is partially expressed by the diverse types of zoning of the plagioclase, even within one thin-section or rock specimen. Unzoned crystals were found adjacent to crystal aggregates showing oscillatory to normal zoning, as well as overgrown and incorporated within other phenocrysts (see Fig. 8).

Alteration commonly left only a suggestion of original plagioclase twinning and/or zoning, and former crystal outlines enclose clay pseudomorphs. The phenocrysts reach diameters of 10 mm, averaging about 5 mm.

Accessory Minerals

Accessory primary minerals of the Foster Park and Letir rocks are sphene, zircon, and epidote. Ferromagnesian minerals and iron oxide were probably originally present.

Minerals of recognized post-emplacement origin, although in part also of primary origin, are: leucoxene[1], clays, epidote, penninite and other chlorite minerals, wad, pyrite, calcite, limonite, jarosite, sericite, sulfur, alunite(?), halotrichite, and other weathering products, especially sulfates.

1. See discussion of leucoxene (p. 67) for the definition of this term as used in this paper.

FIGURE 7

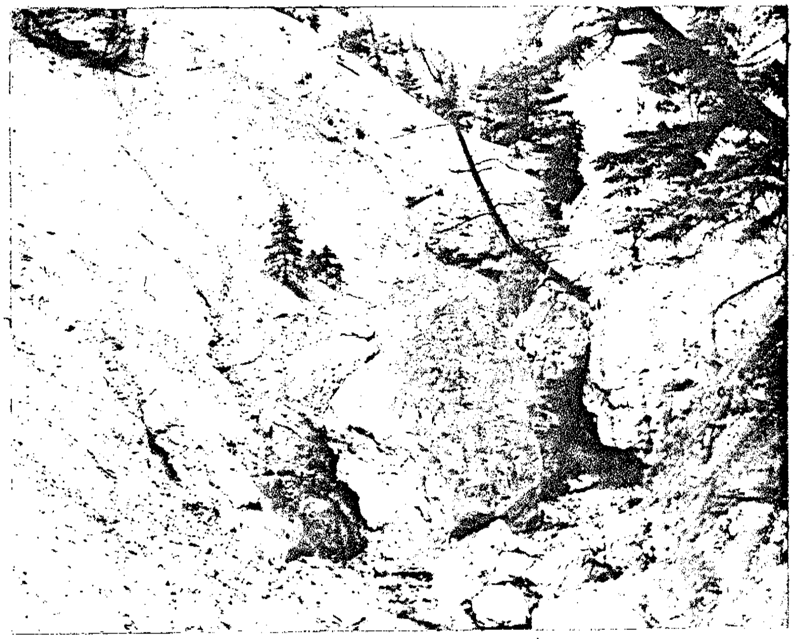
Clogged Stream Channel

The main stream in Area #1 showing several large slumped boulders. Steep slopes are characteristic of this area. Gravels dammed by slumped boulders have been cemented.

FIGURE 8

Thinsection of a Feldspar Phenocryst in Latite
(X-nicols)
(X30)

One large phenocryst has overgrown several individual grains. One crystal is not zoned, but displays carlsbad twinning. Other nuclei around which oscillatory zoning is conspicuous are clearly represented. The separate grains pictured here are poikilitic inclusions in a large euhedral plagioclase grain.



Rhyolite

Rhyolite Tuff

The rock referred to by Schilling (37, 38) and McKinlay (30, 31), as rhyolite tuff is a distinctive gray to maroon-brown rock with characteristic dark, glassy streaks that are often recognizable even where the rock has been highly altered. The tuff is aphanitic with a few euhedral to subhedral bipyramidal quartz crystals and small euhedral feldspars set in an aphanitic to cryptocrystalline groundmass. The feldspars probably were altered during cooling of the extrusive sequence, inasmuch as very little of the original crystalline material could be identified in even the freshest-appearing samples. Traces of relict polysynthetic twinning provide evidence to identify some of these grains as having originally been plagioclase phenocrysts. The feldspars are generally about 2 mm in length, whereas the quartz phenocrysts are 1 mm or less. Quartz comprises more than 75 percent of the phenoclast fraction, and 12 percent of the whole rock. The groundmass is well over 50 percent quartz, some of which may have been introduced since emplacement of the tuff either by autogenetic volatiles or from outside sources. Mosaic salt-and-pepper texture is prominent, with sutured, or locally graphic texture, formed by quartz. The dark, glassy-appearing streaks are completely crystalline and locally entirely silicified, with ferruginous material trapped in the quartz grains. Coronas and rims of quartz commonly border relict glass streaks and blebs as well as quartz phenoclasts.

Alpha quartz, as well as pseudomorphs after beta quartz are abundant, and tridymite(?) is present in minor amounts. Silicification has been intense to moderate throughout the entire district. The introduced silica in the rhyolite tuff commonly replaced original mineral grains and obscured the character of the groundmass. Quartz veinlets in many places merge into quartz-rich areas of the rock.

Felsite Flows, Rhyolite Sills and Plugs

The denser stony rhyolite that overlies the welded tuff appears to be identical with a rock that makes up several small stocks, dikes, and sills. It is white to light gray, and aphanitic, with quartz phenocrysts.

Quartz phenocrysts comprise up to 19 percent of the rock, and about 90 percent of the phenocrysts. The quartz phenocrysts vary from distinctly euhedral to angular, to rounded and embayed. Overgrowths are common, especially on the rounded grains. Overgrowths are commonly accentuated by a thin rim of trapped opaque material and clays along the earlier grain boundary. Fracturing and undulatory extinction of quartz is common throughout this rock type.

Andesine and sanidine phenocrysts make up about 2 percent of the rock, and 10 percent of the phenocrysts. Cumulophyric aggregates of hypidiomorphic granular feldspar crystals consist of unzoned grains, with distinct albite and carlsbad twinning in the andesine.

Pyrite and clay minerals are present, probably as alteration products. Minor green to brown, euhedral biotite flakes, zircon, and sphene constitute the accessory minerals.

The groundmass, which constitutes over 75 percent of the rock, is composed of a dense quartz-feldspar salt-and-pepper textured, microcrystalline aggregate. The feldspars are microcline, andesine, and sanidine. Andesine and alkali feldspar make up about 30 percent of the groundmass, and quartz about 30 percent, with a cryptocrystalline quartz-illite-sericite matrix composing the remainder.

Quartz Monzonite and Monzonite Porphyry

The rock type described by McKinlay (30, 31) and Schilling (37, 38) as monzonite porphyry is similar in texture and structure, and generally has the same mode, as a dike and stock-forming rock in the altered zones. This rock, one of the youngest igneous rocks, is light gray to greenish-gray to white in the altered areas, and has been altered to such a degree that all the primary mafic minerals, other than biotite and sphene, can no longer be recognized. Pseudomorphs after biotite are preserved, and leucoxene-filled pseudomorphs after sphene appear throughout the rock. The feldspars are only partially preserved, with the alkali feldspars showing the most extreme alteration.

These rocks range from hiatal porphyritic textured varieties to medium- to fine-grained porphyry. The hiatal texture is shown in Fig. 4 where the protruding end of what was originally a sanidine crystal is associated with several poikilitic eye-like quartz phenocrysts below the pseudomorph after sanidine. The outline of another more altered relict sanidine crystal is faintly recognizable in the extreme right-hand portion of the rock.

In the area of detailed study, none of the sanidine crystals in the monzonite porphyry were sufficiently preserved for identification. In order to identify some of the minerals in rocks of this type, a sample was collected 5 miles north of the town of Red River, and the composition of the phenocrysts and groundmass studied. The groundmass, now a quartz-clay aggregate in the altered areas, was found to be cryptocrystalline to vitreous with about 50 percent feldspar crystals. The feldspar crystals in the groundmass are subhedral to anhedral plagioclase and potassium feldspar, with minor microcline.

The plagioclase phenocrysts are subhedral andesine (An_{40}) with relatively minor zoning; albite and carlsbad twinning are well developed. Large potassium feldspar phenocrysts commonly show reaction rims and some rounding. These features suggest that in a melt of intermediate to basic composition the physical-chemical conditions permitted growth of the more siliceous minerals potassium feldspar and quartz, to nearly pegmatitic size in preference to the crystallization of more basic minerals, and that later rapid cooling preserved these unstable minerals. This texture also could have developed from a mixing of magmas, or by their contamination. The complex history of this rock is suggested by Fig. 9, which shows potassium feldspars overgrown by plagioclase (chloritization of the cores is a product of alteration).

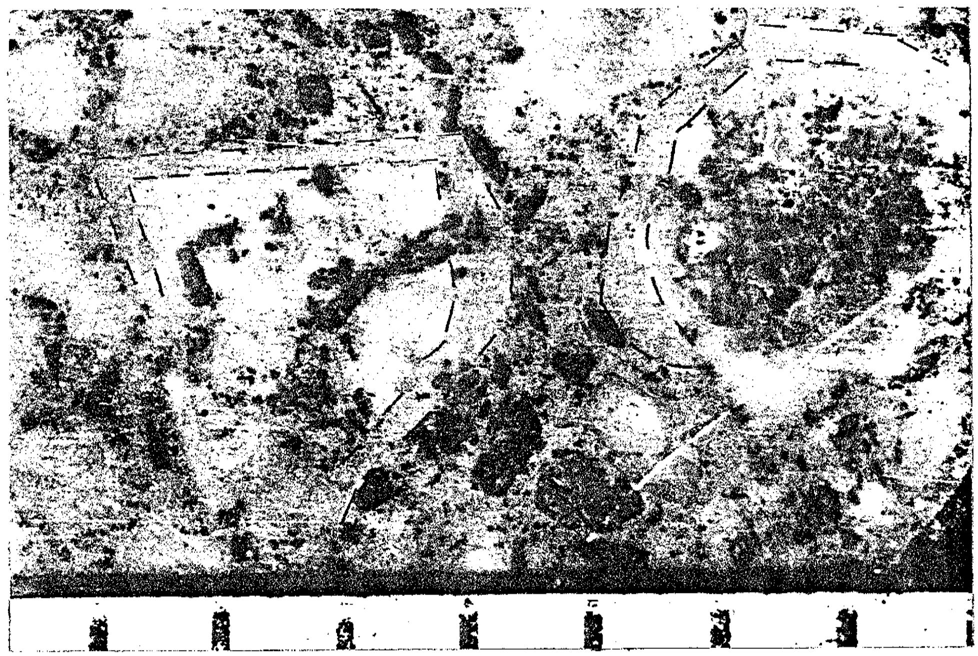
Quartz is present as anhedral, well-rounded and corroded grains, locally with only wormlike blebs remaining. Quartz grains range from microscopic to as much as 3/4 inch in diameter. In the larger grains there is a tendency for inclusions of gas, clay, and opaque material to form a radial texture. Fracturing and recrystallization are common features in these grains, many of which have overgrowths of fine-grained quartz optically continuous with the larger grain, and contain an excess of opaque, probably ferruginous, dust (Figs. 10 and 11).

The range in composition of this rock includes both monzonite and quartz monzonite porphyry, with abrupt variations in the abundance of phenocrysts and the amount of quartz over even short distances. The structure is massive. Fracturing and jointing are not pronounced. Monzonite rocks form some of the extreme topographic features (see frontispiece, the cliff-forming material west of the saddle).

FIGURE 9

Plagioclase Overgrowths on Sanidine
(Scale divisions equal 1/8 inch)

Monzonite porphyry stained with sodium cobaltinitrite and rhodizonate reagent (Bailey and Stevenson, 2). The darker gray borders are plagioclase feldspar stained brick-red by rhodizonate reagent. The potassium feldspars form the cores, and have been partially chloritized. The potassium feldspars were stained yellow with sodium cobaltinitrite. The plagioclase border is partially outlined in ink to accentuate the contacts. The groundmass is composed of clays, chlorite, and quartz.



FIGURES 10 (upper) and 11 (lower)

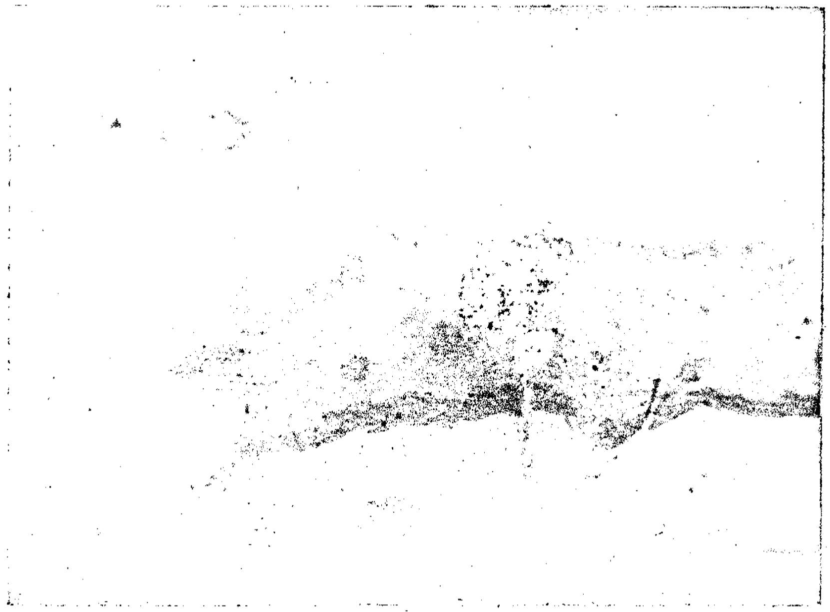
Thinsection of Monzonite Porphyry Showing
Overgrowths on Quartz Grains
(X25)

Rounded quartz phenocrysts with dark borders of ferruginous opaque material rimmed by quartz that has the same optical orientation as the host grain.

Figure 10 (Ordinary Light). The quartz grains are uniformly bordered by a zone of fine-grained opaque material.

Figure 11 (X-nicols). The orderly orientation of the quartz rims illustrated. The rims are illuminated or in extinction in accordance with the orientation of the adjacent grains.

The grains are set in a groundmass of quartz and sericite.



In outcrops where no mafics are preserved and the plagioclase is badly altered, it is nearly impossible to identify this rock as monzonite; in such cases, only by studying the relict texture, can identity with the monzonite and quartz monzonite be recognized.

A uniform gray to greenish monzonite porphyry crops out as a narrow dike that is possibly related to the monzonite-quartz monzonite intrusives. The dike rock (Fig. 15) is a hypidiomorphic granular porphyry. This rock contains about 15 percent sanidine, 40 percent andesine, 8 percent biotite, and 2 percent quartz as phenocrysts, with the remainder partially to completely altered groundmass. Accessory minerals are magnetite, zircon, sphene, and apatite. Plagioclase grains are white, subhedral to euhedral, and up to 8 mm in length. A few grains show distinct oscillatory zoning. The twinning is according to carlsbad and albite laws. Sanidine crystals are pink, euhedral to angular, and range up to 20 mm long. These sanidine crystals differ from the extremely large ones in most of the monzonite, quartz-monzonite rocks by their lack of reaction rims in the rock, their size, and twinning habit. These crystals are generally untwinned or only rarely show carlsbad twinning. The much larger sanidine crystals display penetration twinning and mutual intergrowth, along with abundant carlsbad twinning. Two generations of biotite were found: books up to 5 mm long, and an earlier form appearing as shreds resulting from cataclastic deformation.

ALTERATION

The compositional and structural characteristics described above under petrography are most likely primary features, and none of these features has been related to post-volcanic alteration. Hydrothermal feldspathization has not been recognized in these rocks.

General Nature and Type of Alteration

Alteration features in Red River canyon closely resemble the quartz-sericite alteration described in many other districts (Schwartz, 40, 42). The Red River alteration is also similar to that described by Burbank (8), in Colorado, as sericite-type alteration zones.

Lead, zinc, copper, and gold are associated with this form of alteration in many western mining districts, but only small veins and traces of disseminated lead and zinc were found or have been reported around Red River. Gold and silver have been mined and placered sporadically throughout the district since 1680, so legend has it (Schilling, 38). Copper minerals are widely distributed and ores of copper have been mined locally. The only metal extensively mined at present is molybdenum.

Alteration minerals are quite varied and the assemblage of minerals changes radically, even in a local area. It has been pointed out that hydrothermal solutions undergo constant change (Grim, 16, Lovering, 27). A change in chemical environment can be brought about by the solution, replacement, or precipitation of material, and a change in physical environment, pressure, and temperature, merely by the mobility of the solutions. A fuller understanding of the identity and distribution of the clay minerals could lead to a clearer comprehension of the composition and source of the altering solutions, but such a study is beyond the scope of this report.

Three possibilities will be considered regarding the origin of the altering solutions in the vicinity of Red River: (1) a deuteric origin involving escaping gases of the thick volcanic sequence; (2) a deep-seated origin, possibly from the parent magma of the volcanic and intrusive rocks; or (3) an unrelated magmatic source.

There is little doubt that there have been some deuteric effects. Evidence for this is found in the ubiquitous distribution of alteration features, chloritization and sericitization, in even the freshest-appearing extrusive rocks. Feldspar phenocrysts appear to be most susceptible to this type of alteration, and were nowhere found unaltered in the extrusive sequence. Alkali and calcic feldspars were found to range from fresh to partly altered in some of the younger intrusive rocks.

Intrusive dikes near areas of intense alteration locally contain fresh feldspar phenocrysts, but post-volcanic intrusives locally suffered extreme alteration along with the extrusive rocks.

Intense alteration is generally closely associated with large faults and zones of brecciation. Where pronounced fracturing is not evident, intrusive contacts appear to have served as structural controls of the locus of alteration. On the basis of this association, it is concluded that intense alteration was structurally-controlled.

There is no evidence to suggest an unrelated magmatic source for the origin of the altering solutions.

Alteration is dated post-monzonite porphyry because of the intensity of alteration suffered by all the intrusive rocks in the area including the monzonite porphyry, the youngest recognized intrusive rock.

It appears from the above that some general deuteric alteration is present throughout the extrusive sequence, but that the striking alteration prevalent through Red River canyon and some of its subsidiaries is hydrothermal in nature.

Supergene alteration, occurring at present, is expressed by surficial bleaching and characteristic minerals, (Fig. 21).

The uniformity in mineral assemblage of areas of extreme alteration is reflected in the similarity of differential thermal analyses of the altered rocks (Fig. 12), and in the relative intensities of significant reflection peaks recorded by X-ray diffraction patterns. The composition of the end products of alteration is the same regardless of the original rock type. Original rock types are often identifiable by relict structures and textures preserved in clay-mineral pseudomorphs, pseudomorphs of white mica after biotite, and quartz that resisted alteration.

There is an extensive literature on the genesis of clay minerals (Badger, 1; Burbank, 8; Butler, 9; Grim, 16, 17; Gruner, 19; Lovering, 27, 28; Rogers, 36; Schwartz, 39, 40, 41, 42; Stephenson, 44, among others). A chart by Stringham (45) partially reproduced here (Fig. 13) shows some of the generally accepted fields of formations of clays and other hydrothermal minerals. Alteration in the Red River district appears to have occurred in the neutral to alkaline range of the chlorite-sericite-illite zone (shaded, Fig. 13).

Alteration Zones

The end product of alteration in the Red River district is a quartz-sericite-illite assemblage. Although the alteration can be divided into several sequential zones, there is in every case observed a continuous transition from one zone

FIGURE 12

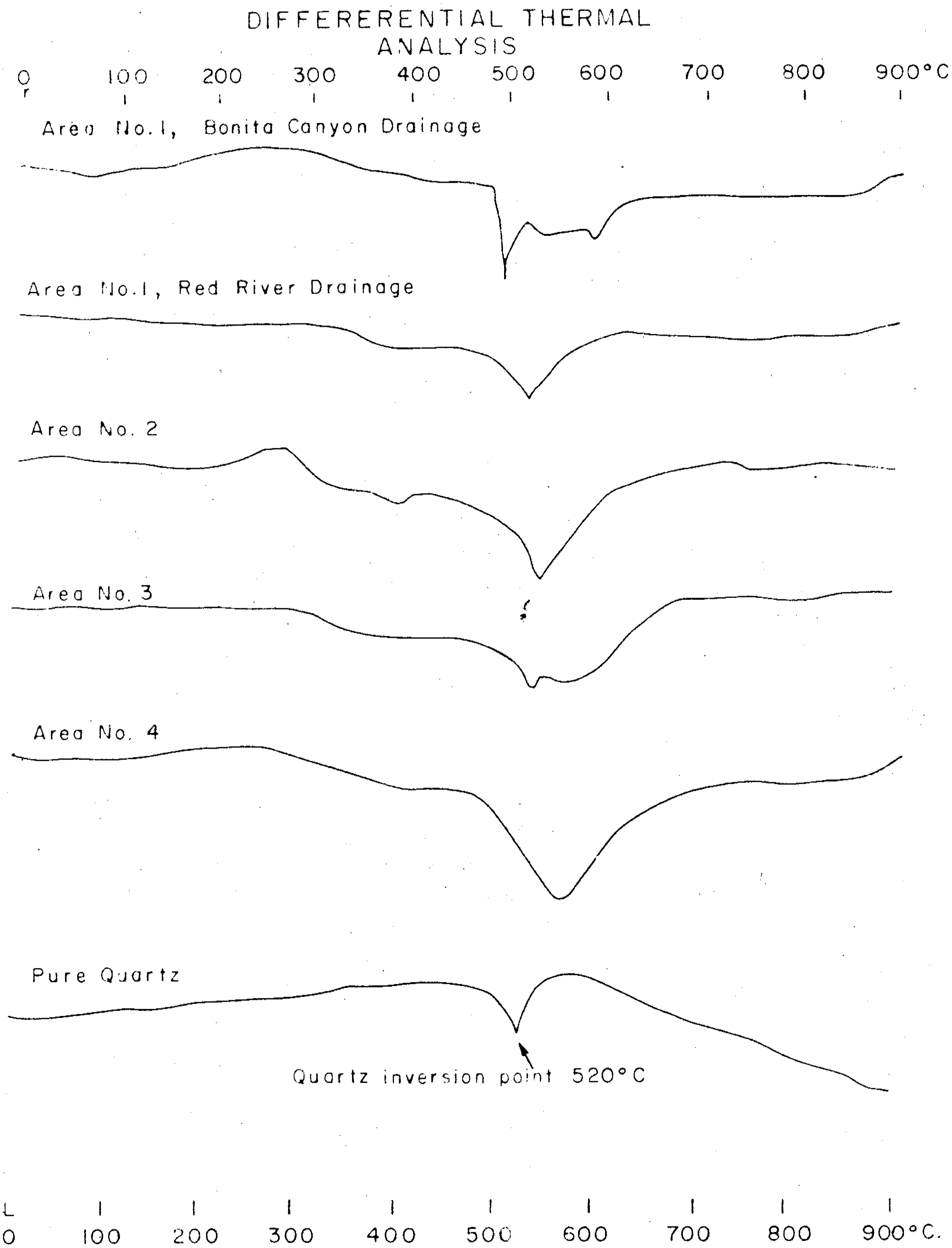
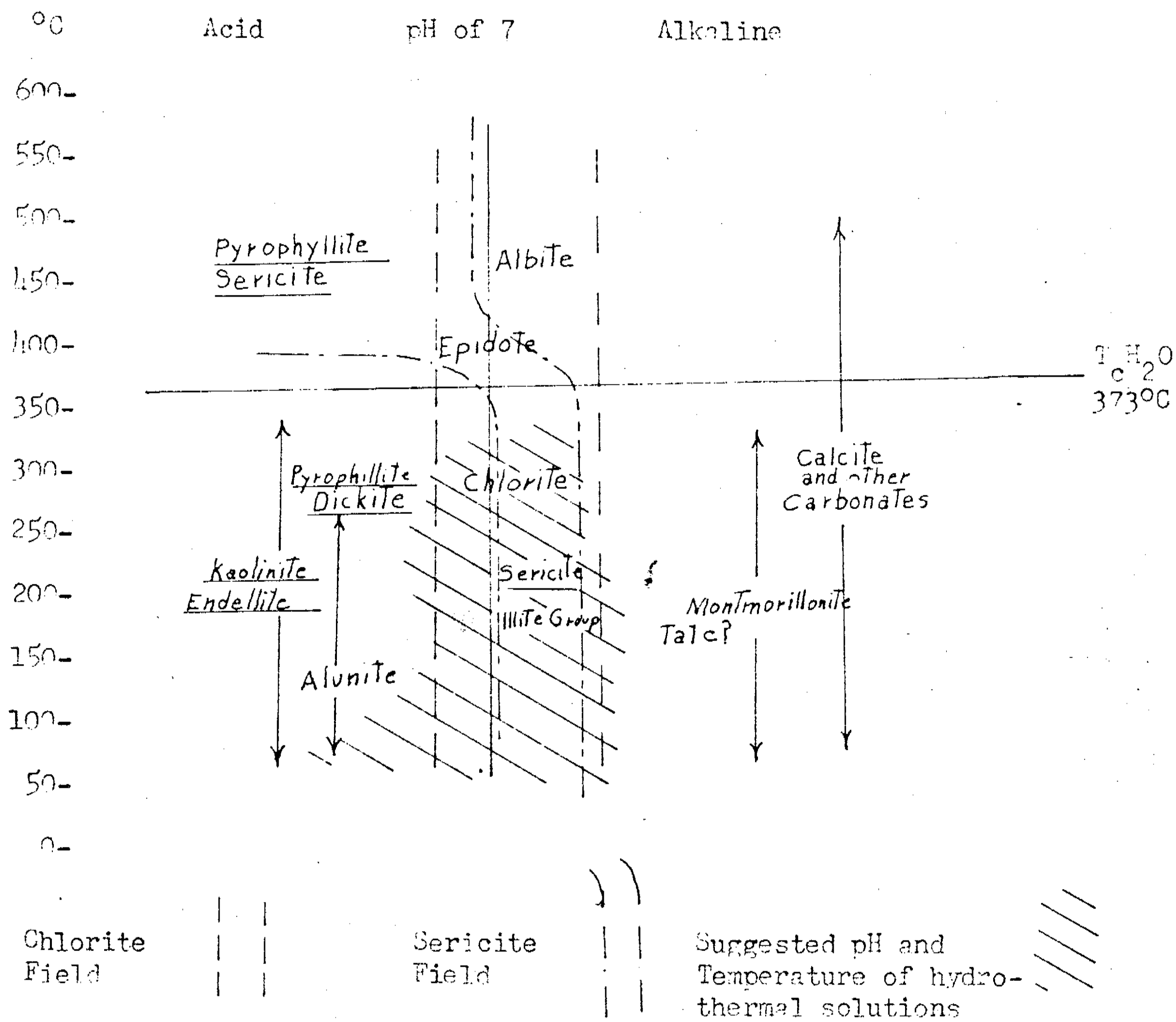

DIFFERERENTIAL THERMAL
ANALYSIS
0
100
200
300
400
500
600
700
800
900°C.
Area No.1, Bonita Canyon Drainage
Area No.1, Red River Drainage
Area No. 2
Area No. 3
Area No. 4
Pure Quartz
Quartz inversion point 520°C
0
100
200
300
400
500
600
700
800
900°C.

Figure 13

Fields of Formation of Some Common Hydrothermal Minerals



Fairly definite field established for underlined minerals

After Stringham (1952)

to the next. The relative abundance of various minerals and mineral habits recognized in a group of regularly spaced samples traversing part of one alteration zone (Area #1) is brought out in a chart (Fig. 14). Twenty-four specimens were collected at vertical intervals of 10 feet along a 35 degree slope, which represents about 14.5 feet horizontally for each 10 foot interval (two localities were not sampled due to lack of fresh in place rock). Fig. 14 summarizes the results of analyses of these samples. Frequencies of sericite and clay minerals are plotted from relative intensities of the characteristic peaks of the respective minerals, as recorded by a goniometer attachment on an X-ray powder diffraction unit. Heavy minerals were also concentrated by panning and studied for each sample locality.

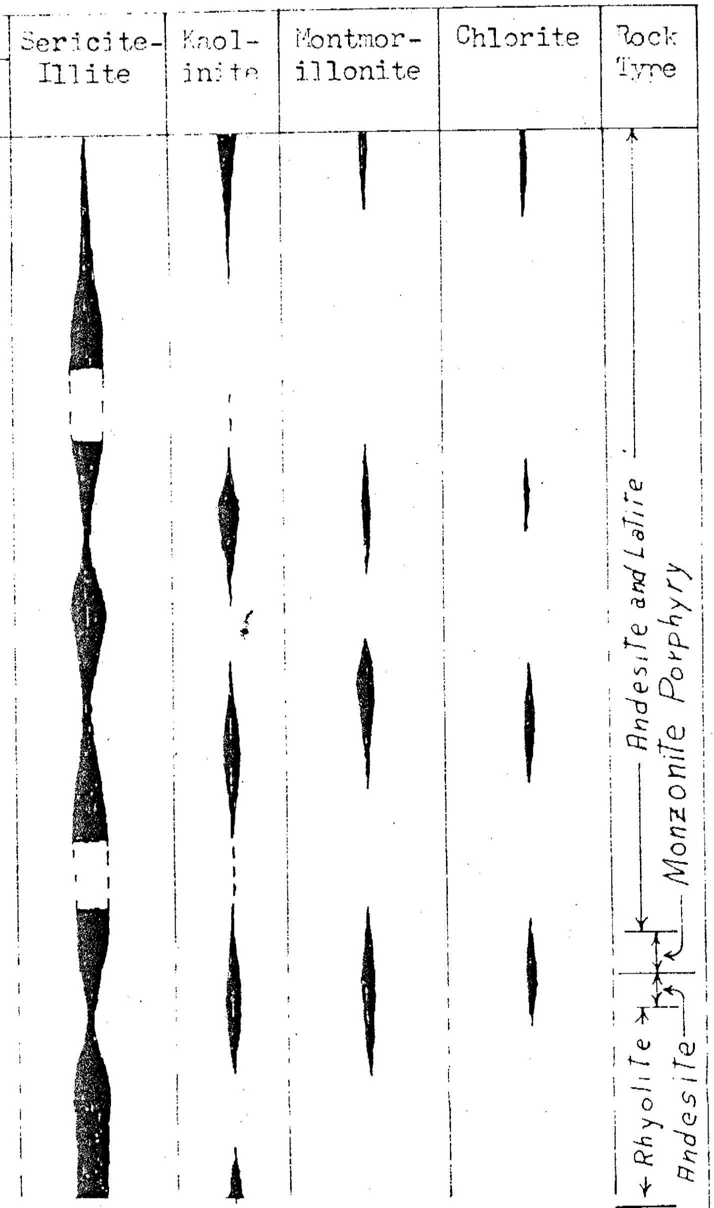
Thinsections from this zone show that apatite, epidote, and leucoxene are also present as secondary products. Pyrite probably appeared late in the chlorite stage or early in the kaolinite stage. Following chloritization, which principally affected the mafics and to a lesser degree the feldspars, kaolinization and the formation of montmorillonite occurred primarily as an alteration of plagioclase.

On Fig. 14 sericite-illite minerals, to the relative exclusion of the other alteration products, dominate samples 3, 9, 15, and 21. These samples are at intervals of approximately 60 feet vertically or 87 feet horizontally. From

Figure 14

Relative Abundance of Alteration Minerals in Area #1

Sample No.*	Pyrite %	Pyrite Habit
26	5	Q
25	4	Q
24	2	Q
23	2	Q
22	4	Q
21	2	Q
19	5	
18	2	Q
17	5	Q
16	4	Q
15	5	
14	8	Q-P
13	3	Q-P
12	2	Q-Z
11	3	Q-P
10	3	Q-Z
9	4	Q
7	4	Q
6	1	Q
5	3	Q
4	<1	
3	<1	Q
2	1	Q
1	1	Q



Stream course

* No. X 10 = vertical distance in feet

Pyrite Key: Q - Cubic habit; P - Pyritohedral habit; Z - 210 faces developed these localities, progressing either up or down the traverse, kaolinite becomes more abundant at the expense of sericite and illite. Montmorillonite then appears and finally small amounts of chlorite appear, except in the rhyolitic rock. This progressive transition from sericite-illite to chlorite is the suggested sequence from the center of alteration outward. Throughout these zones of alteration chlorite is a dominant secondary mineral in the areas of less intense alteration.

The writer believes that these sericite-illite zones represent central areas of hydrothermal solutions. The sampling was done on a one dimensional basis and possibly could be interpreted to two dimensions, but the extent of the present information does not justify any postulation as to the three dimensional configuration of these alteration centers. It is possible that flow units are represented by the repeated mineral sequences, or their repeated occurrence could be a result of fault planes or permeable zones discordant with the flows.

Faulting in the rhyolite tuff led to the formation of a white gouge along the fault planes (Figs. 2 and 3). Powder X-ray diffraction analyses show that this gouge consists exclusively of a kaolin-group mineral, probably dickite(?), and quartz. A series of three samples from a rhyolite tuff specimen were analyzed to determine the relationship of the dickite(?) to slip joint surfaces. The three specimens for this study were taken from the same rock at progressively greater distances from the surface of a slip joint. Contamination of the samples was inevitable because of transverse fractures. In spite of this contamination, the ratio of dickite(?) to sericite-illite was radically reversed in a very short distance. Dickite(?) is dominant near the slip joint surface, whereas sericite-illite is more abundant farther from the slip joint.

It is concluded that kaolin-group minerals were formed in two distinct environmental situations: (1) relatively widespread development of kaolinite that resulted from deuteric and hydrothermal processes; (2) local development of dickite(?) along fracture surfaces.

MINERALOGY

Alteration and Effects on Minerals

Pyroxenes and Amphiboles

No pyroxenes and amphiboles were found in, or adjacent to, the altered zones. A few crystal outlines with relict amphibole cleavage patterns are indicated by the assemblage and orientation of secondary mineral accumulations, as mentioned previously. The scarcity as well as uncertainty of origin of these accumulations do not justify any conclusions as to the type, nature, or abundance of specific pyroxenes or amphiboles.

Biotite

One occurrence of hydrothermal biotite was noted. The biotite occurs as small specks in an otherwise completely-altered rock. Its apparent distribution as a secondary mineral in the area of investigation is limited to the head of the part of Area #1 that drains north into Bonita Canyon. This biotite occurs as small, euhedral books about 0.1 mm in diameter.

Both pleochroic green and brown varieties of igneous biotite are abundant both as euhedral books and as shreds. Biotite in the chloritized zone is sometimes associated with zoisite, rutile(?), or hornblende(?) needles, and apatite. This assemblage is thought to be the residue of former amphibole or pyroxene. Biotite is partially chloritized, but usually before chloritization of the biotite has progressed far, bleaching becomes prominent. Iron is extracted from the structure and possibly combined with titanium, either from the biotite and/or from other minerals in the country rock to form leucoxene borders and fillings in the cleavage traces of the biotite (Fig. 16). The opaque minerals in Fig. 16 (leucoxene) are eventually removed, leaving a white mica recognized by Schwartz (42) and others as an alteration of biotite. The "white mica" mineral has the optical properties of phlogopite. Berry and Mason (5) describe the division between biotite and phlogopite as an "arbitrary division of a single phase of variable composition", and if such is true, the replacement of iron, and possibly titanium, by magnesium in biotite could produce phlogopite.

Quartz

Silicified rock, residual quartz phenocrysts, and quartz veins and dikes are prevalent throughout the district.

Deuteric solutions could account for some of the secondary quartz and quartz overgrowths in the volcanic rocks.

Quartz in veins and dike-like masses, ranges from milky white to nearly black. The dark variety is the earlier-formed of the vein quartz. It locally contains centers of pyrite or clearer quartz. White quartz veins cut

FIGURE 15

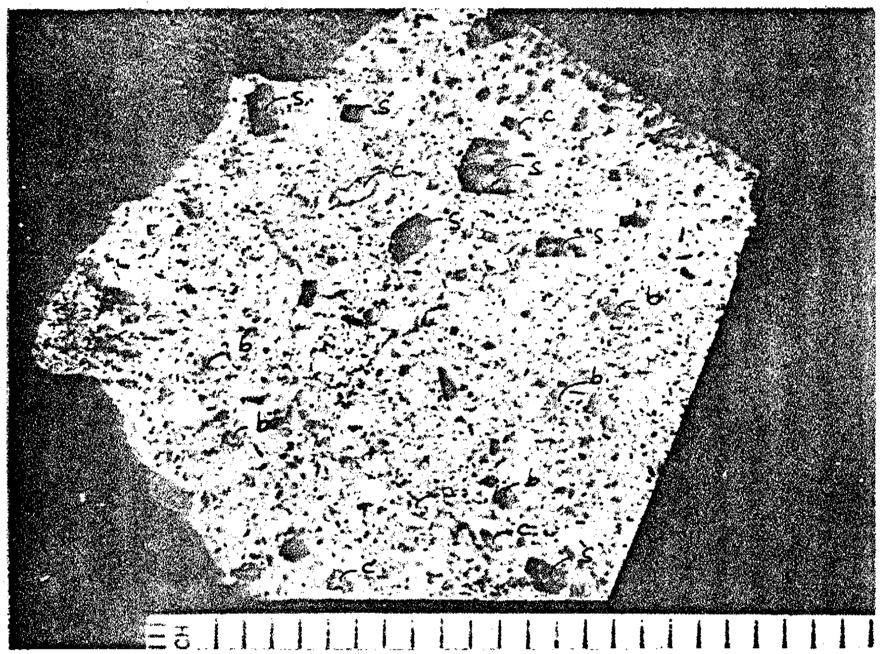
Altered Monzonite Dike Rock
(Scale divisions equal 1/8")

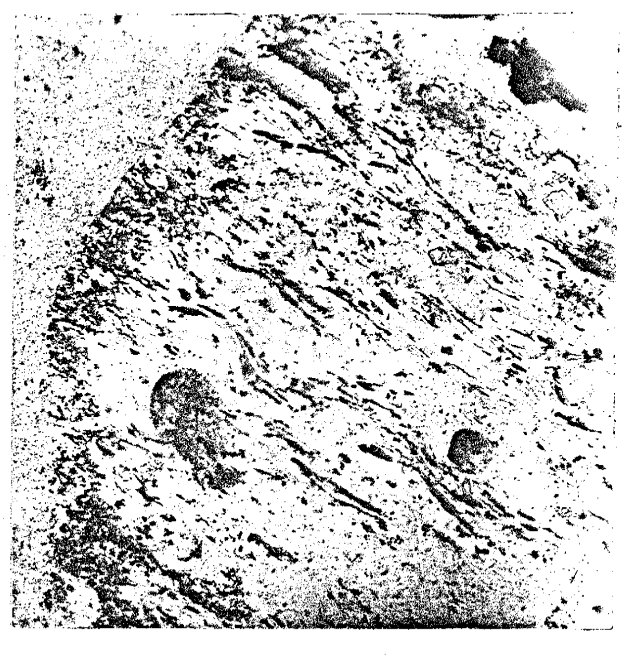
The large dark grains are chloritized sanidine (s - chloritized sanidine). Several books of biotite are visible (b - books of biotite). Medium-sized feldspar crystals can be recognized with partially chloritized cores (c - chloritized cores). The dark material partially permeating the upper right border is manganese oxide stain. The groundmass is mostly microcrystalline clays and quartz.

FIGURE 16

Thinsection of Altered Biotite in
Dike Rock of Intermediate Composition
(Ordinary Light X25)

Part of a euhedral biotite crystal that has been bleached. The opaque minerals concentrated at the edge of the crystal and along cleavage faces are formed in part at least by the separation of iron and titanium from the biotite. This opaque material in transmitted light appears as dark streaks and borders in the biotite, but is white to yellow under reflected light, whence its designation as leucoxene. The biotite is set in a groundmass of cryptocrystalline clays and quartz.





and displace the darker veins and are themselves broken and displaced by later fractures.

Neither hydrothermal alteration nor weathering appear to have affected the quartz grains or veins to any recognizable extent. In zones of most extreme alteration, euhedral prismatic and bipyramidal quartz crystals show no evidence of corrosion.

The most recent silicification has been deposition of quartz by groundwater resulting in cavity linings of euhedral crystals, and there appears to be massive cementation of permeable rock by siliceous material.

Feldspar

Plagioclase, most of which was originally andesine, readily altered to kaolinite, sericite, and illite in varying amounts, depending on the nature and intensity of alteration. An abundance of poorly crystalline illite is present in the extremely altered phenocrysts. The strongest reflection of illite, from the basal 9.96Å spacing, has a rounded, indistinct apex rather than a sharp peak. Rounding of this sort is not characteristic of well-formed crystalline sericite, but is a common feature of illite. The white clay pseudomorphs which replace plagioclase are easily recognized after the rock has suffered intense alteration.

Pyrite is disseminated throughout the rocks. It rarely occurs within the margins of clay pseudomorphs after plagioclase, but not uncommonly borders the pseudomorphs. This concentration probably forms to compensate for the inability of the pyrite to crystallize within the pseudomorphs, or possibly due to a volume change resulting from alteration of feldspar that provided a favorable zone bordering the grains.

Sanidine phenocrysts have yielded to chloritization with further alteration yielding a sericite-illite-montmorillonite-kaolinite(?) assemblage. The final alteration product of sanidine is generally quartz-illite-sericite, which is the composition of the large white phenocryst in Fig. 10. Not always, however, does the alteration include all these phases. Where chloritization was effective, it appears to have started in the center of the sanidine grain (Figs. 4 and 8). Complete chloritization of the grain eventually occurred, resulting in a chlorite pseudomorph (predominantly pennine with possibly other chlorite minerals) after feldspar. Fig. 15 shows a specimen in which the sanidine has been almost completely chloritized.

Sphene and Leucoxene

Very little sphene survived deuteric alteration, and none was recognized in rocks that had been subjected to moderate hydrothermal alteration. Volcanic and intrusive rocks of intermediate composition (monzonites, latites, andesites) contain varying amounts of leucoxene pseudomorphous after sphene. In some intrusives, relict sphene outlines are abundant whereas they are rare in others. A genetic separation of these intrusive rocks could possibly be made on the basis of the abundance of pseudomorphs after sphene.

Titanium is abundant throughout the district, as indicated by strong lines of that element on all the emission spectrograph films. The abundance of magmatic titanium minerals provides a source of material for the common occurrence of secondary titanium minerals. The secondary minerals have been categorized in this paper as leucoxene. The term leucoxene has been applied to undifferentiable aggregates of anatase, brookite, and rutile. The difficulty in applying this term in a more specific sense has been discussed by Golding (14). Golding favors the concept that leucoxene includes a large compositional range represented by a triangular diagram with end members of SiO_2, TiO_2, and $FeO + Fe_2O_3$. A continuous series having this composition provides a reasonable explanation for the abundance of material designated as leucoxene throughout the chloritized rocks of the Red River district, where it is associated with the mafic minerals rather than exclusively with sphene. The biotite grain in Fig. 16 illustrates a characteristic association in this area.

Zircon

Zircon occurs as a primary magmatic mineral in small, euhedral crystals in the intermediate rocks. Its resistance to alteration and weathering is demonstrated by its frequency in heavy-mineral concentrates from altered as well as fresh rocks.

Pyrite

Pyrite is disseminated throughout the rock in all areas of alteration, averaging approximately 3 percent of all altered rocks. Two distinct varieties have been recognized: (1) euhedral crystals disseminated throughout the rock; and (2) veins of massive pyrite up to a few inches wide. The vein pyrite is a very late mineral, occasionally forming cores in quartz veins. There appears to have been no alteration of the adjacent country rock by the emplacement of these veins. In Areas #5 and #6, abundant titaniferous magnetite nodules were found in the late pyrite veins. The very fine-grained disseminated pyrite shows a preference for the more basic or intermediate rocks, and is less abundant in the rhyolites and tuffs. The Foster Park volcanic rocks contain as much as 10 percent pyrite, whereas pyrite makes up only about 1 percent of the rhyolitic rocks.

The earlier disseminated pyrite is present in three habits: cubic, octahedral, and pyritohedral. Cubic pyrite is most ubiquitous. It is transitional into the other habits, by mixtures of euhedral crystals of different forms, there being no sharp demarcation between the presence of these forms. Cubic pyrite occurs in both untwinned crystals and twinned varieties. Development of (210) faces on the cubic pyrite is characteristic of the transition into zones of dominantly pyritohedral pyrite. These faces become more prominent inward toward a central zone in which the pyritohedral form predominates (Fig. 14).

Octahedral pyrite occurs as small, euhedral, untwinned crystals. These crystals are generally smaller than those of the other habits, and are locally abundant. Their occurrence has shown a preference for the rhyolite welded tuffs, generally where the rock is moderately to intensely altered.

No conclusions are justified as to the association or genetic control of the various forms of pyrite within the limitations of the samples available. Sphalerite was identified in two of the three localities where pyritohedral pyrite is abundant, suggesting a possible correlation between the two. Because the three habits of pyrite occur within a relatively local area, and possibly form during the same period of deposition, a determination of possible controls of pyrite habit would be of interest.

An effort to determine possible trace element differences between each of the three forms of pyrite by X-ray fluorescence methods proved futile due to the inadequate sensitivity attained. Chemical analyses[1] revealed that pyrite contained up to 35 ppm molybdenum. Analyses by emission spectrography revealed variable amounts of copper present in the pyrite, more appearing in the pyritohedral and octahedral forms of the samples studied. Traces of

1. Courtesy of American Metal Climax, Inc.

nickel were found in the grains that have (210) faces developed. The number of samples studied was very small; consequently the above-mentioned habit and composition correlations are not established as generalizations.

Both post- and pre-alteration pyrite were found. Most of the pyrite is either contemporaneous with, or post alteration in age, but some clearly has been replaced by clay minerals (Fig. 17). Replacement embayments of sericite and illite extend into pyrite, and later quartz veins transect and displace some of the disseminated pyrite.

Masses of slumped gouge and breccia found in stream courses and along fault contacts locally contain massive, partially weathered to fresh pyrite (see Fig. 18). These rock masses are composed of small, rounded breccia fragments in a clay matrix that is plastic or puttylike when wet. Pyrite is disseminated throughout this material, and forms local concentrations of pure pyrite. The pyrite shown in Fig. 18 was deformed by ~~resulted from~~ removing and handling the sample while it was moist and plastic. This pyrite is probably of the late vein-filling sequence. The freshness of the pyrite in such porous materials reflects the rapid erosion experienced by these rocks.

Minor Minerals

Small amounts of talc were found in rocks of the Foster Park series. The talc appears as small green spots near the zones of intense brecciation and alteration.

FIGURE 17

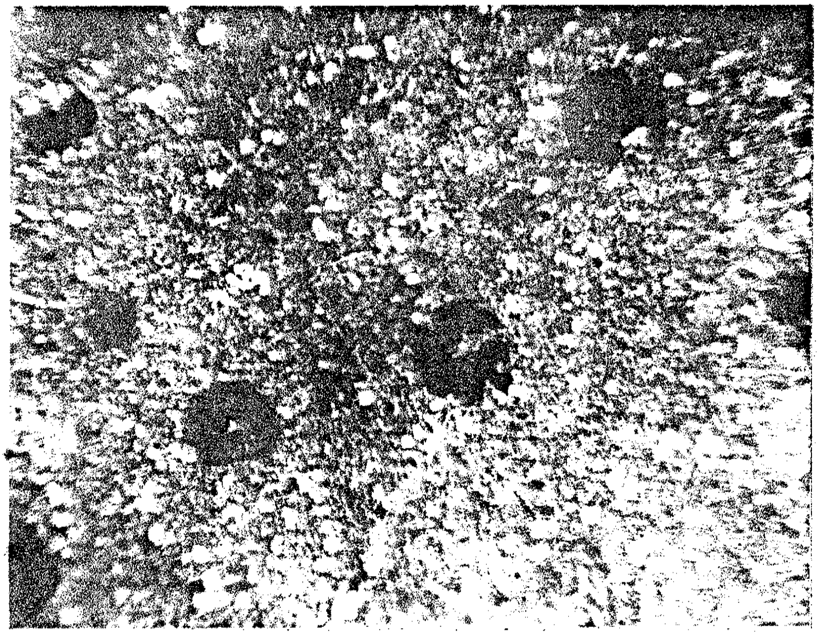
Thinsection of Early Pyrite in Rhyolite
(X80 Ordinary Light)

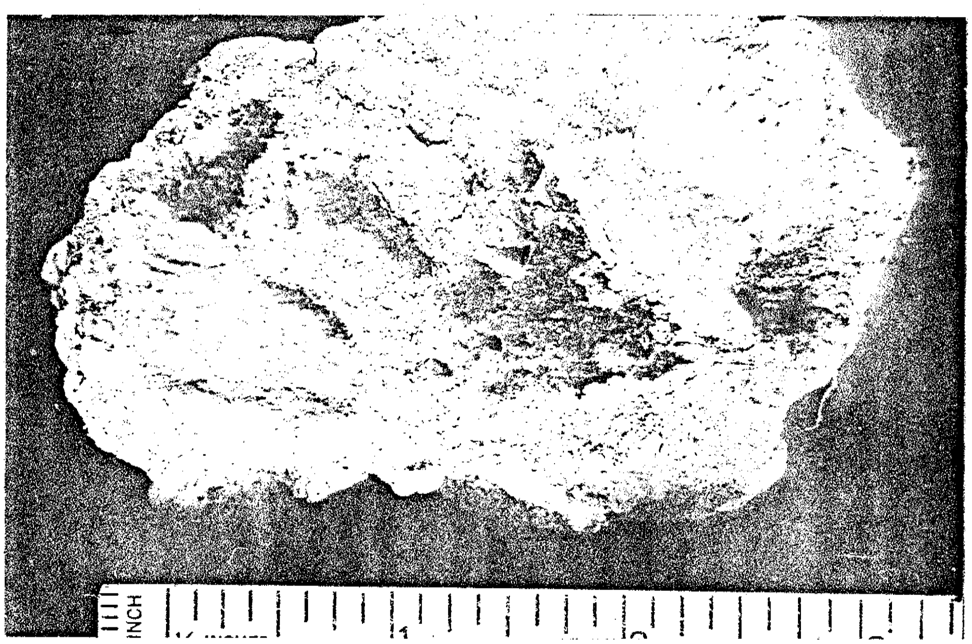
Cubic pyrite grains (dark) have been partially replaced by clays or previous material that embayed the pyrite, either by emplacements or inclusions within the pyrite crystals which then altered to clay. The groundmass is a cryptocrystalline aggregate of quartz-sericite-illite. Very small quartz veinlets that appear to cut through the pyrite are not recognizable in the photograph.

FIGURE 18

Pyritic Clay and Breccia
(Scale divisions equal 1/8 in.)

This material occurs as plastic masses which become mobile when sufficiently saturated with water. The clastic fragments are rounded from movement, and cemented by clays. The dark material is slightly weathered aggregates of massive pyrite.




INCH

Sphalerite was identified in one panned heavy-mineral concentrate as small grains about .25 mm in diameter. The sample was taken from andesite in place near the base of the sampled traverse on the east wall near the head of the canyon in Area #1. Another occurrence of a small vein of sphalerite with galena, pyrargyrite(?), and chalcopyrite was found on upper Bitter Creek, associated with Precambrian metamorphics in Area #6.

Fluorite, in a vein of brecciated quartz, crops out near the mouth of the canyon on the west side of Area #1. Pale greenish-blue fluorite is exposed in a vein quartz outcrop striking N 10° W and dipping 45° E. Associated manganese minerals are present as stain and wad.

Calcite occurs in veins that fill fractures in small brecciated faults. The calcite is white and fine-grained. A second type of calcite occurs locally in association with quartz dikes. This calcite is very coarse-grained and manganiferous. Its genetic relationships are uncertain due to the limited exposures.

Molybdenum and Copper Distribution

The entire Red River area shows geochemical copper anomalies, but specific copper minerals have been identified in only a few localities. A minor amount of chalcopyrite is exposed in the alteration zones in upper Mallett Creek and Bitter Creek, Areas #5, 6, and 7. Copper carbonate stains are associated with a large dike-like quartz mass south of Red River. The stains are confined to cracks and joints near the base of the massive quartz outcrop. A copper deposit, located due south of the town of Red River at the foot of the mountains, was mined by underground methods intermittently for a period of several years between 1867 and 1956. Most of the copper in this location is in the form of oxides and carbonates. Pyrite locally contains varying amounts of copper (as determined by emission spectrograph). There is, however, no over-all relationship between the abundance of pyrite and the amount of copper. Possibly the copper is associated with a particular generation of disseminated pyrite.

Molybdenum anomalies from rock samples and pyrite concentrates range up to 350 ppm and are not restricted to a specific rock type, nor is there a recognizable zonation of molybdenum content which would identify any central source of molybdenum.

Geochemical molybdenum determination[1] on selectively sampled rocks show that in areas quite rich in molybdenum, such as Sulfur Gulch, much of the country rock does not provide a favorable host for molybdenite, possibly due to impermeable country rock during the time of molybdenite deposition. A vein of molybdenite commonly is not bordered by a significant geochemical anomaly in the adjacent country

1. Courtesy of American Metal Climax, Inc.

rock, regardless of the intensity of alteration of the rock.

The only molybdenum-mineral-bearing material which was found in the subject area consists of very fine-grained molybdenite in quartz veins. Fine molybdenum flakes disseminated throughout the quartz give a dark gray to black cast to the veins. Five samples of quartz, ranging from milky white to nearly black, showed a gradation in molybdenum concentration directly related to the darkness of the quartz.

The molybdenite either crystallized from the transporting medium with quartz or was possibly reworked from some deeper source and carried in suspension in the silica-bearing solution. The small black flakes shown in Figs. 19 and 20 are molybdenite in vein quartz. In this sample the flakes are generally oriented nearly normal to the walls of the vein and suggest a general alignment which DeSitter (13) attributes to the motion of a slow viscous fluid.

Quartz grain boundaries in the vein are unrelated to the distribution of molybdenite flakes. Milky-white quartz in veins that cut and displace molybdenite-bearing quartz is probably the youngest quartz introduced. Supergene silicification from groundwaters is presently taking place throughout the district in favorable localities such as stream beds and alluvial gravels.

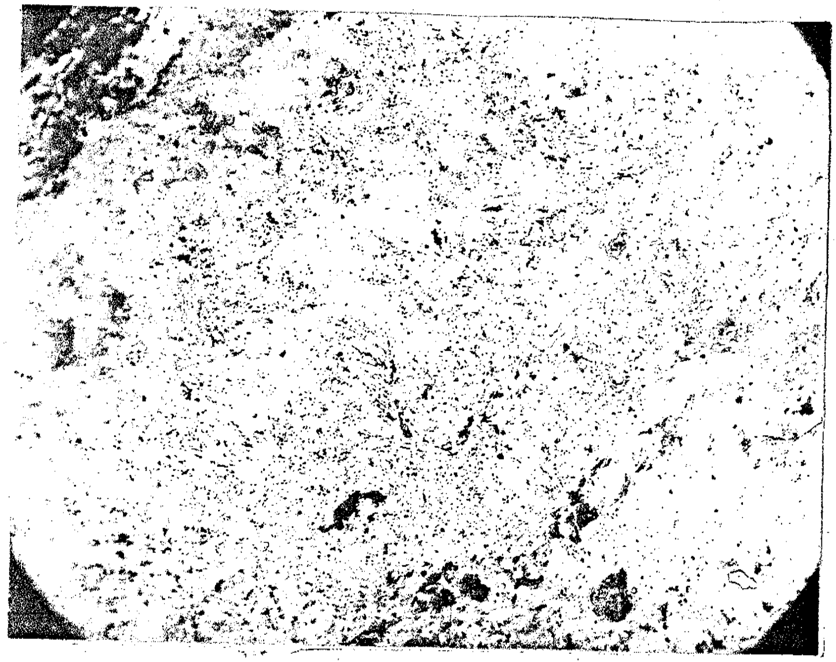
FIGURES 19 (upper) AND 20 (lower)

Thinsection of Molybdenum-Bearing Vein Quartz
(X45)

Vein quartz with minute flakes of black disseminated molybdenite. The general orientation of the molybdenite slivers is normal to the walls of the vein. The specimen is from a monzonite porphyry dike in Area #3.

Figure 19 (Ordinary Light) shows the orientation and texture of the molybdenite with relationship to the quartz grains and borders of the vein.

Figure 20 (X-nicols) shows the anhedral crystalline texture of the quartz. Molybdenite flakes show no controlled distribution related to grain boundaries of the quartz.



Weathering and Leaching Products

Minerals Formed

Supergene minerals formed during the weathering process include abundant rosettes of gypsum crystals in joints and fractures. These crystals reach four inches in length and are usually clear.

The iron released by weathering of pyrite has been precipitated as limonite, goethite, jarosite, halotrichite, and other hydrous sulfates. In the process of oxidation of pyrite, small crystals of sulfur form in the rock. Potash(?) alum, wad, clays, and quartz were also products of weathering. Several species of hydrous sulfates form as efflorescent crusts on rocks at the base of cliffs, where evaporation concentrates the sulfates. Most of these minerals redissolve during the wet seasons, but alum minerals as much as one foot thick have been found.

Water

Three samples of surface water, collected in the fall several weeks after the last summer rains had fallen, were analyzed qualitatively for trace elements. The samples were taken from stream beds in Areas #1, 2, and 5.

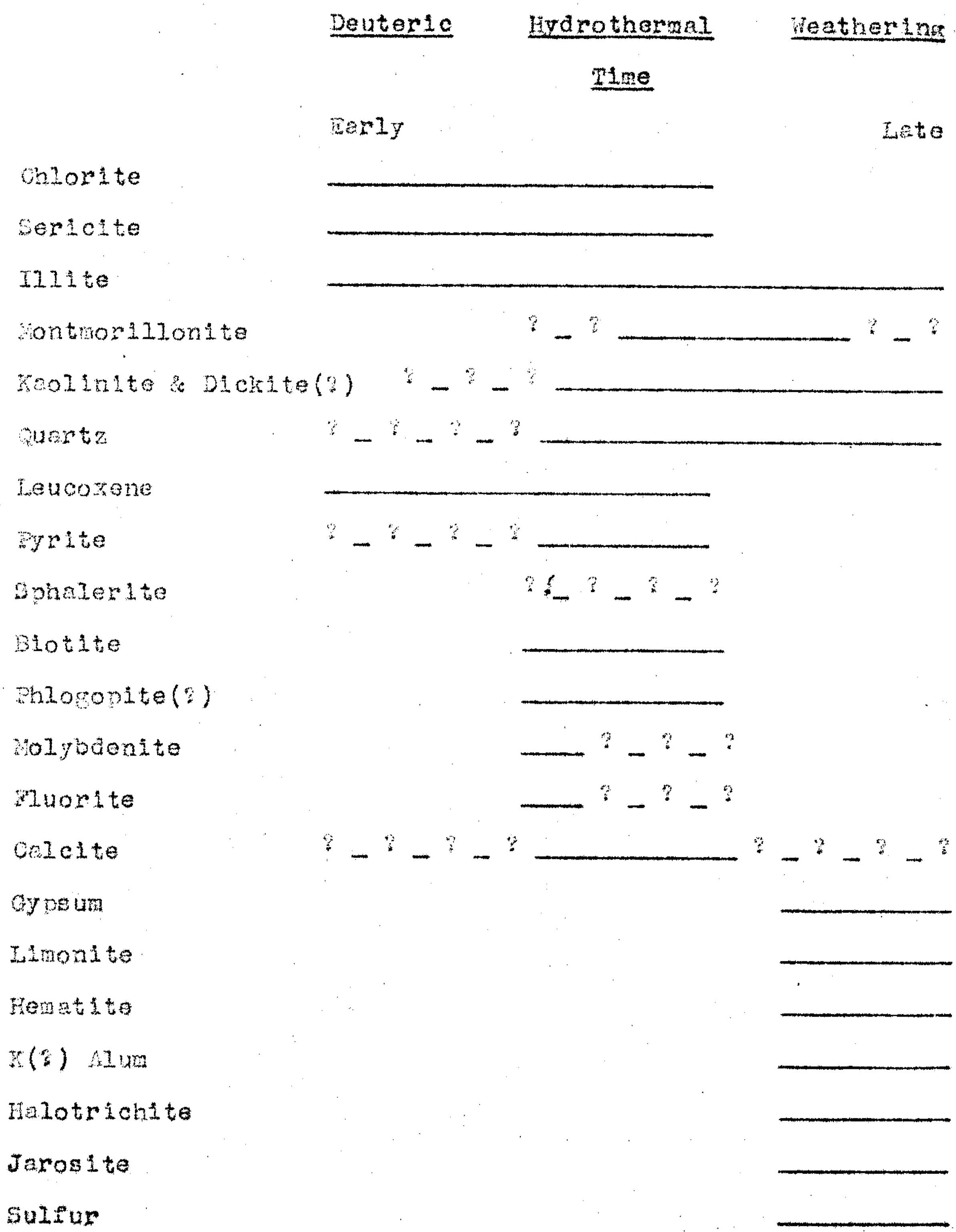
The pH of all these water samples was about 2. Emission spectrographic analyses of dissolved solids revealed a close similarity in the content of many elements. Iron, aluminum, silica, and titanium were abundant in all the samples.

Differences in composition were correlable with minerals that are unique to specific areas. Lead, zinc, silver(?), and strong copper lines were recorded by spectrographic methods for the water sample from Area #5. Zinc also was identified in water from Area #1.

Paragenesis

A generalized paragenetic summary of the alteration products is given in Fig. 21. Applicability of this sequence to areas other than those studied in this investigation has not been established. The sequence of clay mineral formation implies a progressive migration of alteration zones away from the source of hydrothermal fluids rather than a real time difference in their formation.

FIGURE 21
PARAGENETIC CHART



CONCLUSIONS

Tertiary volcanic and intrusive rocks overlie and cut Paleozoic and Precambrian rocks in the Red River district. The Tertiary volcanics suffered some deuteric alteration from the escaping gases of the extrusive sequence. The youngest igneous rocks, monzonite to quartz monzonite porphyry, suffered intense hydrothermal alteration along with the volcanics and older rocks.

Quartz, sericite, and illite comprise the end products of alteration in a zone adjacent to an intermediate kaolinitic zone. A less intencely altered zone is characterized by chloritized rock.

Quartz was introduced continually throughout the hydrothermal stage. An earlier phase of dark molybdenite-bearing quartz is cut and displaced by later white quartz.

Chemical analyses of rocks adjacent to molybdenite veins near the Questa mine showed only insignificant amounts of molybdenum in the volcanic country rocks.

Copper oxides, carbonates, and sulfides occur locally in the district. Geochemical copper anomalies are, however, attributed to the copper content of pyrite. The copper anomalies are not related directly to the abundance of disseminated pyrite, but are possibly associated with a particular stage in the deposition of pyrite.

Pyrite makes up 3-4 percent of the rock. It occurs both as massive veins and disseminated in cubic, pyritohedral, and octahedral crystals. Most disseminated pyrite is cubic, but it locally grades into the other forms. Octahedral pyrite is generally very fine-grained, locally abundant, and possibly more compatible with rhyolitic host rocks than are the other forms. A correlation is suggested between pyritohedral habit of pyrite and the presence of sphalerite.

Sphalerite and galena appear in minor amounts in the Precambrian metamorphic terrane. Some sphalerite, as well as fluorite, was deposited in the volcanic rocks.

Surface waters draining the areas of alteration are strongly acidic from weathering pyrite. These waters contain trace elements that are similar, but which reflect even minor minerals unique to a particular drainage basin.

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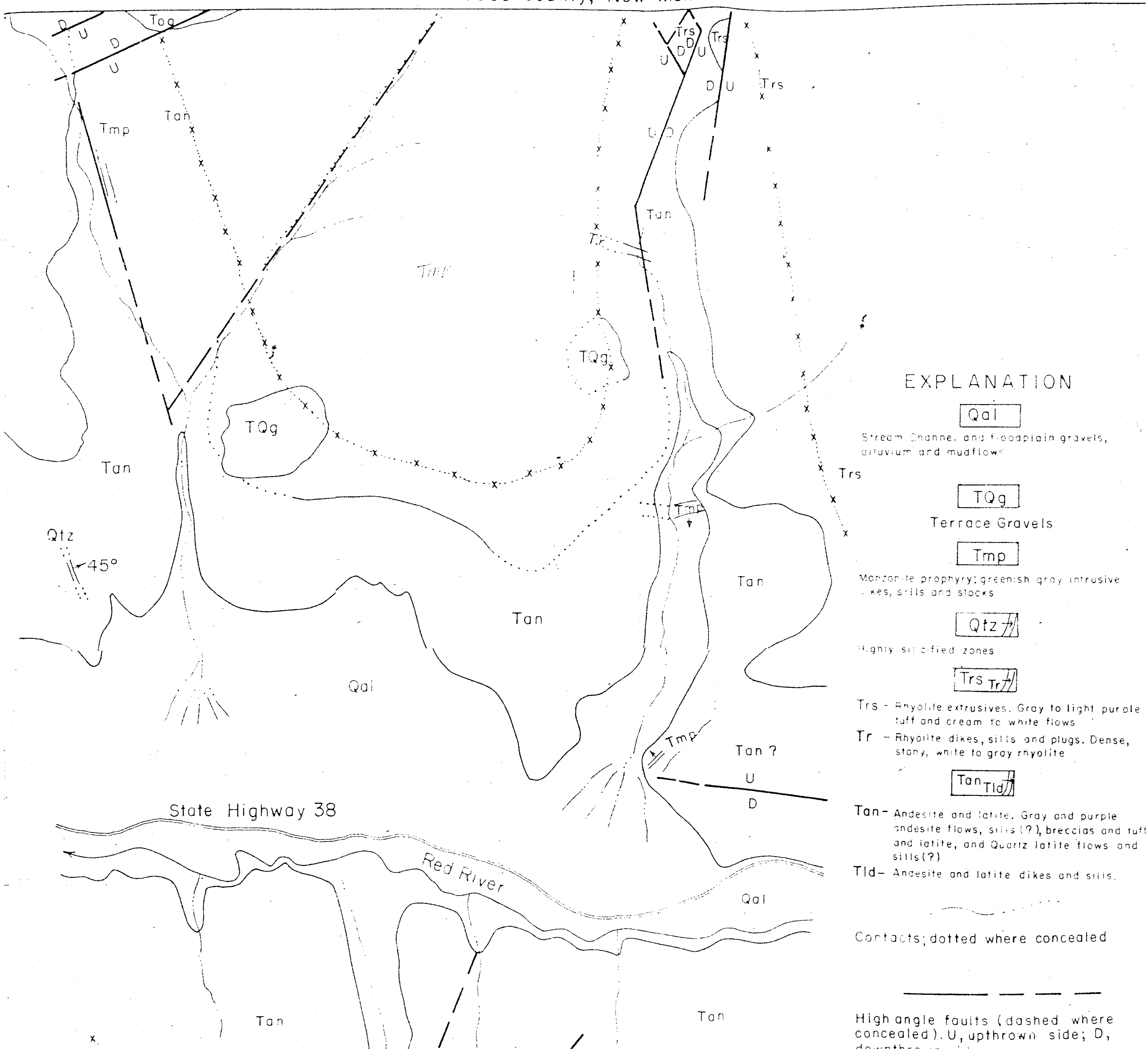
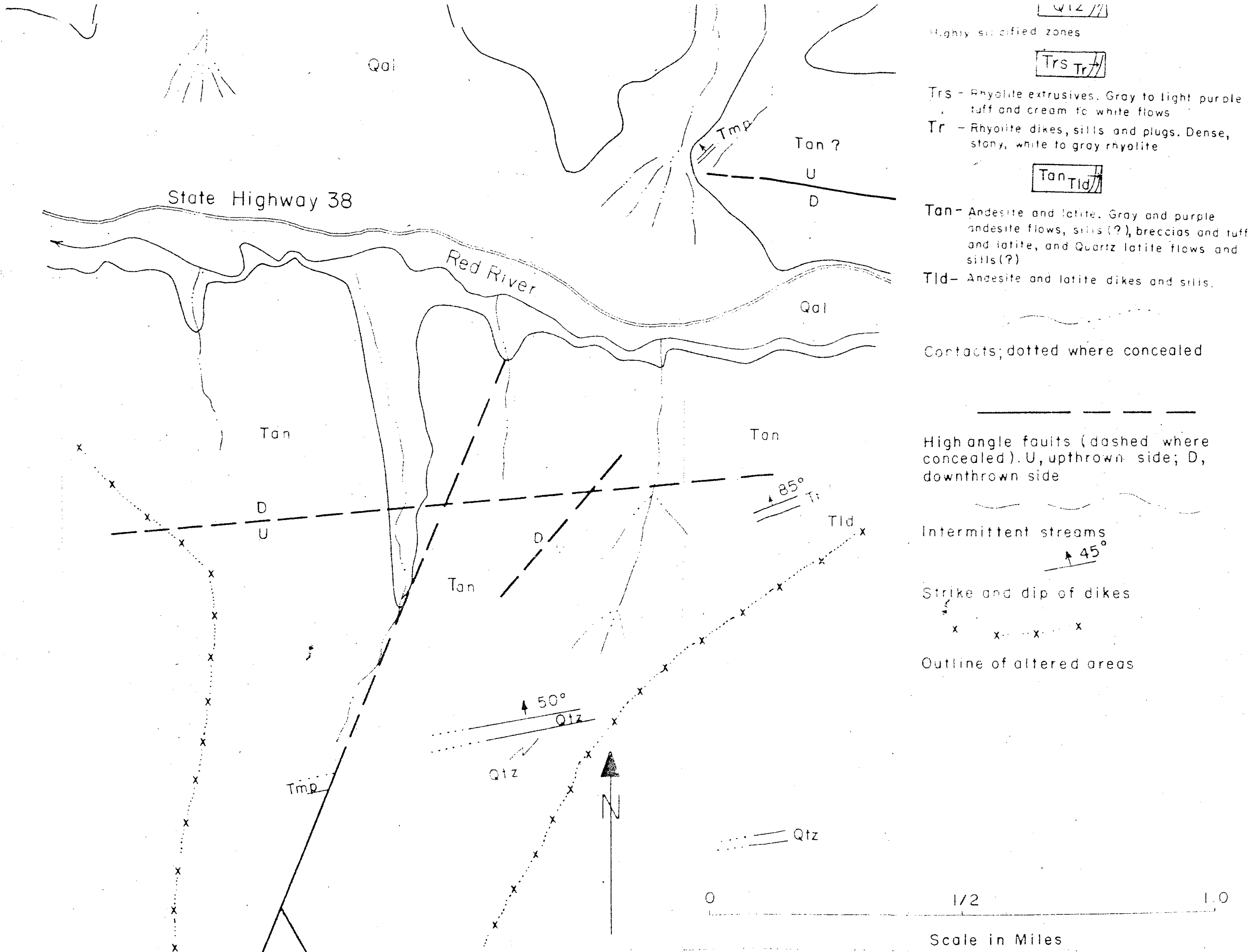
Date: May 31, 1962

Plate 3

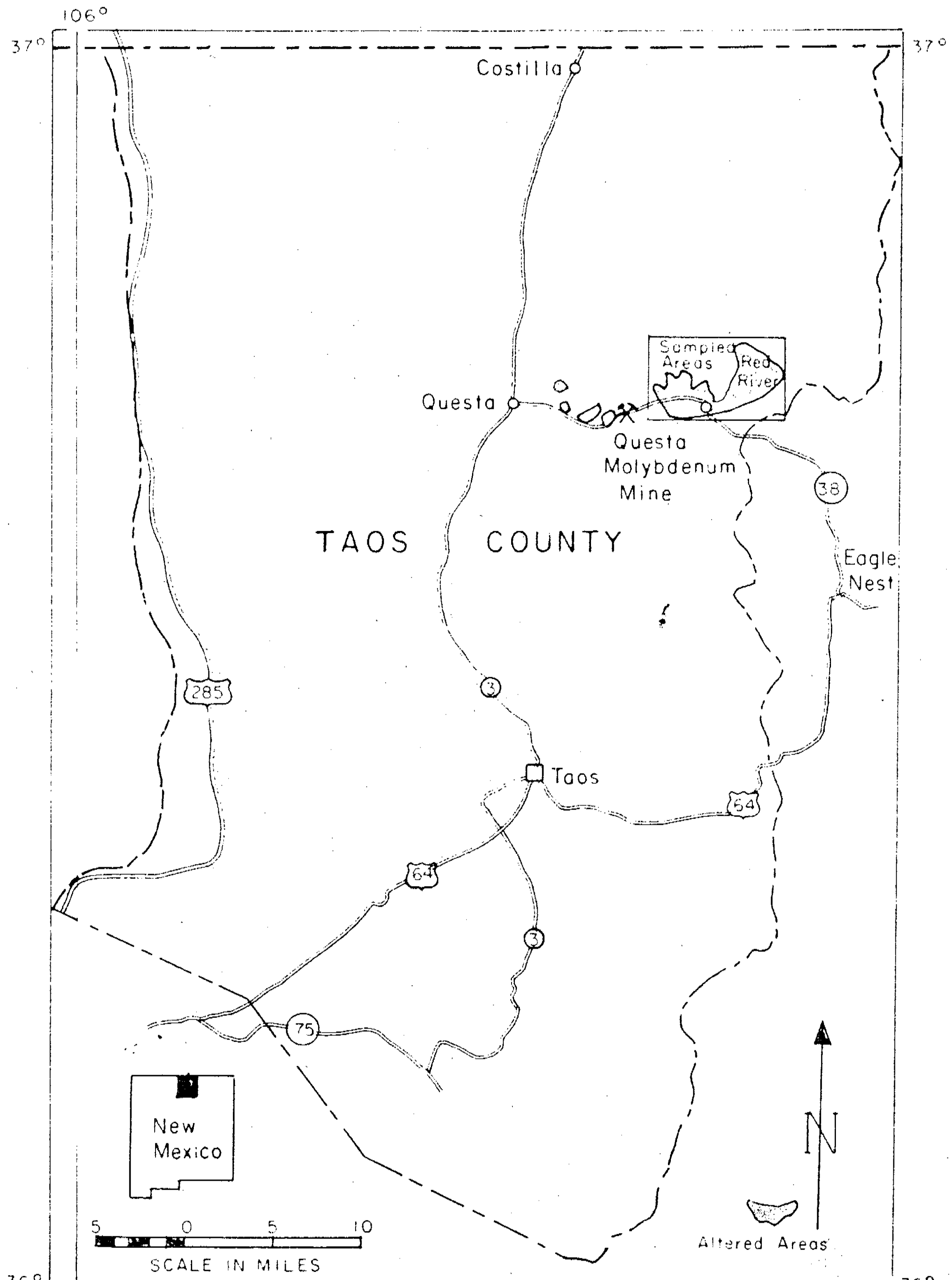
GEOLOGIC MAP
of Altered Areas Immediately West of Red River
Taos County, New Mexico



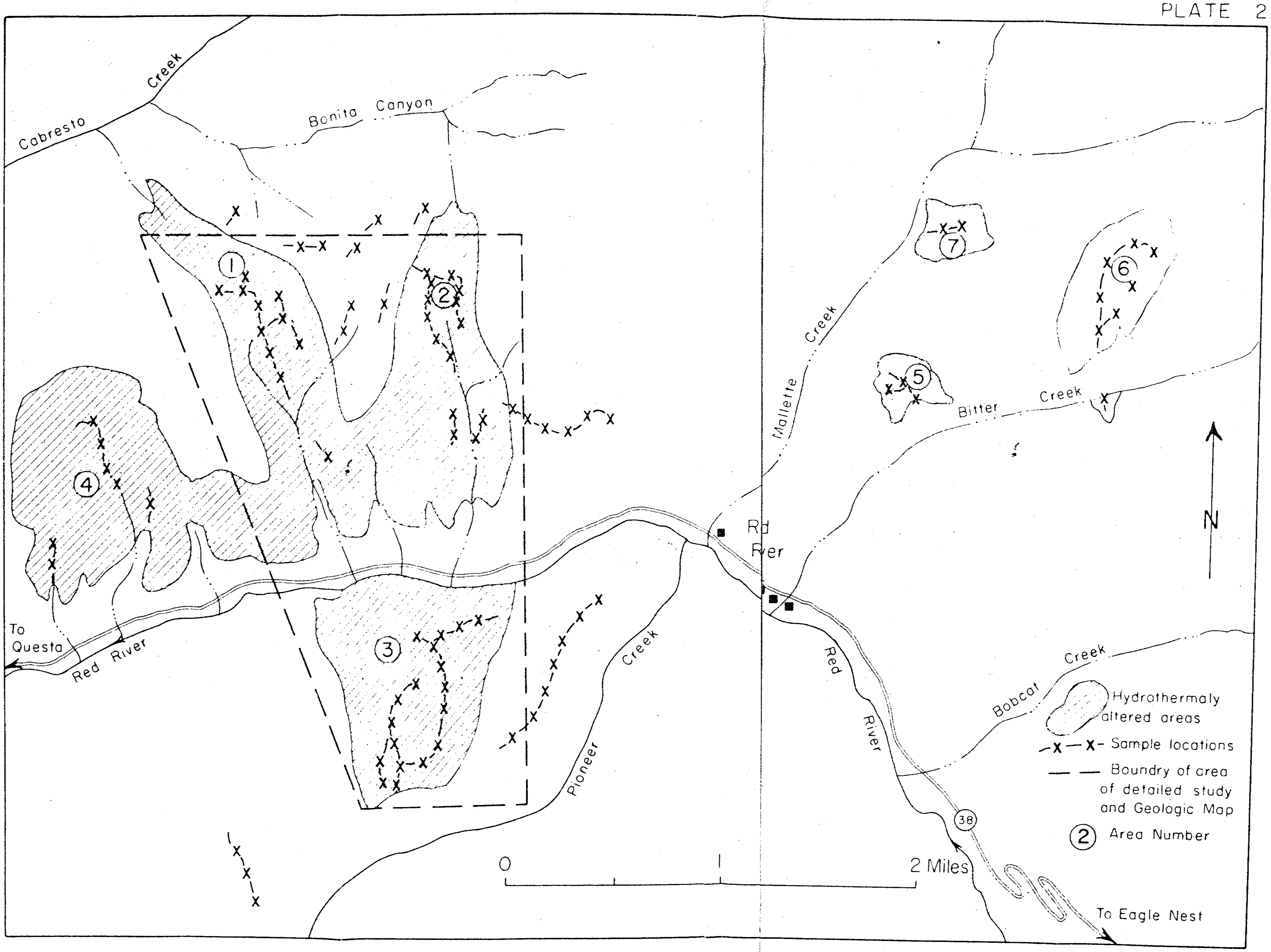


Geology by Marvin W. Ratcliff supplemented by unpublished work of J. H. Schilling and P. F. McKinlay

Plate I



Index Map of Taos County Showing Area of Plate 2



LOCATION MAP