GEOLOGY AND STRUCTURAL ENVIRONMENT OF THE SIERRITA MOUNTAINS, PIMA COUNTY, ARIZONA

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INTRODUCTION

Geologic mapping was undertaken in the Sierrita Mountains as part of a Doctoral program at the University of Arizona, Tucson (Fig. 1).

During the study, approximately 35 square miles was mapped in detail, with particular attention given to specific areas of great or significant structural complexity and their relation to mineralization in the vicinity.

A combination of field studies and photogeologic interpretation was used in order to define regional and local structural controls for disseminated copper-molybdenum mineralization in and adjacent to the study area.

Gratitude is expressed to the faculty of the University of Arizona, Department of Geology for their assistance in this work and to Bear Creek Mining Company for making numerous reports and drill cores available for study.

SUMMARY AND CONCLUSIONS

Rocks ranging from Lower (?) Cretaceous through Quaternary in age are exposed in the eastern Sierrita Mountains. A thick sequence of andesitic and rhyolitic pyroclastics and flows, the Oxframe Formation of Lower (?) Cretaceous age, is unconformably overlain by dominantly rhyolitic pyroclastics of Upper (?) Cretaceous age. The entire volcanic sequence is intruded by a complex group of intrusives, ranging from diorite to alaskite and including quartz monzonite, granodiorite, and granite, as well as dikes of basaltic, andesitic and latitic composition. The intrusives are early Tertiary in age, related to the Laramide orogeny. Though compositionally and geographically separate, the intrusives appear to represent products of the differentiation of a single magmatic source and were emplaced over a very short span of time (approximately 5 million years).

Structural elements defined include (1) a post-volcanic, pre-intrusive east-west compressional force which produced northwesterly-trending, high-angle wrench faults characterized by left lateral movement, (2) a similar east-west compressional episode, post-intrusive in age, which produced northeasterly-trending wrench faults, (3) domal uplift associated with emplacement of the intrusives which tilted the volcanic sequence and produced essentially north-trending faults in the pediment east of the range.

Mineralization, ranging from extensive porphyry copper-type concentrations of copper and molybdenum to small high-grade veins containing lead, copper, silver and gold, is present in the district. Small uraniferous

concentrations occur at one locality. Radiometric age dating indicates a close correlation between ore deposition and intrusion of the equigranular granodiorite, suggesting a genetic relationship between the two. Structural control of the Esperanza Wash copper-molybdenum deposit is very apparent. Localization has occurred at the intersection of major northwesterly and northeasterly fault zones.

The hydrothermal phase of the intrusive activity includes metasomatic introduction of biotite, quartz and orthoclase. A crude zonal pattern of

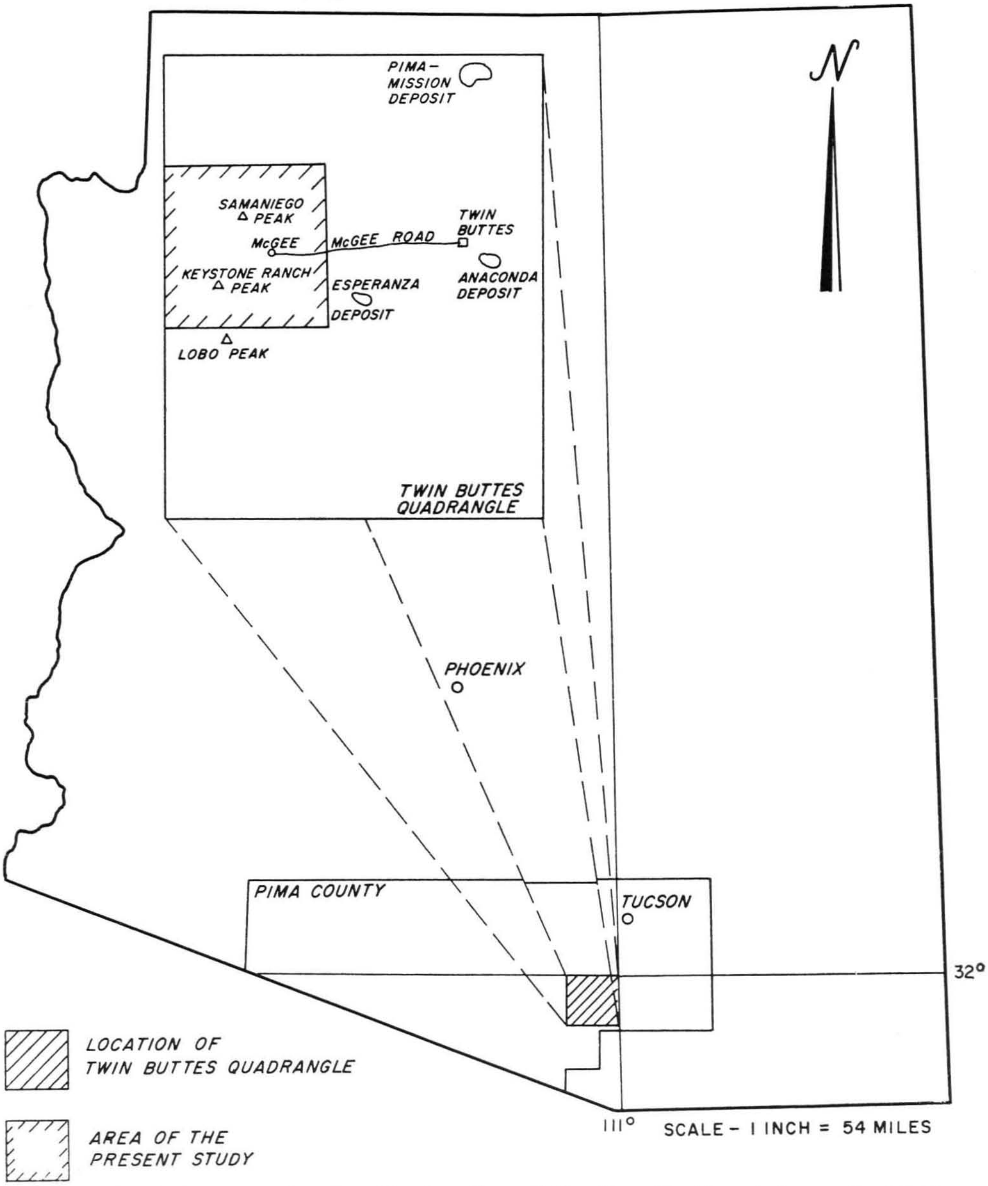


FIGURE 1. Index map showing the location of the Sierrita Mountains and vicinity.

sericite and epidote is present in the mineralized area. Locally, the sulfide mineralogy is at least in part controlled by composition of the wallrock, with molybdenite associated with the acidic intrusives and calcopyrite-pyrite with the more basic diorite body.

DESCRIPTIVE GEOLOGY

Introduction

The Sierrita Mountains are situated in the heart of the Basin and Range country of southern Arizona. They represent a range separated spatially from others in the area. This tends to make structural correlations difficult and stratigraphic correlations tenuous. In this regard, the work being done by the University of Arizona Geochronology Laboratory (Damon, 1964) in dating the rocks and geologic events in southern Arizona is of great value.

Rocks of Paleozoic age are exposed in the Twin Buttes area and also along the western flank of the range. Within the area specifically covered by this study, no rocks older than Cretaceous were recognized. Cretaceous and Tertiary igneous rocks, both intrusive and extrusive, constitute the bulk of the rocks mapped. An intrusive episode of Tertiary age followed the extrusion of a thick series of intermediate to acid volcanic rocks. The volcanics cover much of the southern and western portions of the area mapped, and in general, form a wide belt which wraps around the intrusive core of the Sierritas. This intrusive core was the site of local uplift and doming in early Tertiary time, which has produced a gentle to moderate dip in the volcanic rocks.

Two main periods of structural activity were recognized, one late Cretaceous and one mid-Tertiary. These two periods bracket the intrusion of the igneous complex.

A complex group of intermediate to acid intrusive rocks occurs over much of the area mapped. They are intrusive into an equally complex sequence of andesitic and rhyolitic volcanics. The volcanic sequence includes flows, tuff breccias, welded and nonwelded tuffs and agglomerates with thin interbeds of clastic sediments. This sequence is present over much of the southern and western part of the range. Thoms (personal communication) mapped a similar and more extensive section on the west side of the range. The intrusive complex ranges in composition from diorite to alaskite and includes quartz monzonite, granodiorite, granite and latite, as well as a variety of dike rocks.

The structural history of the area is nearly as complicated as the rocks involved, with two major periods of deformation represented over the entire region and numerous local deformational episodes. The early period of deformation occurred subsequent to the deposition of the volcanics, while the later deformational episode followed intrusion of the igneous complex.

Mineralization ranging from extensive "porphyry copper-type" concentrations of copper and molybdenum to small high-grade veins of lead, silver and gold is present in the district. Small concentrations of uranium minerals are present at one locality. Though post-intrusive in age, the mineralization is controlled by both early and late structural trends.

The area, as a whole, is rather typical of the ranges of southern Arizona. The geologic and structural history of the Cretaceous-Tertiary interval is extremely complex and is marked by abundant igneous activity, both intrusive and extrusive.

Volcanic Rocks

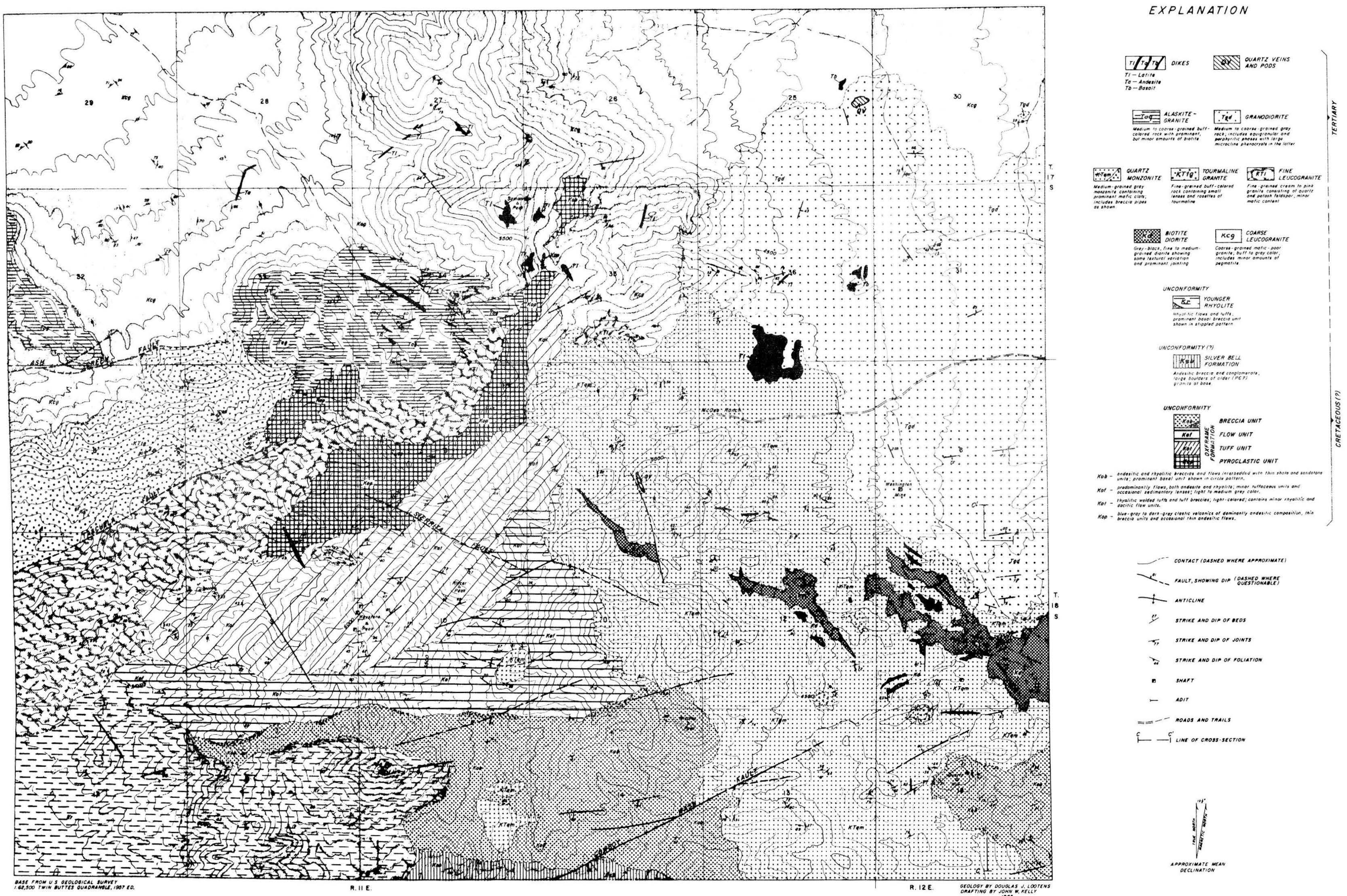
A complex sequence of Cretaceous (?) volcanic rocks occurs over much of the southern part of the map area. Broadly speaking, the sequence is a group of alternating flows and clastic volcanic accumulations with some interbedded sedimentary units. For the most part, the sediments are not continuous over great lateral distances but appear to represent local areas of sedimentation under subaerial conditions which occurred during the volcanism.

A three-fold subdivision of the volcanics has been made, from oldest to youngest: the Oxframe Formation, the Silver Bell Formation, and the younger rhyolite. The Oxframe Formation has been further subdivided into four units which represent a general classification to assist in field mapping and interpretation of the structural and volcanic history of the area.

OXFRAME FORMATION

The Oxframe Formation is named for exposures of the sequence which occur in Oxframe Canyon east of Red Boy Peak. The formation consists of a thick sequence of andesitic and rhyolitic volcanics which occur as flows, flow breccias, agglomerates, tuff breccias, welded and nonwelded tuffs. Interbedded with the volcanics, particularly in the upper part of the formation, are thin sedimentary horizons consisting of shale, sandstone, quartzite and occasional local conglomeratic zones. A total thickness of 6,000-6,500 feet is represented by the formation. The base of the formation is not exposed and the actual thickness of it may be greater than that exposed. This great thickness of volcanic rocks has been broken down into four units, based on the predominance of various types of volcanic accumulations. These units are, from top to bottom of the formation, the breccia unit, flow unit, tuff unit and pyroclastic unit. Virtually all types of volcanic deposits are represented in each unit, but one or another type predominates.

Rocks assigned to the Oxframe Formation are exposed over about six square miles of the south-central and central part of the map area. They are unconformably overlain by rocks of the Silver Bell and younger rhyolite formations and intruded by various of the hypabyssal igneous bodies. The



GEOLOGIC MAP OF THE EASTERN SIERRITA MOUNTAINS, PIMA COUNTY, ARIZONA

SCALE 1:12,000

1000 500 0 500 1000 2000 3000 4000 5000 FEET

[PUBLISHED SCALE APPROX. 1:44,000]

CONTOUR INTERVAL - 100 FEET
DATUM IS MEAN SEA LEVEL

[Bound between p. 36 and 37 in original publication] volcanics dip away from the core of the range at moderate (40°-50°) angles. They form an incomplete arc around the south and east sides of the range. The strike of the formation gradually changes from about N70° W in the sauthwestern part of the area, through east-west, to about N20°-30° E along the eastern flank of the mountains.

The character of the exposures of these rocks varies widely due to the great disparity of compositions and modes of accumulation involved in their deposition. In general, the flow units are the most resistant to erosion, while the tuff horizons are most readily eroded.

The base of the Oxframe Formation is nowhere exposed in the map area, having been cut out by later intrusives. This makes the placing of an older limit for the age of the Oxframe somewhat speculative. A very similar sequence of volcanics and interbedded sediments was mapped on the west side of the range. In that area, the volcanics rest unconformably upon probable Paleozoic sediments (Thoms, personal communication). Evidence from other ranges in southern Arizona, which will be discussed in greater detail in a later section, indicate the widespread occurrence of extrusive and explosive volcanic rocks which have been assigned to the Cretaceous. The Cat Mountain Rhyolite has been dated (Bikerman, 1963, p. 80) at about 65 million years. The younger rhyolite in the Sierritas is very similar to the Cat Mountain sequence and has been tentatively correlated with it. Thus, if this correlation is valid, the Oxframe beds are pre-Cat Mountain in age and, based on western Sierrita exposures, post-Paleozoic. The volcanics on the west side of the range underlie beds which resemble the Recreation-Amole sequence in the Tucson Mountains. Bryant (1952, p. 42) indicates that the Amole is probable lower Cretaceous. It seems most plausible that the Oxframe Formation is pre-Amole, but still part of the Cretaceous.

SILVER BELL FORMATION

The Silver Bell Formation, named by Courtright (1958, p. 7) for occurrences near the Silver Bell mine, occurs as a narrow, east-west-trending band along the extreme southern margin of the map area. The formation has been adequately described in the literature (Courtright, 1958; Richard and Courtright, 1960; Lynch, 1965) and will only be briefly described here.

About 500 feet of Silver Bell-type rocks are exposed in the map area. Southward from the limits mapped, additional members of the formation crop out. The total thickness of the entire sequence in the area is probably in the range of 1,000 feet.

A sequence of predominantly andesitic mudflows, agglomerates and breccias are interbedded with occasional thin andesitic flows. The sequence is dark gray to purple in color. The agglomeratic and breccia zones are largely composed of andesite fragments of varying sizes set in an andesitic matrix of probable mudflow origin. Near the base, coarse fragments and boulders of granitic rock up to two feet across are enclosed in the andesitic matrix. These granitic fragments do not resemble any of the intrusives encountered elsewhere in the area and may represent Precambrian(?) intrusives. Thoms (personal communication) felt that similar boulders and cobbles occurring in Silver Bell-type accumulations on the west side of the range might be fragments of intrusives which he mapped as pre-Cretaceous.

The accumulation of Silver Bell volcanics probably occurred in late Cretaceous time. Richard and Courtright (1960) showed that accumulations similar to the Silver Bell Formation are widespread in southeastern Arizona and they felt that such accumulations took place early in the Tertiary representing the early stages of a long and widespread volcanic episode.

Damon (1964, p. 15) provided a K-Ar date of 65 million years for the Cat Mountain Rhyolite in the Tucson Mountains. Richard and Courtright (1960, p. 2) considered the acid pyroclastics overlying the Silver Bell at the type locality to be the equivalent of the Cat Mountain type in the Silver Bell Mountains. On this basis, the Silver Bell Formation can be no younger than late Upper Cretaceous.

YOUNGER RHYOLITE

About 300 to 500 feet of predominantly acidic tuffs, both welded and nonwelded, are exposed in the southwestern corner of the map area. Like the Silver Bell Formation, the younger rhyolite is more extensive south of the area mapped. The younger rhyolite lies unconformably on the Oxframe and Silver Bell Formations. The older sequence dips about 40° to 50°S, while dips on the younger rhyolite average 20° to 30°S. The sequence strikes approximately east-west or slightly north of west.

The younger rhyolite consists of three main tuffaceous beds, each about 100 feet thick, separated by and occasionally intercalated with thin rhyolite flows. The base of the unit is locally marked by a prominent breccia zone up to 50 feet thick.

The basal breccia unit consists of subangular volcanic fragments of older extrusive and pyroclastic origin set in a very fine-grained tuffaceous groundmass. The sporadic occurrence of the unit suggests that it may represent an erosional accumulation upon which later tuffaceous material was deposited. Other possibilities include an explosive origin as suggested by Bikerman (1963, p. 65) for similar rocks which occur at the base of the Cat Mountain Formation or formation as a tectonic breccia as postulated by Kinnison (1959) for the Tucson Mountain chaotic breccia.

The tuffaceous units are buff to gray in color and closely resemble some of the tuffaceous members of the Oxframe formation. They are of the vitric-crystal variety and consist of a mixture of glass shards, broken crystals of quartz, sanidine and hornblende and small lenticular pumie fragments. Devitrification has destroyed much of the original texture and the vitric portion of the rock is largely a crypto-crystalline mass of quartz and feldspar. Partial welding of the tuff has occurred in the lower portion of both the lower and upper members. The middle tuff member is essentially nonwelded. The change from welded to nonwelded texture in the units where both occur is a gradational one. In the welded zones, the pumice fragments are flattened and, in some cases, further elongated from their original lenticular shape.

Thin porphyritic rhyolite flows separate the tuffaceous horizons. Phenocrysts of quartz, and occasionally plagioclase, are set in a fine-grained matrix of quartz, feldspar, hornblende and magnetite. Flow banding is prominent and wraps around the phenocrysts. The flows are light gray to nearly white and form quite resistant outcrops.

The younger rhyolite closely resembles the Cat Mountain Rhyolite in the Tucson Mountains (see Brown, 1939 and Bikerman, 1963). The dominantly acidic pyroclastic nature of the bulk of the Cat Mountain sequence together with the associated rhyolite flows are very much like those in the Sierrita Mountains. No unit comparable to the chaotic breccia which Bikerman (1963, p. 87) places at the base of the Cat Mountain sequence is present in the Sierrita section unless the discontinuous breccia at the base is considered to be correlative with the chaotic breccia. Though the two are quite dissimilar in appearance, they may both represent a common mode of origin. If the younger rhyolite is correlative in time with the Cat Mountain Rhyolite the age of the younger rhyolite would be late Upper Cretaceous.

The younger rhyolite overlies the Silver Bell Formation and is intruded by fine leucogranite. The fine leucogranite is known to be older than the granodiorite (60 million years) and younger than all of the volcanics.

The bulk of the evidence would seem to favor a correlation with the Cat Mountain sequence and hence, a late Upper Cretaceous age.

Igneous Rocks

Approximately 60-70 percent of the area mapped consists of intrusive igneous rocks. While a wide variety of individual types is represented, the intrusives are, as a group, intermediate to acid in composition, medium grained in texture and hypabyssal in origin. They occur over the entire eastern half of the area, much of the area north of Samaniego Peak and as a north-south strip along the western border of the area. Except for that part of the area lying on the Sierrita pediment, outcrops are generally good. East of the McGee Ranch, the outcrops become somewhat spotty and are continuous only along the major drainage courses.

Though seven major intrusive igneous varieties have been mapped, as well as several dike rocks, it is felt that all were emplaced during late Cretaceous or Tertiary time. Creasey and Kistler (1963) have shown that the equigranular granodiorite, defined originally by Cooper (1960) and mapped extensively in the present study, was emplaced during very latest

Cretaceous or earliest Tertiary times. The intrusion of the equigranular granodiorite was preceded by the emplacement of the biotite diorite of Cretaceous age. Igneous rocks of undoubted Tertiary age include the alaskite-granite, the latite plugs and the aplite dikes which occur over much of the area.

BIOTITE DIORITE

A body of biotite diorite crops out in the southeastern part of the area mapped. It covers about two square miles just west of the Esperanza mine on the extreme eastern edge of the area. It appears to be bounded on the east side by the Esperanza Wash fault, but rocks mapped as andesite in the Esperanza Pit by Duval Corporation geologists (Lynch, 1965, in preparation) may be equivalent to the biotite diorite. The biotite diorite forms a roughly rectangular outcrop pattern with the long dimension of the rectangle trending approximately N70°W. This trend is a representation of the early north-west-trending structures described by Cooper (1960). It is further accentuated by the existence, at the northwest end of the main biotite diorite outcrop area, of two parallel, elongate prongs of diorite which extend outward from the main diorite mass. In addition, small outcrops are scattered through the quartz monzonite and, though some of them reach significant size, they are thought to represent blocks caught up in the quartz monzonite.

COARSE-GRAINED GRANITE

The northern part of the map area is occupied by a coarse-grained gray granite characterized by a low mafic content. It forms a wide band which lies across the north end of the range, extending well out into the pediment on both the east and west sides. Though the rock shows no discernible difference, its outcrop pattern is quite different in the pediment than it is in the mountains. In the lower areas, outcrops are generally confined to washes although inter-wash areas may consist of smooth outcrops of granite covered by a thin layer of granite detritus. Outcrops are generally deeply weathered and very soft. They vary from buff to a fairly deep red-brown color. Some of the red color may be due to the presence of small amounts of iron oxide. Outcrops of the granite in the mountain range itself are much more prominent than those just described. The rock is buff to gray in color and the outcrops are very rounded. Jointing is very prominent in some areas. Granite areas are covered by weathered granite detritus consisting of granular rubble up to one inch in size.

BIOTITE QUARTZ MONZONITE

Biotite quartz monzonite occurs extensively over much of the pediment east of the main range and south of the McGee Road. It is in contact with Cretaceous (?) volcanics on the slopes west of the McGee Ranch and also in the extreme southeastern part of the area in the vicinity of Quartz Hill. In both of these areas, the quartz monzonite intrudes the volcanic sequence although at the Quartz Hill locality the evidence is not unequivocal. Quartz monzonite surrounds the biotite diorite on three sides in Section 7 and in this area, its position, like that of the diorite, appears to be controlled by the Sierrita fault trend. North of the diorite, the quartz monzonite is intruded by equigranular granodiorite. When mapping was first initiated in this area, it was felt that the rock lying between the diorite and unquestioned outcrops of granodiorite represented a border phase of the granodiorite because it resembled that rock quite closely. There were some differences and Cooper (1960, p. 70) referred to the rocks here as "somewhat atypical granodiorite." Continued mapping, however, showed that in the area of the granodiorite intrusion, the quartz monzonite assumed a character quite distinct from that of the granodiorite. It is now felt that the outcrops north of the diorite, rather than being atypical granodiorite, are somewhat atypical quartz monzonite. Contacts between the two rocks can be seen, though their delineation is made difficult by the great similarity of the two and the scarcity of good exposures.

TOURMALINE GRANITE

One of the smaller intrusives mapped is a tourmaline-bearing granite which crops out over an area of about one square mile in the west-central part of the map area. Outcrops of the same rock are more extensive down the western slopes of the range (Thoms, personal communication). Tourmaline granite is bounded on the south by fine-grained leucogranite, the contact representing the trace of the Ash Creek fault. Coarse-grained granite bounds the tourmaline-bearing variety on the north and on the east, alaskite-granite and the lowest unit of the Oxframe volcanics are in contact with tourmaline granite. The emplacement of the granite was, at least in a general sense, structurally controlled, elongated along a northeasterly trend.

The rock forms good exposures which weather to distinctive dark gray color. Along the trace of the Tascuela fault, the dark tourmaline granite outcrops are in sharp contrast to the buff-hued fine-grained leucagranite exposures south of the fault.

FINE-GRAINED LEUCOGRANITE

An elongate body of a fine-grained light-colored granite occurs in the west-central part of the map area. It is elongate in a northeast-southwest direction, parallel to major faults of this trend. Indeed, it is bounded on the northwest side by the Tascuela fault. Though present existence of the Tascuela fault structure post-dates the intrusive, it is apparent that a northeasterly-trending zone of weakness in the area acted as the major structural control on the location and shape of the leucogranite. A small body of leucogranite occurs on the east slope of the range, southeast of Samaniego

Peak. It lies along the contact between the quartz monzonite and the coarse-grained granite. It also occurs on the eastward extension of the Tascuela fault zone.

Exposures of leucogranite are generally good although contacts in the easternmost body are often difficult to see. In the main body, the fault contact with the tourmaline granite is easy to follow and both the alaskite and coarse-grained granites can be distinguished texturally from the fine-grained leucogranite. The predominantly gray hues of the Oxframe Formation and the younger rhyolite are in sharp contrast to the pinkish-yellow color of the leucogranite. Outcrops weather to somewhat rounded shapes although blocky occurrences along washes are not uncommon. Joint patterns are well-developed in the western body, but less apparent further east.

EQUIGRANULAR GRANODIORITE

The east central part of the map area is occupied by equigranular granodiorite, a rock named and described by Cooper (1960) in his preliminary study on the geology of the Pima mining district. In this study, the rock mapped as equigranular granodiorite actually includes a variety of textural types including a porphyritic phase with feldspar phenocrysts up to two inches in length. Lutton (1958) distinguishes between porphyritic and non-porphyritic phases of the rock, but Cooper (1960) includes them all as a single map unit. The convention established by Cooper has been followed here not so much because the different units were not distinguishable and mappable in the field, but because it was felt that the textural differences, rather than representing different rock types, actually represented phases of the same magmatic surge.

As a rule, the equigranular granodiorite does not form bold outcrops, although it forms considerably better outcrops than the biotite diorite. It weathers to a buff to gray outcrop in which the phenocrysts, where present, appear as milky white blotches. Outcrops of granodiorite are most common along dry washes. In places where the stream gradient is higher and the stream channel has been scoured clean the granodiorite outcrops are a light gray color, very near to that seen on a freshly-broken surface. In general, weathered outcrops of granodiorite are very soft and crumbly. Rubbly, granular surfaces are characteristic of areas underlain by the granodiorite. A few, more resistant, granodiorite outcrops stand up as isolated knobs five to fifteen feet high.

ALASKITE-GRANITE

Two bodies of alaskite-granite occur in the area mapped. One is located at the extreme western edge of the area, well down the northwest flank of the mountains. Its occurrence here is not extensive, but Thoms (personal communication) has mapped the same rock more extensively further to the west. The other occurrence of alaskite-granite is in the north-central part of the area in the basin formed by the northwesterly-flowing drainage west of Samaniego Peak. The Diamond Head prospect is located near the alaskite-coarse leucogranite contact in this area.

In the western area, the coarse texture of the alaskite makes it readily distinguishable from all other rocks in the area except the equally coarse-textured leucogranite which surrounds the alaskite on three sides. The main field criterion used to differentiate these two very similar rocks was color. The coarse granite is normally gray-hued, while the alaskite tends more toward a buff to yellowish color. Subsequent microscopic studies revealed the presence in the alaskite of very minute crystals of a mineral thought to be monazite. Similar occurrences were not noted in the coarse leucogranite. In the Diamond Head area, intense shattering and alteration make field differentiation of the two coarse-textured rocks even more difficult and the location of the contact between them must be regarded as approximate.

In outcrop, the alaskite weathers to a buff to yellow color and rounded outcrops are common. In areas of less relief, such as the Diamond Head basin, a coarse rubble soon develops from physical breakdown of the alaskite and the alluvial stream deposits tend to be considerably coarser than normal. Thin yellowish-white aplitic dikes are not uncommon and are considered to represent a late magmatic phase of the alaskite intrusion. There is no significant mineralogical difference between the two — only the textures are different.

Mineralization

From an economic point of view, the Sierrita Mountains lie in the midst of the mammoth southern Arizona copper province — one of the great copper-producing areas of the world. Were it not for the immense production of copper, the region might indeed have been known for its lead-zinc and precious metal output, but these have been far overshadowed by copper.

Arizona produces approximately half of the new copper in the United States annually. Virtually all of this production comes from southern Arizona. The mines at Bisbee, Morenci, Ajo, Mission, Pima, Silver Bell, Ray, San Manuel and the Globe-Miami area together produce about 1,500 tons of copper metal per day. Within this "mega-district," the fastest growing segment is the Twin Buttes-Sierrita Mountains. Since 1950, when the district was virtually dead, exploration has revealed the Pima, Daisy, Mission, Esperanza, Palo Verde and Twin Buttes orebodies. These deposits represent reserves of close to one billion tons of low grade copper ore. Within this framework of tremendous metallic concentrations, the mineralization of the Sierrita Mountains seems puny by comparison. It is, however, an integral part of the metallization of the district and, as will subsequently be shown, it fits into the structural picture involved in the overall metallization of the district.

To a degree, the mineralization of the Sierrita Mountains can be grouped for discussion by merely following the historical development of the search for ore deposits in the area. That is, the precious metal deposits sought by early prospectors, the high-grade base metal concentrations which were the target of the prospectors until very recently, and the large tonnage, low-grade copper-molybdenum deposits which are the object of current activity in the area. The brief flurry of activity connected with the search for economic concentrations of radioactive minerals completes the list of types of deposits occurring in the region.

Inasmuch as the current emphasis in exploration of the district is directed toward the large, low-grade concentrations of metal and also because they potentially represent by far the most economically significant deposits, this discussion will be restricted to a description of these occurrences.

LOW-GRADE COPPER-MOLYBDENUM DEPOSITS

The Esperanza deposit, located in Section 16, T18S, R12E appears to represent the locus of a large zone of low-grade disseminated copper-molybdenum mineralization covering approximately six square miles on the southeastern flank of the Sierrita Mountains. Since this deposit lies outside of the area under discussion, it will be referred to only insofar as it relates to mineralization within the area. Excellent discussions of the Esperanza deposit have been given by Schmitt (1959) and Lynch (1965, in preparation).

The large, elongate body of biotite diorite cropping out in Section 7, west of Esperanza, is the center of a satellitic metallic concentration. In this area there has been no significant formation of a blanket of secondarily enriched copper. Chalcocite is present only in trace amounts. The main metallic minerals are chalcopyrite and molybdenite, along with small, but persistent, amounts of silver and traces of gold. No silver or gold-bearing minerals were noted in the polished sections studied and it is probable that these metals are contained within the structure of other sulfide minerals.

The sulfides occur as disseminated grains and narrow veinlets, usually associated with quartz veins which cut the diorite. The country rock is highly fractured and many of the fractures have been healed by quartz veins ranging from one-eighth to three inches in width. The quartz is massive and usually milky, although some glassy quartz veins were seen. Associated with the quartz, one normally finds small amounts of orthoclase and epidote. A few occurrences of calcite were noted, but these are more probably related to later calcite ceinlets which cut the quartz veins.

The pyrite-chalcopyrite ratio in the diorite is low, probably in the range of 1:1. Though erosion has cut deeply into the mineralized zone, the low pyrite-chalcopyrite ratio has no doubt inhibited development of a significant secondary blanket of enriched ore. Chalcocite was found only sparingly, occurring as thin coatings on pyrite and chalcopyrite.

Studies of drill core and polished sections cut from some of the core reveal a reasonably straightforward paragenetic history for the mineralization. Sericite, quartz, secondary potash feldspar and secondary biotite were formed following a period of deformation which cracked the country rock. After further fracturing, quartz and potash feldspar were introduced along fractures. Molybdenite was introduced early along the margins of the quartz veins. Its presence with the other sulfides indicates, however, that it is at least in part contemporaneous with them. Pyrite and chalcopyrite appear to be contemporaneous and their introduction began sometime after the quartz. For a time, all of the minerals were being deposited together. Pyrite-chalcopyrite introduction, however, continued beyond that of quartz and possibly after a pause during which some deformation occurred.

Some conclusions can be drawn as to the age of these deposits. They are younger than all of the intrusive rocks, since all of them are mineralized. The K-Ar date of 60 million years for the granodiorite (Creasey and Kistler, 1963, p. 1) provides an older limit for the mineralization. Mauger (1964, p. 1) dated biotite from mineralized veins in the Esperanza Pit at 60.8± 2 million years. He states that though this date is slightly older than the granodiorite, it falls within the limits of experimental error and that field and petrologic evidence show that mineralization followed granodiorite emplacement. This study confirms Mauger's findings. Furthermore, the close relationship in time of the granodiorite and the mineralization strongly suggests a genetic tie between the two.

STRUCTURE AND TECTONICS

An understanding of the structural framework is essential to a logical and defensible explanation of the geologic history of the area. A very brief summary of the structure history of the Pima district was given by Cooper (1960). The Pima district overlaps the area of present study on the eastern side.

Two avenues of study were followed in analyzing the structure of the Sierrita Mountains. One of the prime areas of emphasis in field mapping was a clear delineation of the structural elements and their patterns in outcrop. This work forms the foundation of the present interpretations. In addition, however, availability of a good set of aerial photographs, both low-level and high altitude, pointed to the possibility of a photostructural analysis of the area. This was undertaken in an effort to determine whether structural elements were present in the area which were not discernible in outcrop. In addition, the high altitude photos, covering nearly a quadrangle in area, were examined in an attempt to delineate broad regional structural patterns.

Faulting

Three main directions of faulting were mapped in the Sierrita area. The three directions differ not only in trend, but apparently also in age. Faults trending approximately N70°W, N60-80°E and north constitute the main directions of movement. Each of these directions represents a "family" of faults, including major members and innumerable small structures. For the most part, steep dips, ranging from 60-90°, were recorded on the faults.

Faults trending about N70°W are quite common throughout the area. The Sierrita fault belongs to this group. Faults of this trend are often difficult to recognize and, indeed, the Sierrita fault is only intermittently traceable along its length. The Sierrita structure ranges from about a foot in width to a zone 75 to 100 feet across at its maximum. It is generally a discrete structural entity, as opposed to the northeast-trending structures which tend to be more diffuse zones of multiple fracturing.

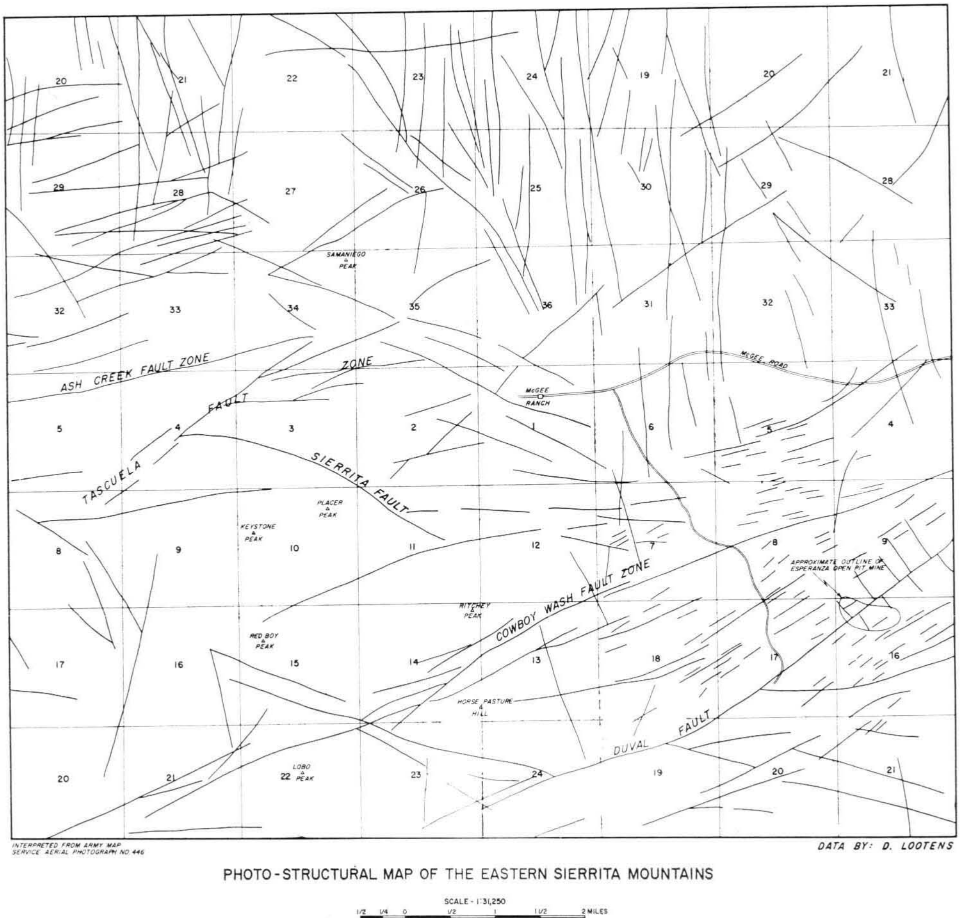


PHOTO-STRUCTURAL MAP OF THE EASTERN SIERRITA MOUNTAINS

SCALE - 1:31,250

1/2 1/4 0 1/2 1 1 1/2 2 MILES

FIGURE 3.

The Sierrita fault dips steeply (80°) to the northeast and relative movement on the fault, where discernable, appears to have been left lateral with displacement of the magnitude of a thousand feet. The Sierrita fault is offset in the northern part of Section 11 by a later northeasterly-trending structure. The evidence, however, indicates that the Sierrita fault (and probably the other northwesterly trends) has had a complex history involving several periods of activity. Though the structure is not traceable farther east than Section 11, elongation of the diorite body in Section 7 along this trend and the linearity of the quartz monzonite-granodiorite contact in the same area indicate that the zone of weakness represented by the Sierrita fault extends beyond the limits mappable in the field.

A number of important northeasterly-trending structures were mapped in the area. Among the more important are the Cowboy Wash fault, traceable for several miles along the southern boundary of the range, the Ash Creek fault in the northwestern part of the district and the Tascuela fault located in the west-central part of the map area. Both the Ash Creek and Tascuela structures are known to extend for several miles down the west flank of the range (Thoms, personal communication). In addition to the specific structures mentioned, numerous smaller northeasterly faults are traceable for distances up to several thousand feet. In fact, the photostructural map shows a very strong predominance of northeasterly-trending structures, particularly in the southern part of the area.

Northeasterly-trending faults are generally steeply-dipping, either northwest or southeast and exhibit, like the northwesterly faults, left lateral movement with the strike-slip component apparently dominant over the dip-slip. Faults of this trend show a greater tendency toward highly-fractured complex fault zones than do their northwest-trending counterparts. The Cowboy Wash fault is a case in point. Over much of its length this fault is actually a complex zone of faulting ranging from 100 to 500 feet in width. Brecciation of the country rock and development of 10 to 20 foot gouge zones are common along this zone. The Cowboy Wash fault zone has had a profound effect on the present physiography, closely controlling drainage and topographic patterns along its trace. An important parallel structure occurs south of the Cowboy Wash fault. It is here called the Duval fault because it passes through Duval's Esperanza pit and represents a major regional control for copper-molybdenum mineralization. Though structural control of mineralization will be considered in detail in a later section, it can be mentioned here that the Cowboy Wash fault serves as a regional control for mineralization in the area of the diorite.

The Ash Creek and Tascuela faults are not as well exposed in outcrop as is the Cowboy Wash structure. The Tascuela fault is readily apparent as it crosses the hill in the center of Section 4. In this area, strong outcrops of tourmaline granite which weather to a distinctive dark gray hue are in fault contact with the more subdued buff-colored outcrops of fine-grained leucogranite. The fault plane is marked by the development of a narrow gouge zone and, locally, brecciation of both rock types. As with the Cowboy Wash fault the Tascuela structure is actually a zone of complex faulting. With the Tascuela fault, however, individual faults are discernible and shattering along the bone is not as fully developed. The Ash Creek fault is the most difficult of the faults to trace in the field. Its trace follows a valley up the west flank of the range and seems to die out at higher elevations. Evidence for the existence of the structure can be seen intermittently along the valley and in one or two places on the hillside. A steep dip is inferred from the straightness of the fault trace. Off-setting of the contact between the coarse-grained and fine-grained leucogranites seems to indicate right-lateral movement, but the strong preference for left lateral movement shown by other faults throughout the area may indicate that the apparent right-lateral movement probably represents either late movement on the fault or an apparent movement produced by intrusive relations.

North-trending faults are not especially well-developed in the area, although the photo-structural map shows a strong northerly trend in the pediment east and north of the McGee Ranch. These north photo-structures are rigidly restricted to the nearly level pediment surface and may represent faults formed in conjunction with late Basin and Range-type block faulting. Outcrops are very poor in the pediment area and little field confirmation of the photo-structures was obtainable.

No major north-trending faults were mapped, although a number of smaller breaks do occur. One of these, occurring in the northeast corner of Section 11, is marked by a silicified zone about six feet wide. The fault is traceable along a narrow canyon for about a thousand feet and appears to have a near-vertical dip.

The history of movement on each of the three major fault directions is complex. The northwesterly-trending faults, and particularly the Sierrita fault represent an old direction (possibly Precambrian) which was re-activated in Cretaceous-Tertiary time. That a zone of weakness existed prior to the intrusive episode has been pointed out. The existence of northwesterly-trending structures in the diorite indicates a re-activation of this direction again after the emplacement of the diorite and the presence of northwest-trending andesitic and basaltic dikes, particularly in the area of Diamond Head prospect, suggests a possible post-ore movement along this trend.

The northeasterly trend, possibly a reflection of older Precambrian structures, was produced following the intrusive episode. Post-ore movement is also indicated by the brecciation and off-setting of quartz-sulfide veins in the diorite and displacement of a latite dike in the western part of Section 18. This occurrence may be of considerable significance because it indicates at least some movement on the northeast trend after the deformation which produced northerly faulting. Lynch (1965, in preparation) indicates that north-trending faulting occurred in the Esperanza area in the midst of the intrusive episode. Mapping in this area shows that such trends are at least post-quartz monzonite in age and, if the structures mapped are related in time to the photo-structures which exist in the pediment area, the trend must be post-granodiorite in age. It seems on the basis of the available evidence, that the northerly trend is the youngest of the three, although recent movement along the northeast trends probably post-dates the formation of the northerly structures.

To summarize then, the major movement on the northwesterly-trending faults occurred after deposition of the volcanic sequence, but before emplacement of the intrusive complex. The major northeasterly movement occurred following emplacement of the intrusives and the northerly trends were formed at some time after the northeast structures. They may represent either tensional breaks formed in response to the relaxation of the forces which produced the earlier faults, or breaks formed as a part of the Basin and Range block faulting.

Jointing

For purposes of this study, joints are defined as open fractures of small lateral extent in the rock which show no evidence of movement, either vertical or horizontal. If indications of movement were present, the structures were classed as faults. If the structures were healed by quartz introduction or the introduction of like material, they were not classed as joints.

The development of jointing varies considerably from rock type to rock type in the Sierritas. For example, though jointing is well-developed in the diorite, the joints are poorly preserved due to the softness of the rock and its lack of resistance to weathering. In general, jointing is better developed in the intrusives than in the volcanic rocks, although individual flow units, particularly the more acidic varieties, show good joint patterns. In some areas, such as the pediment northeast of the McGee Ranch, measurements had to be taken at every opportunity because of the poor bedrock exposures. Through most of the area, though, joints were readily available for measurement and representative readings were taken.

The joint measurements were plotted in the form of a rose diagram. Inspection of this diagram shows three primary joint directions — northeast, northwest and north. In gross aspect, these directions correspond very well with similar analyses made for faults mapped in the field and faults interpreted from aerial photographs. Rose diagrams of these two sets of data are also included. Regardless of strike, the predominant dip of the joints is quite steep (60°) although about five to ten percent of the readings showed dips of less than 20 degrees. There is no pattern to the direction of the dip of the joints, nor is there any discernible relationship between any given strike direction and dip direction. The only possible exception to this statement is a suggestion that, more often than not, joints with low dips tend to be most closely related to the north-trending group. This relationship may be more apparent than real, however, because the greatest single concentration of joint trends lies between N15°W and N15°E so it is perhaps logical to expect more of the near-horizontal joints to have this trend.

Of interest in the analysis of joint patterns is the discrepancy between the relative importance of the main joint directions and that shown by the main fault directions. The joints show a much better "scatter" than do the faults. That is, directions other than the primary directions, though still of minor significance, are better represented by jointing than they are by faulting. The great predominance of north-trending joints is not reflected in the fault diagrams. Since the joint patterns are at least in part a reflection of the latest tectonic adjustments in the vicinity, the northerly pattern probably represents the result of a combination of late doming of the main range and normal block faulting in the valley. The occurrence of concentrations of joint readings on northeast and northwest trends corresponding to the major shear directions is not unexpected.

Photo-structures

An analysis of structural elements observable on aerial photographs has been made. The area covered is somewhat larger than that covered by the field studies, primarily because it was felt that certain photo-structural features occurring outside of the area mapped were essential to an understanding of the structural framework of the area as a whole.

Reference to the photo-structural map indicates, broadly speaking, the existence of three structural environments. These are the pediment area north and east of the McGee Ranch, the main mountain mass and the foothill extension of the main mass in the southern part of the area. Each of these areas is characterized by a separate and distinct structural pattern. By far the most prominent pattern shown by the photo-structures is the strong northeasterly trend which dominates the foothill extension. Included in this zone are two of the major fault systems mapped in the field, the Cowboy Wash and Duval structures. In the foothill area, the northeasterly structures have virtually eliminated any other trends which might be present.

The pediment area is characterized by a dominance of north to northwest structures. A similar pattern is shown in the extreme northwest corner of the area. Here, however, the trends are north to slightly east of north. This area is also one of low relief, off the flank of the main mountain mass.

The structural pattern of the main mountain range reflects most closely the overall structural framework as it has been developed in field mapping. Both northeasterly and northwesterly trends are present, along with subordinate north trends. Though the rose diagram of photo-structural trends shows a strong preference for the northeast direction, this is a reflection of the obvious abundance of these structures in the foothill extension. Were a rose diagram constructed using only trends delineated in the main mountain mass, it likely would closely resemble that diagram made for faults mapped in the field.

The significance of these structural trends will be considered in the discussion of the origin and development of the structural and tectonic framework of the area.

Tectonics

The structural patterns described above are the result of the interaction of magmatic and tectonic forces. The petrology and origin of both the intrusive and extrusive rocks will not be considered from the standpoint of their relationship to, and their effect on, the origin and development of the structural framework of the Sierrita Mountains.

INTERPRETATION OF STRUCTURAL PATTERNS

It seems most advisable, in discussing the structure of the Sierritas, to begin with the regional patterns shown and graduate downward to smaller features and relate them to the overall pattern.

The regional pattern shown by the photo-structural map reveals several elements relatable to the tectonic history of the area. Very briefly, the tectonic history can be viewed as a sequence of events involving possible pre-volcanic doming resulting in the shedding of Paleozoic sediments, extrusion and deposition of the sedimentary-volcanic sequence, erosion and deformation producing northwesterly structural trends, doming of the main range with contemporaneous tilting of the volcanics, intrusion of the igneous complex, contemporaneous with, and subsequent to the doming, major deformation forming the northeasterly trends and finally doming of the range, accompanied by further tilting of the volcanics and, probably, block faulting along the margins of the mountain mass.

In the context of this sequence of events, the dominantly north trends observed in the pediment areas east and northwest of the mountain mass probably reflect a crudely-developed concentric pattern developed by doming, both the early and late phases. Verification of the existence of these structures in the field is difficult because of the poor outcrops in the pediment area. The importance of the north direction is shown by the rose diagram of joint directions.

The lack of a well-developed radial pattern such as that described by Knopf (1936) and Lootens (1959) in the Spanish Peaks area of southeastern Colorado can be accounted for in several ways. The radial pattern in the Colorado locality (Lootens, 1959) resulted from the intrusion of a roughly circular stock of quartz monzonite into a flat-lying sedimentary sequence which forms part of Huerfano Park (Briggs and Goddard, 1956). Experimental studies carried out by the author in 1958-59 showed that if the intrusive body varies significantly from a circular shape, the radial pattern is often not developed. Likewise, a concentric fracture pattern, well-developed with circular intrusions, shows only incipient development when the intrusive force is non-circular. As the intrusive approaches an elliptical or rectangular shape, the fractures that develop tend to parallel the long axis of the intrusive.

The existence of strong northwesterly trends prior to doming also would have had an effect on the fracture pattern developed by the uplift. They certainly would have provided a mechanism for relieving the stress produced by uplift before new, radial patterns were developed.

A final factor of significance in this regard is the great disparity in rock types involved — at least in the later uplift. Evidence is not available to indicate with certainty whether the volcanic sequence covered the entire region or whether older intrusives were present in the northern part of the range at the time of the initial doming. If part of the area was made up of intrusive rocks, as was the case at the time of the later doming, fracture development would have been influenced by this inhomogeneity.

The strong northeasterly trends exhibited by the foothills extension area show many of the characteristics considered to be typical of wrench faults (De Sitter, 1956, pp. 173-4). The northwesterly trends, though formed at a different time than their northeasterly counterparts, are quite similar to them and undoubtedly were formed by the same type of mechanism. The straight traces of the structures, their high angle of dip and the presence of significant amounts of strike-slip movement tend to eliminate the possibility that they are thrust faults. The topographic expression of the Cowboy Wash fault is very similar to that described for parts of San Andreas rift zone (Wallace, 1949).

The formation of these wrench structures is apparently independent of any genetic relationship to the uplifts which affected the area. Development of the northwesterly structural trend was accomplished prior to the emplacement of the intrusive complex (Cooper, 1960, p. 63). Though no direct evidence can be offered other than the trend of the faults, compressive forces oriented approximately east-west are suggested as the means by which the northwesterly structures were formed. Some indication of the direction of compression may be gained from the existence, on the west side of the range, of a series of north to northwest-trending folds in the volcanics (Fair, personal communication). That later movement occurred along these structures has been pointed out previously. The development of the main northeasterly trends took place following intrusion of the igneous bodies and, hence, after the initial domal uplift. Again an essentially east-west compressive force is postulated for the formation of these structures and repeated movement along these faults has occurred. At least some post-ore movement has occurred as evidenced by the off-setting of mineralized quartz veins and late dikes in the eastern part of the area.

Though the development of the major part of the north structures is probably related to doming, the majority of such structures now evident, both in the field and on aerial photographs probably reflect the last uplift. In all probability, two periods of north-trending fault development occurred, associated with each of the two uplifts. This accounts for the otherwise anomalous occurrence on the post-structural map of wrench faults being offset by northerly-trending structures.

TECTONIC HISTORY

Based on a knowledge of the petrology and structural pattern of the area, the tectonic history of the Sierrita Mountains can be pieced together. In many respects, the tectonic history of the region is essentially the geologic history since tectonic activity has been such a major factor throughout geologic time.

Upon an erosion surface of pre-Cretaceous (?) rocks, the pyroclastics and flows of the Oxframe Formation were deposited. The fact that the base of this formation is not exposed in the area makes a determination of the nature of the pre-Oxframe rocks impossible. Thoms (personal communication) mapped Paleooic sediments and pre-Cretaceous (?) intrusive rocks below the volcanic sequence on the west side of the range. That the pre-Oxframe surface was of relatively low relief is indicated by the general consistency of thickness of the units in the lower part of the formation. Volcanic activity gradually became sporadic and was interspersed with progressively longer periods of subaerial erosion. It seems probable that the red-ber sequence described by Thomas (personal communication) was also deposited in the eastern Sierrita area but was subsequently removed by erosion. Volcanic activity of a dominantly explosive nature began again following this and may have continued on through at least part of the compressional phase which produced the northwesterly structures. Evidence for this possible overlap lies in the fact that the younger rhyolite shows little in the way of northwest-trending structures and may have still been in the depositional process when they were formed.

Uplift of the range followed the compressional phase. With regard to this initial uplift, it is well to consider the mechanics of such a movement in the context of the Sierrita area. The question arises as to whether the overlying rocks were forced upward or outward by the intrusions which accompanied and, in large part, were probably responsible for the uplift. Field evidence indicates that, in all probability, both situations existed. The presence of small patches of volcanics in the northern part of the area indicates that at least some of the volcanics were forced upward. On the other hand, the upturning of the volcanics at the intrusive contact in some places and the steepness of the regional dip of the volcanics indicates that an outward movement also took place. The center of the uplift probably lay in the general vicinity of the area west and north of McGee Ranch, although the upward movement is viewed as a large, rather gentle and probably slow event. The more gentle dips of the volcanics in the southeastern part of the area indicates that they lay farther from the center of the uplift than those in the Oxframe Canyon area. Weaver (1965, in preparation) postulates doming of the granodiorite east of the McGee Ranch and, since the granodiorite is younger than the other intrusives, it is possible that the upwarp moved eastward with time. Such movement would probably reflect a gradual shift in the location of the magmatic conduits.

Following doming and intrusion, compressive forces again came to the fore, forming predominantly northeasterly trends, but probably also reactivating, to a certain extent, the pre-existing northwesterly trends. North trends which had formed in connection with the domal uplift were offset by northeasterly movement at this time. A striking example of this is shown southeast of the Esperanza Pit.

The final significant tectonic phase involved a domal uplift, centered in the Keystone-Placer Peak area, which was accompanied by tilting of the nearby volcanics and, probably, Basin and Range-type block faulting at the edge of the pediment. Pedimentation had probably already begun at this time and has continued on to the present. The exceptionally well-developed pediment surrounding the Sierrita Mountains must have resulted from a relatively long, uninterrupted period of pedimentation.

In summary then, domal uplifts have alternated with compressional episodes throughout much of Upper Cretaceous and Tertiary time. Intrusive activity accompanied the early period of uplift and, represented by late dikes, may have continued throughout the latter compressional phase.

STRUCTURAL ENVIRONMENT RELATED TO MINERALIZATION

The Esperanza Wash deposit provides an excellent example of structural control of mineralization. The main zone of shattering, alteration and mineralization lies at the intersection of the northeasterly-trending Cowboy Wash fault zone and the northwesterly-trending Sierrita fault zone. Though the Sierrita structure cannot be traced as a discrete mappable entity into the Esperanza Wash area, numerous small parallel structures can be seen in the field. In the area of the intersection between the Sierrita structure and the Duval fault, which parallels the Cowboy Wash fault, provides a regional control for the Esperanza deposit. Lynch (1965, in preparation) mentions the strong northwesterly orientation of the Esperanza orebody — an orientation which coincides with the Sierrita fault zone.

On a local basis, mineralization occurs along fractures and in veins of all trends. There is a separation of the sulfide minerals, which is by no means complete, based on rock type. The better-grade molybdenite seams occur predominantly in the quartz monzonite and granodiorite, while copper mineralization is more highly developed in the diorite. Undoubtedly, this is a function of the pre-sulfide preparation of the ground which, in turn, developed the pattern of biotite-orthoclase-quartz partly as a result of reaction with the wallrock.

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