MAJOR THESIS

PART 1

CONTROL OF ORE BY PRIMARY IGNEOUS STRUCTURES:
PORCHER ISLAND, BRITISH COLUMBIA

Thesis

by

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ILLUSTRATIONS

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INTRODUCTION

Mapping internal structures of an intrusive has proven of value in quarrying but only about a dozen examples appear in the literature wherein metalliferous deposits in intrusives were found to occupy features such as cross joints or marginal upthrusts e.g., (Emmons and Grout 1935), (Kerr 1936), (Barr and Gardner 1940). This study therefore is presented as an additional example of structural control of an ore deposit by primary igneous structures. The lode deposits described in this paper show a rigorous control by a relatively small primary flow structure, an arch of flow layers.

The area studied is the northwest portion of Porcher Island, B. C. (Fig. 1). The principal deposits are those of the Surf Point and Edye Pass Mines. These properties lie about 25 miles southwest of Prince Rupert, B. C., the western terminus of the northern branch of the Canadian National Railways.

The climate is wet and equable. Temperatures remain below freezing for only a few weeks each year. The region is for the most part heavily forested with spruce, hemlock and red cedar, but adjacent to the mines, muskeg, moss and scrub cover most of the area mapped. Although bedrock commonly lies within a short distance of the surface, outcrops, excepting along the shoreline, in the mine workings and at higher elevations, are isolated and small. However, as a result of Pleistocene glaciation, they are of fresh rock. The relief in the area mapped varies from sea-level to a maximum of 2200 feet on the ridge south of Surf Point Mine.

Previous Work in the Area.

The geology of the coastline and islands of the northerly portion of British Columbia has been mapped and described by V. Dolmage (1922). The progress of the properties has been reported on from time to time by J. T. Mandy of the Provincial Department of Mines (1928-1935). R. E. Legg (1934) has described the milling methods at Surf Point and H. V. Warren and J. M. Cummings (1936) conducted a microscopic investigation of the ores.

Purpose and Extent of the Present Study.

The primary purpose of this investigation was to determine the structural control of ore bodies in a quartz-diorite stock thereby furnishing a geological guide in the development of the deposits. The principles and technique employed were those developed by Hans Cloos and his co-workers and admirably described by Robert Balk (1937) in a recent memoir.

Structures were mapped in great detail. The accompanying Plates I and II are generalized from field maps, of scales 1" = 300' and 1" = 100' respectively, on which hundreds of flow and fracture orientations were recorded. Mapping was not confined to the area described in this report but was extended to include adjoining areas and adjacent islands. Since this work did not add materially to the interpretation of the igneous structures, it has been omitted from the present report.

Acknowledgments.

The writer is indebted to Dr. V. Dolmage for suggesting application of the Cloos methods to the problem of control of the ore deposits. The field work was completed in the summer of 1936 and permission to use the results for thesis and publication was kindly given by Mr. C. P. Riel, managing director of the Reward Mining Company, Ltd., at that time operators of the properties. The writer wishes to express his sincere thanks to Dr. Campbell of the California Institute of Technology, under whose guidance and supervision the study has been completed.

GENERAL GEOLOGY

Relationship of the Area to the Coast Range Batholith.

The quartz-diorite stock in which the ore deposits occur is a satellite of the composite coast range batholith of Upper Jurassic and Lower Cretaceous age (Buddington and Chapin, 1929, p. 252-253). The western contact of the main batholith lies about 20 miles to the east. To the west of the massive batholithic rocks there is, along the coast and islands, a wide zone in which older rocks are injected by smaller bodies of Coast Range intrusives. Porcher Island lies in this western marginal zone. Much the greater part of the island consists of older rocks but there are numerous small and a few larger bodies of the intrusives (Dolmage 1922)

Geologic History

The significant events of the geologic history of the map area are summarized in Table 1.

Prince Rupert Schists.-The Prince Rupert schists are highly metamorphosed rocks containing varying amounts of amphibole, pyroxene, chlorite, mica and garnet with a few layers of limestone included (Dolmage 1922). They are Carboniferous and/or Triassic in age. In the area covered by this report the Prince Rupert series are principally amphibolite schists derived by dynamic metamorphism of andesitic and basaltic flows, tuffs and sills. The schists attained

TABLE 1. Geologic Column

Age	History	Formation	Lithology
Recent	Post glacial uplift.		
Pre-Pleistocene	Long period of erosion with repeated uplift and peneplanation. Intrusion of small dikes.	Dikes	Andesites Basalts
Upper Jurassic	Ore deposition in quartz-diorite stock.	Veins	Auriferous quartz-pyrite veins.
	Faulting along N30E shears and associated movements.		
Upper Jurassic	Intrusion of the Coast Range batholith and the associated minor intrusives of the map area.	Coast Range intrusives.	Quartz-diorite granodiorite gabbro.
Upper Jurassic	Dynamic metamorphism of the rocks of the Prince Rupert Series.	Prince Rupert schists.	Amphibolite schist.
Carboniferous and/ or Triassic	Vulcanism and sedimentation	Prince Rupert series.	Andesites Basalts

their present characteristics prior to the injection of the small Coast Range intrusives of the map area. Their metamorphism however is associated with the intrusion of the batholith (Buddington and Chapin, 1929, p. 293-298).

The regional strike of the schistosity is northwest with an average dip of 50° to the northeast. Bedding, in the few cases where it could be determined, parallels the schistosity.

Coast Range Intrusives.-In addition to the quartz-diorite stock, one small mass of gabbro and numerous sill-like injections of granodiorite are found in the map area. The gabbro occurs to the east of Little Useless Creek as a small isolated body in the schists.

Quartz-Diorite.-The quartz-diorite (tonalite) stock in which the veins occur is about 1 3/4 miles in diameter. It is subcircular in outline, the contact is fairly regular without large protuberances or re-entrants. The intrusive is rather uniform in composition and texture but there is a slight change towards the core where the rock becomes more leucocratic and approaches a granodiorite in appearance and composition. This gradation between quartz-diorite and granodiorite is common in the Coast Range batholith (Dolmage 1922, p. 15). Small grey inclusions, characteristic of the normal quartz-diorite, become scarcer towards the central portion and are not present in the granodiorite core. There is no well defined basic border facies in the intrusive nor any noticeable zone of thermal metamorphism in the country rock. Although the actual contact with the schists is rarely exposed it appears to be fairly sharp.

Granodiorite.-Sill-like bodies of granodiorite, ranging in thickness from a few inches to several hundred feet, intrude the schists, often in lit-par-lit relationships. In the map area the volume of granodiorite that has been injected into the schists more than equals the volume of the schists. In the field this granodiorite can readily be distinguished from the normal quartz-diorite by its more leucocratic appearance and the abundance of small barren quartz veinlets. Megascopically it is similar to the granodiorite core of the satellite.

The age and structural relationships of the granodiorite injections with respect to the quartz-diorite are not clear. Although the areal distribution of the granodiorite is widespread and is not related to the quartz-diorite satellite, yet in the map area their relationship might suggest that the granodiorite was a lit-par-lit injection into the schists of an acid phase of the quartz-diorite magma. There is no evidence indicating that the granodiorite sills are later than the stock. Most of the injections probably preceded intrusion of the stock, but the structural relations along the western margin of the stock suggest that some may have been injected during the intrusion of the stock as offshoots from the quartz-diorite magma.

Ore Deposits.-Following the intrusion of the quartz-diorite, faulting occurred in, and adjacent to, the stock along shears trending N30E. At the same time movement along pre-existing joint planes formed the future ore-bearing structures.

The ore deposits are auriferous quartz-pyrite veins with the values enclosed in the pyrite as minute blebs of telluride and free gold

(Warren 1936). They are of a rather high temperature, close to hypothermal origin. Individual quartz veins vary in width from a fraction of an inch up to 2 or 3 feet. The average assay of such vein material is of the order of 1 ounce gold per ton. The pure pyrite assays about 8 ounces gold per ton. A few small veins occur in the schists near the contact but most of the veins lie within the quartz-diorite in a zone trending N20E. They vary in strike from N30E to S80E and dip from 60°N to vertical.

Post-Ore History.-Basalt and andesite dikes cut the schists, the quartz-diorite and the ore. They are the only post-ore formations in the area. These dikes may be much younger than the ore deposits. Basalt and andesite flows and dikes of Tertiary and Quaternary age are found in nearby areas on the coast (Dolmage 1922).

The Tertiary history of the region is one mainly of repeated uplift and erosion. Pleistocene glaciation stripped the map area of all weathered rock, soil and detrital deposits.

PRIMARY FLOW STRUCTURES

Introductory Statement

Except in the core of the stock, flow layers, though faint, are clearly discernible. There is a good platy alignment of small tabular inclusions and hornblende crystals. However, there are no well defined schlieren, basic clots, or segregations into light and dark bands. Flow lines, resulting from the alignment of elongated inclusions and hornblende, have an almost constant trend. They often lie in the plane of the flow layers but flow lines occur in which the trend is at variance to the plane of the flow layers.

Flow Layers.

Near the margins of the intrusive flow layers invariably parallel the nearest contact. On the northeast and southwest margins of the intrusive, the contact and the flow layers parallel the trend of the intruded schists. Along the western contact, in the northerly section, flow layers and contact strike northeast at a high angle to the trend of the schists. Towards the south the internal structures of schist and intrusive again become concordant.

The most striking structural feature in the intrusive is a well defined arch of flow layers. (Plates I and II). The axial plane of this arch strikes N20E and dips about 85° southeast subparallel to the trend of strong N30E shears. The northerly plunge of the arch increases from 55° at the north contact to over 85° near the core. The flow layers in this arch are arranged in a nose comparable to a steeply plunging anticline in sedimentary rocks. On approaching the axis from the flanks, the flow layers become more nearly parallel to the axial plane of the arch, i.e., towards the axis the structure becomes tighter and isoclinal.

Southward along the axis of the arch the flow layers become fainter until in the southern portion of Surf Point Mine workings (Pl. II) they cannot be distinguished along the axis although they are still strongly developed on the flanks. Here there is locally a divergence between the platy alignment of inclusions and of hornblende (Fig. 2) with the inclusions forming a more open arch. In this core zone the quartz-diorite grades into a more leucocratic rock, a granodiorite.

The arch of flow layers probably continues southward of Surf Point Mine. As the flow layers along the southern margin of the intrusive dip 65° north, these layers, combined with the arch of flow layers may form an elliptical funnel-like structure, pitching northeast and tapering upwards. (Fig. 9). Other less well defined arches occur. No detailed field work was done on the southeastern portion of the stock, hence on the map (Pl. 1) the lack of detail does not indicate that the intrusive in this section is devoid of flow structures.

Flow Lines.

Linear structures in the quartz-diorite are neither as widespread nor as easily identified as the flow layers but their trend is more regular.

Along the northeast margin the flow lines subparallel the dip of the overlying schists, i.e., pitch 55°NE.

On the arch of flow layers, the lineation trends almost parallel to the axis but has a more gentle and constant pitch of about 55°NE. on the flanks, flow lines dipping about 50°NE occur within the plane of the flow layers. Locally a lineation with this trend is found where flow layers are not discernible. Exceptions to the relatively constant trend of the lineation occur on the axis of the arch where flow layers dip steeply (80°). Here flow lines are uncommon but occasionally a lineation of variable pitch, sometimes horizontal, is found in the plane of the flow layers.

If one were to disregard the platy structures and plot only the flow lines the stock would show a regular pattern of linear structures striking N20-30E and dipping about 50°NE. No arch or nose would be apparent. The general trend of the lineation is slightly more easterly than the N20E axis of arch of flow layers (Fig. 4).

JOINT PATTERN

General Statement.

The joint systems in the quartz-diorite are more closely related in orientation to linear structures in the intrusive and regional jointing in the schists, than to the arch of flow layers. The attitude of the flow layers, however, influences the frequency and persistency of joints of a given orientation. Several prominent joint sets occur in both schist and intrusive but the age and genetic significance of these joints may differ in the two rocks. Certain types in the intrusive have been classed as primary joints, but this designation is not nearly as clean cut as in the case of some larger intrusives described in the literature (Balk 1937, p. 97-117).

Joint Systems.

Table 2 summarizes the information regarding the principal joint sets in schist and intrusive and their relationships to flow structures and schistosity (see also Figure 3). These types may vary 10°-15° in strike or dip from the orientation given. In the schists this variation seems systematic and in sympathy with a change in the trend of the schists. Locally other sets of joints occur but they are less numerous and constant than the types described.

The age relationships and genetic significance of the

TABLE 2. Joint Sets.

Orientation: Strike	Orientation: Dip	Rock	Characteristics: Persistency, Spacing etc.	Characteristics: Filling	Relation to flow structures or schistosity	System
N20-30E	75-90SE	Sch.	Continue into intru- sive-nearly parallel to N30E shears.	Basalt dikes	Nearly normal to schistosity.	Tension * joints.
		Int.	Continue into schists	Basalt dikes	Parallel to trend of flow lines and axial plane of arch of flow layers.	Primary Longitudi- nal joints? *
N40W	50NE	Sch.	Common, persistent, parallel to schistosity		Plane of schis- tosity (plane of maximum shear).	Plane of schistosi- ty.
		Int.	Common only south of mines. Spacing 5-30' persistent.			?
N40W	50SW	Sch.	Common, persistent spacing 1'-5'.		Complement of plane of schistosity. Plane of maximum shear.	
		Int.	Even remarkably per- sistent spacing 10'-50' slickensides	Gouge, Pyrite, Andesite dikes.	Nearly normal to flow lines.	Primary cross joints? *
N75W	65-85NE	Sch.	Not persistent		Diagonal to schistosity	Diagonal joints?
		Int.	In zones of closely spaced joints along arch of flow layers, some slickensides	Quartz- pyrite veins.	Diagonal to flow lines planes of shear.	Primary Diagonal joints? *
N65E	55-85NE	Sch.	Not persistent		Diagonal to schistosity	Diagonal joints?
		Int.	In zones of closely spaced joints along arch of flow layers, some slickensides.	Quartz- pyrite veins	Diagonal to flow lines. Planes of shear.	Primary Diagonal joints? *

*Joints of this type are described by Balk (1937, p. 27-42).

various types in schist and intrusive are not fully understood. In the schists many of the joints may have formed prior to intrusion. Types common to both intrusive and schist may be either related to the intrusion or of post intrusive age. Even some of the primary joints in the intrusive could be expected to have the same orientation as older joints in the schists for joints (type 1 and 2, Table 2) in the schists played an important part in the emplacement of the quartz-diorite. Flow lines which control the orientation of primary joints in the intrusive, parallel the dip of the schists.

Primary Joints in the Intrusive.

Joints of types 1, 3, 4 and 5 in the intrusive might, on the basis of their orientation relative to the lineation, be classed as primary joints (Balk 1937, p. 27-42). They would be longitudinal joints, (type 1); cross joints, (type 2); and diagonal joints, (types 4 and 5). Their persistency, spacing, surface characteristics and fillings correspond closely to descriptions given in the literature. However some doubt on their primary origin is cast by the occurrence in the schists of joints of similar orientation, and by anomalous features such as an unusual orientation of slickensides on diagonal joints.

Influence of Flow Layers on Jointing.

On the arch of flow layers the orientation of the primary joint system is apparently little affected by the changing attitude of the flow layers. Yet, in any portion of the structure, the continuity and spacing, and even the types of joints which occur, are governed largely by the attitude of the layers.

This control results probably from the structural anisotropy of the quartz-diorite. The plane of the flow layers is one of easy splitting. It is difficult for the rock to split along planes at angles of 20°-70° to the flow layers except on planes including the lineation.

In the northerly portion of the arch, diagonal joints are conspicuous where the orientations of flow layers and joints coincide. This occurs principally along the axis of the arch. At Surf Point Mine in the central area of the stock where flow layers are faint, zones of closely spaced diagonal joints (types 4 and 5) are strongly developed; but on the flanks, where strong flow layers lie at a high angle to these joint directions, these zones of close jointing die out. Even the cross joints (types 3) seem to be more frequent and persistent in the central area.

This control of jointing by flow layers has in turn influenced the ore-bearing structures as will be discussed in a later section.

MODE OF EMPLACEMENT OF THE QUARTZ-DIORITE

Theory of Intrusion Developed by H. Cloos.

Before discussing the mechanics of emplacement of the quartz-diorite it will be desirable to summarize the theories developed by H. Cloos (1925). The following paragraphs are abstracted from Balk's discussion (1937, p. 78-83).

> During the early stages of intrusion it is believed that a highly mobile magma or crystal mush intrudes a relatively rigid and mechanically resistant crust. Such a mass must encounter a maximum of retardation of motion along its contact planes. Segregations, inclusions, and tabular crystals will be drawn out into flow layers (schlieren) which thus develop approximately parallel to the nearest contact.
>
> As more and more magma intrudes, the mechanical resistance of the crust is weakened, and the roof or flanks of the chamber begin to yield by folding or faulting. In this second stage the adjacent crust partakes in the motion of the igneous core. There is no longer along the contact the extreme friction and retardation of the magma which in the earlier stages formed the schlieren. Linear flow structures which disregard local contact planes form in the direction of maximum linear expansion. For hundreds of square miles, the projected strike of flow lines may be constant, even if the older schlieren vary in strike and dip. Presumably, where flow lines lie within flow layers, the individual grains had enough freedom to move slightly within the plane of the layers. A few cases are known where isolated flow layers dip more steeply than does the pitch of the flow lines between the layers. Mineral grains within flow layers rich in ferromagnesian crystals may not have been free to rotate any longer, but crystals in the more mobile surrounding magma may have been arranged in accordance with the feeble linear elongation of the magma. The older an arch of flow layers, the longer it will have participated in the subsequent arching, thus attaining steeper dip angles.

Application of Theory to Structures in Quartz-Diorite Stock.

The flow structures in the quartz-diorite conform closely to the theory outlined above. The parallelism of the layers to the nearest contact is very noticeable. The constant pitch of the lineation to the northeast indicates that, during the second stage of emplacement the direction of maximum elongation of the quartz-diorite magma for the levels exposed was upward to the southwest, i.e., up the dip of the schists.

Origin of the Arch of Flow Layers.-The origin of the well developed arch of flow layers might be explained in several ways. Among the possibilities are-

1. Prior to intrusion a steeply dipping, northeast trending shear (or joints of type 1 with similar trend) was present in the area now occupied by the arch of flow layers (Fig. 5). The earliest magma rose nearly vertically in this shear, gradually prying it open to the northward and developing the steep arch of flow layers in almost its present form. In the second stage the magma enlarged its chamber by mushrooming out mainly to the northeast of the shear and by doming its cover. The linear structures indicate that the greatest elongation of the igneous body during this later stage paralleled the dip of the schists.

2. The magma rose from the northeast paralleling the schistosity (Fig. 6). Flow layers were developed, dipping northeast parallel

parallel to the contact. The magma chamber increased in size by faulting along the NE trending shears. In this explanation the shears need not have been of pre-intrusive age. If they formed as a result of the forces of intrusion they could have followed planes of weakness provided by joints of type 1. in the schists.

The offset of the cover along the shear folded the flow layers into the steeply plunging arch. The occasional almost horizontal lineation found in the steeply dipping flow layers on the axis may have formed during this folding.

3. The walls of the magma paralleled the schistosity on the northeast contact, and the N30E joints (type 1) on the northwest contact (Fig. 7). Over the area of the arch of flow layers magma rose, along a shear or zone of weakness, above the general level of the roof. This upsurge of magma to higher levels formed the arch of flow layers.

There is no conclusive field evidence to indicate which of these alternatives is the mode of origin of the stock. The writer regards 1. and 2. as being equally probable. There is no proof, in case 1., of a pre-intrusive shear or of mushrooming of the chamber, or, in case 2. of actual folding of the flow layers. Case 3. offers an explanation only for the steep arch of flow layers and does not apply to the intrusion of the entire stock.

Whatever may have been the origin of the arch of flow layers it is evident that structures in the schists, the plane of schistosity and the N30E shears or joints, exerted a marked control during the emplacement of the intrusive and the development of the arch.

<u>Evidence of Forceful Intrusion</u>.-Enlargement of the magma chamber by movement along the N30E shears in and adjacent to the intrusive indicates that the magma was forcibly injected into the schists. In the early stage of intrusion of the stock, prior to the faulting along N30E shears, lit-par-lit injection of a leucocratic phase (granodiorite) of the quartz-diorite magma into the schists may have aided in the enlargement of the chamber. An upbowing or doming of the schists along the northeast contact and a pushing aside, on the southwest margin, may have been caused by the push of the magma.

<u>Form of the Quartz-Diorite Intrusive</u>.-If one were to project the intrusive contacts on the basis of orientation of the structures in schist and intrusive, the quartz-diorite mass would taper upwards with a northeastern contact dipping 50°NE and the northwestern, southwestern and southern contacts dipping more steeply towards the central portion of the stock. The intrusive is a subcircular stock whose axis plunges northeast at about 55°-60°. At depth the body may continue to parallel the trend of the schists (Fig. 6) or it may be more restricted to a N30E shear (Fig. 5).

Such projections should be used with caution. Flow layers near the margin would not show the influence of a sudden change in the direction of the contact a few hundred feet distant. However, such a change would probably be reflected in the layers at a greater distance from the margin.

THE ORE-BEARING STRUCTURES

Introductory Statement.

The ore deposits occupy faults and zones of close jointing on the arch of flow layers. Veins lie transverse to the axis but the ore-bearing zone extends along the axis. The structures were formed by movements, individually of small magnitude, acting on pre-existing joint planes. The persistency and frequency of these joints, as discussed above, is determined by their relation to the arch of flow layers. The forces which caused the movements were probably directly related to the intrusion of the quartz-diorite stock. Structures developed by regional stresses controlled the emplacement of the stock but it is not known if such stresses were present during intrusion.

The Ore-Bearing Structures.

The outstanding feature of the ore-bearing structures is their control by primary flow and fracture patterns. There are two main structural types of ore deposit, (a) those occupying well defined fissures (faults), and (b) those occurring in zones of close jointing. All gradations between these two types occur. The former are the more persistent; the latter, though of limited extent laterally and vertically, often contain higher grade ore.

To the north of H vein (Plate 2) the veins are of type (a). Here the flow layers are strongly developed on the axis of the arch.

Where the diagonal joints (types 4 and 5) parallel the plane of the flow layers then joints of these orientations are common and persistent. Faults, or fissures, have formed along the plane of the flow layers and primary joints. These structures are strong where they develop parallel to the flow layers on the axis of the structure but die out on the flanks where they transect the flow layers. Several of these fissures curve slightly in concordance with the curve of the flow layers on the flanks before pinching out.

South of H vein many of the veins are of type (b). The flow layers are poorly developed along the axis but strong on the flanks. Movement has been chiefly along the sets of close diagonal joints (types 4 and 5). Ore-bearing structures may roll from one set to the other. With the exception of B vein the displacement has been small, generally insufficient to offset the cross joints (type 3). The persistent southwest dipping cross joints (type 3) form the roofs of many of the ore shoots.

B vein occupies a shear zone in which the quartz-diorite has been in part mylonitized. Movement has been sufficient to offset the cross joints at least 7 feet. A draw lies on the continuation of B vein to the southwest. It is probably underlain by a strong shear of the N30E type. It is significant that no worthwhile deposits have been found south of B vein.

In addition to those on the axis of the arch other veins occur, but here too the control by flow layers is apparent. At Edye Pass Mine D5 vein occupies a persistent fault paralleling the flow layers, and joints of type 5, on the limb of the arch. D3 vein lies in one of the strong N30E shears. This shear zone of highly mylonitized rock is over 6 feet in width. It continues across schist and intrusive regardless of orientation of flow structures, nevertheless, quartz-pyrite lenses occur in this structure where the shear parallels the flow layers. Veins near the mouth of Little Useless Creek also parallel the flow layers; one of these veins lies transverse to a minor arch of flow layers.

Direction of Movement on the Ore-Bearing Structures.--It is difficult to measure displacements on the ore-bearing structures. The data obtained indicate movements were such that the result was a lengthening of the intrusive, in the area of the arch of flow layers, (Fig. 3), in a northeasterly direction. This lengthening was nearly parallel to the axial plane of the arch and the trend of the lineation. The slickensides all have plunges of low angles. Such movements would tend to widen the channelways for the ore-bearing solutions.

Origin of the N30E Shears.

Inasmuch as the ore-bearing structures and the N30E shears probably resulted from the same stresses, a short discussion of these shears is pertinent at this point.

Although N30E joints (type 1) are common in the area, it is only within a mile of the intrusive that conspicuous shears of this orientation occur. Three of these shears lie to the west of the intrusive. D3 (Plate 1) shear cuts both intrusive and schist. These four structures are remarkably straight and persistent; they can be readily traced as draws (depressions) on the surface. A similar draw continues southwest from B vein. In the eastern part of the stock the parallelism of the southern portion of each of the three forks of Little Useless Creek suggests control of the drainage by similar fractures.

Faulting along these shears took place after solidification of the quartz-diorite, at the levels now exposed, and preceded ore deposition. Although these faults do not bear the same relationship to the contacts of the intrusive as the gently dipping marginal thrusts and normal faults described in the literature (Balk 1937, p. 101-111), nevertheless, they may have served the same purpose, namely, to lengthen an expanding intrusive, already solidified at its margins.

Contacts and slickensides on D3 shear suggest that the southeast side of the fault moved almost horizontally northeastward in a manner to be expected if the intrusive was expanding by pushing northeasterly.

Origin of the Ore-Bearing Fractures.

The ore-bearing fractures probably were formed by the same stresses as the N30E shears, but in this case the manner of relief was not by a long continuous fault but by a series of much smaller movements involving the joint planes already developed on the axis of the arch of flow layers. The effect however was the same, namely, to aid in the expansion of the magma chamber to the northeast.

The easiest relief to the stresses was apparently by movement embracing the transverse joint planes rather than by the formation of a through-going shear along the axis. That the stresses were the same is indicated by the presence of a northeast trending shear to the south of B vein.

The elongation to the northeastward would not be a simple dilation in that direction. In the area of D3 and the axis of flow layers the maximum northeastward movement occurred to the southeast. A shearing stress would exist in the area (Fig. 8). The effects of such a rotational stress are discussed by Mead (1920). Relief to this stress was by faulting along D3 shear and by the smaller movements along the axis. The direction of maximum elongation in this rotational stress would be northeast.

The action of this shearing stress on the northwest portion of the intrusive explains the nearly horizontal slickensides found on the joints and ore-bearing fractures (Figs. 3 and 7). If this couple were effective during the earlier stages of the intrusion it may have caused the progressive eastward rotation (Figs. 4 and 7) of succeeding primary structures: axis of flow layers, flow lines and the normal to the cross joints.

Extension of the Ore Zone.

The structural control of the deposits having been established by mapping of internal structures in the intrusive, it is of interest to see what predictions can be made as to the probable lateral and vertical extent of the deposits.

The veins were formerly considered to occupy tension cracks of limited vertical range (200'-300'), formed by cooling near the roof of the intrusive. Reconstruction of the form of the intrusive, using the flow structures, platy and linear, and the trend of the schists, indicates that veins of Surf Point Mine lie a distance of the order of 1000 feet below the roof of the stock. Hence a much greater vertical range for the ore zone is suggested for the deposits.

The lateral extent of the zone is limited by the arch of flow layers. At depth the deposits should continue to occur along the axis of the arch, i.e in a zone striking N20E and dipping 80SE. Within this zone the maximum concentration of ore occurs at present levels between H and B veins. Whether this results from the change in the character of the intrusive and vein structure, or from an increase in the strength of ore-bearing structures on approaching the shear south of B vein, is not known. In either case the maximum concentration within the ore zone should rake steeply to the northeast.

SUMMARY AND CONCLUSIONS

The quartz-diorite stock in which the ore deposits occur was forcibly injected into older schists. The planes of easy parting in the schists, schistosity and tension joints, controlled the outlines of the intrusive. In the stock an arch of flow layers formed early. The succeeding linear structures had a constant trend. Primary joints had fixed orientations but their persistency, frequency and location were controlled by the arch of flow layers. The intrusive expanded partly by movement along N30E shears and partly by movements involving the joints already developed along the axis of flow layers.

The sequence - flow layers, flow lines, primary joints, ore-bearing structures - is directly related to the mechanics of the intrusion. The ore-bearing solutions probably came in shortly after the development of these structures, and originated as an end product of the consolidation of the magma at depth.

Mapping the internal structures of intrusives in which lode deposits occur may yield guides to prospecting and development. The application of Cloos' methods may give valuable information on such practical considerations as the form of the intrusive, the order of depth of known deposits below the contact, an estimation of the vertical range of the deposits, the strike, dip and rake of the ore-bearing zone, and may indicate favorable and unfavorable areas for prospecting or exploration.

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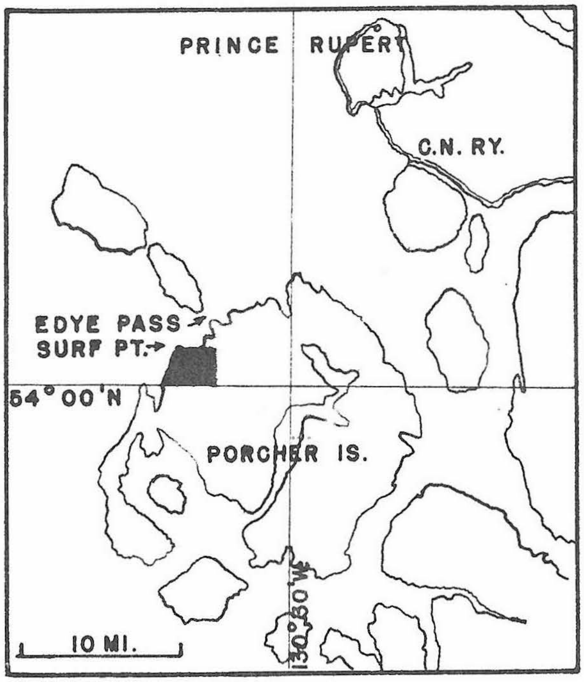

Figure 1
Key map to area.

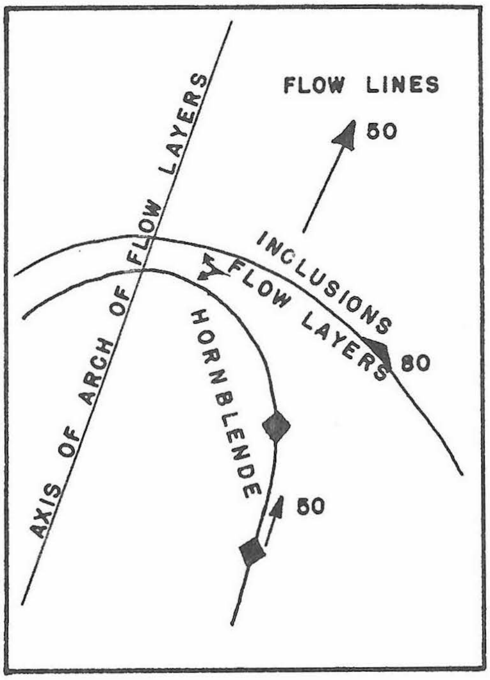

Figure 2
Divergence of
flow structures.

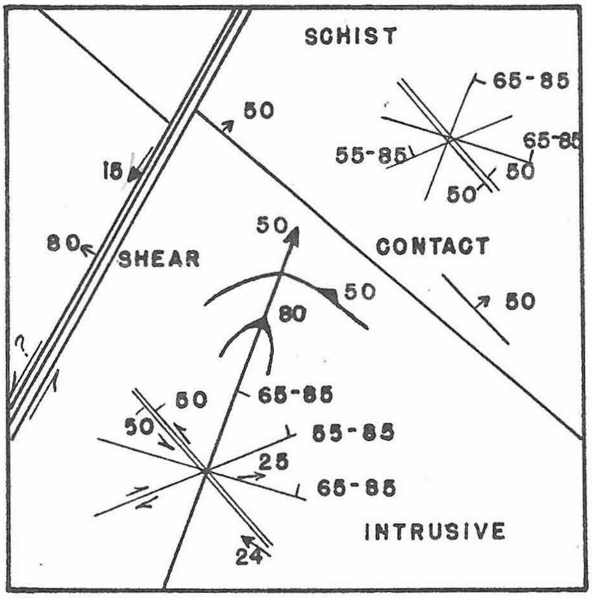

Figure 3
Relationship of flow and
joint patterns.

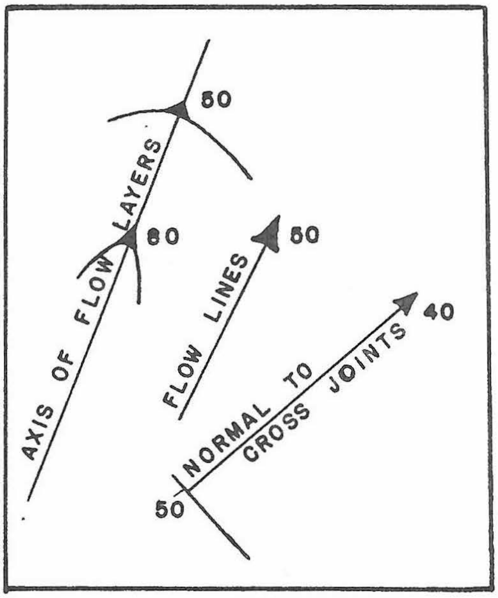

Figure 4
Progressive eastward rotation
of succeeding primary
structures.

Early Stage Final Outline

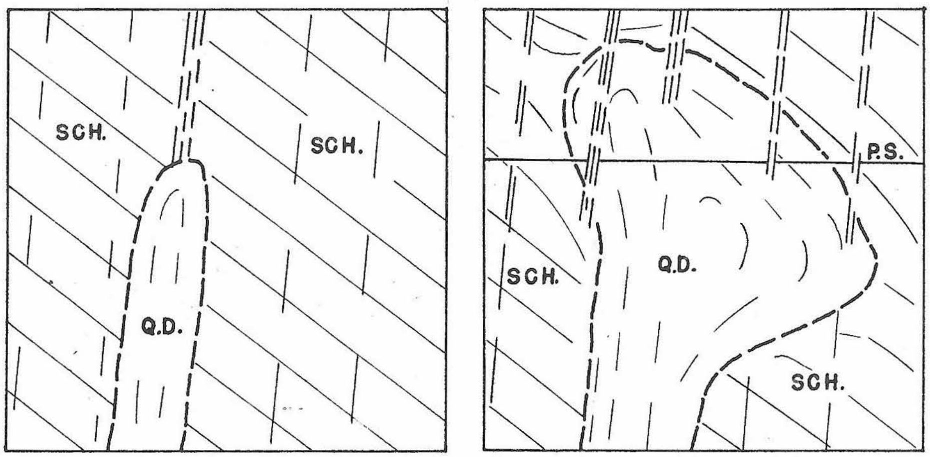

Figure 5.

Figure 6.

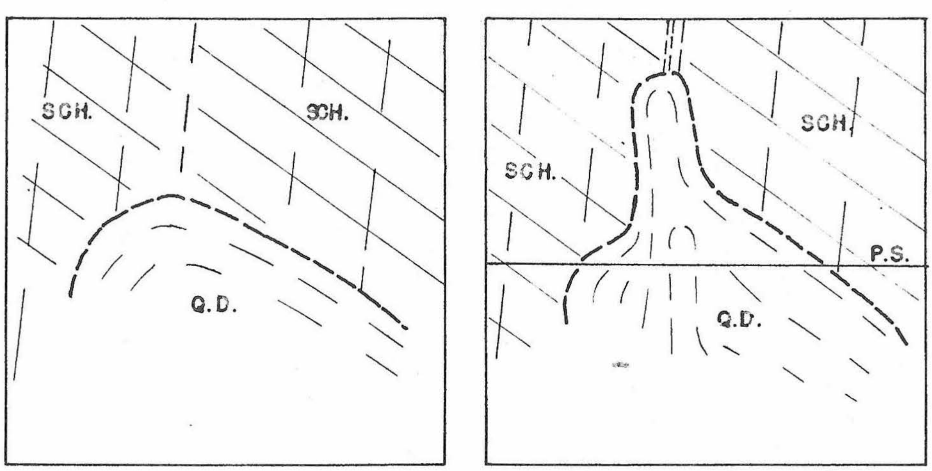

Figure 7.

Vertical E-W cross sections illustrating
possible modes of origin of the arch of flow layers.

Figure 5. Early intrusion along shear and later mushrooming.

Figure 6. Early intrusion paralleling schistosity and later offset of cover.

Figure 7. Late upsurge along shear.

P.S. = Present Surface

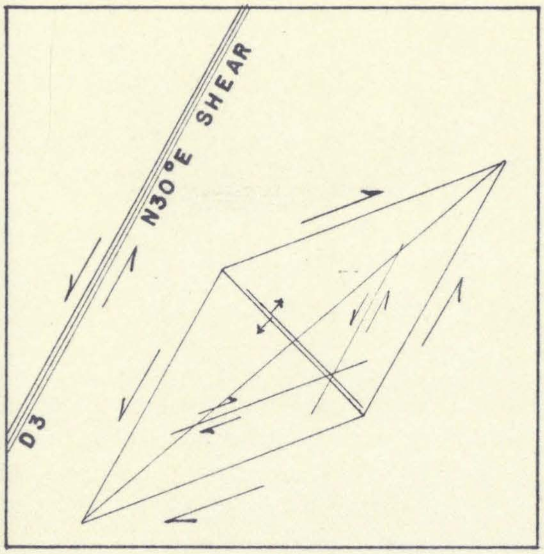

Figure 8
Effect of shear in northwest portion of stock.

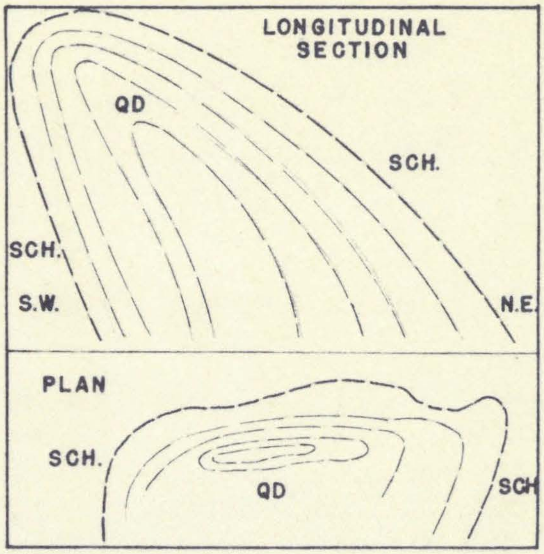

Figure 9
Reconstruction of arch of flow layers.

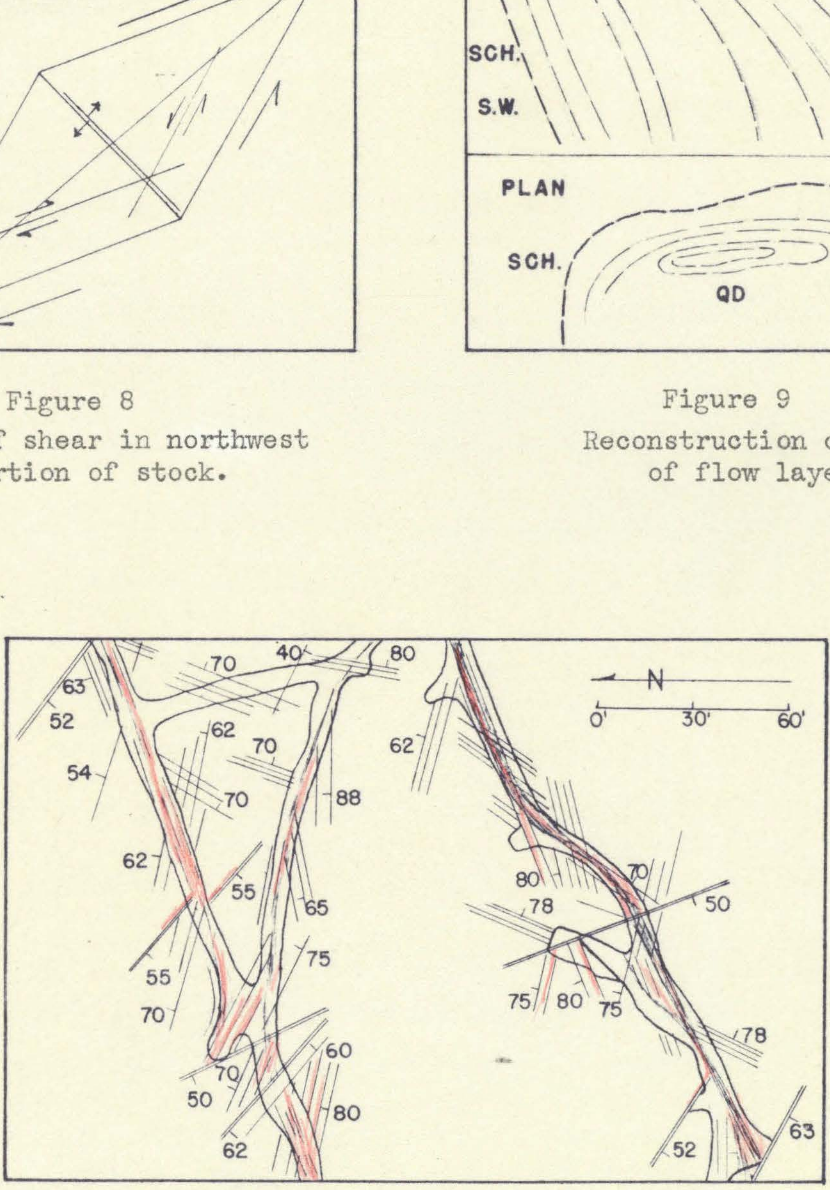

Figure 10
Effect of jointing on ore-bearing structures.

MAJOR THESIS

PART 2

STRUCTURAL PETROLOGY:
CRESTMORE, CALIFORNIA

Thesis

by

Alexander Smith

IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA
1947

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ILLUSTRATIONS

ABSTRACT

The general strike of the metasediments in the area is N.15°W. with dips at medium angles to the northeast. The limestone deposits at Crestmore and Jensen quarries are, however, on minor folds whose axial planes strike N.70°E.

Structural features which pitch easterly at -50° are (1) the general dip of the sediments (2) the axial line of the folds in limestone (3) the flow lines and dip of flow layers in the Perris quartz diorite (4) the dip of flow layers in the other intrusives (5) the axis of the girdle maxima for calcite optic axes. This direction is thought to be the a tectonic axis.

Strong optic axes maxima normal to the tonalite contact indicate the intrusive was forcibly injected and that the magma exerted pressure normal to the contact on the limestone. An unusual feature in the quartz diorite is two sets of flow layers having in common the flow lines therein.

INTRODUCTION

General Statement

The quarries at Crestmore, Riverside County, California are a famous mineral locality. Over 100 minerals have been described from the contact metamorphic assemblage at Crestmore in some thirty articles in the literature. The district also has many interesting problems in petrology and structural geology. The intrusives show primary flow structures and the limestones are suitable for peorofabric studies.

Previous Work in the Area

The mineralogy of the locality has been adequately described in the literature. Numerous papers by A. S. Eakle, W. F. Foshag, A. F. Rogers, E. S. Larsen and others describe individual minerals. J. W. Daly (1931 & 1935) presented the first comprehensive report on the geology of the deposits and the mode of occurrence of the contact minerals. A more recent paper by Woodford, Crippen and Garner (1940) in addition to presenting much new material, summarizes the earlier literature, contains a revised list of more than 100 Crestmore minerals and lists a bibliography of 28 articles dealing with the locality.

The general geology and physiography of the Perris block is described by Dudley (1935 & 1936). Osborn (1939) made a detailed study of the structural petrology and composition of the Val Verde tonalite outcropping some 12 miles to the south.

Purpose and Extent of Present Study

The present paper is principally concerned with the internal structures in the intrusives and adjacent limestone. No detailed study of the complex mineralogy at Crestmore was made. It was hoped that additional information on the origin and mode of occurrence of the minerals could be obtained by use of structural petrology. Also that a correlation of the primary flow structures in the igneous rocks and the petrofabric pattern in the limestone might aid to clarify the mechanics of intrusion.

Detailed maps were made of the Crestmore and Jensen quarries on a scale 1"-50'. Flow structures in the intrusives of the eastern part of the Jurupa Mountains were plotted on scale 1" = 1/4 mi. This area of about 11 square miles had been mapped by Daly (1931).

Oriented specimens of intrusive and limestone were taken from the 660 level of the mine at Crestmore. As

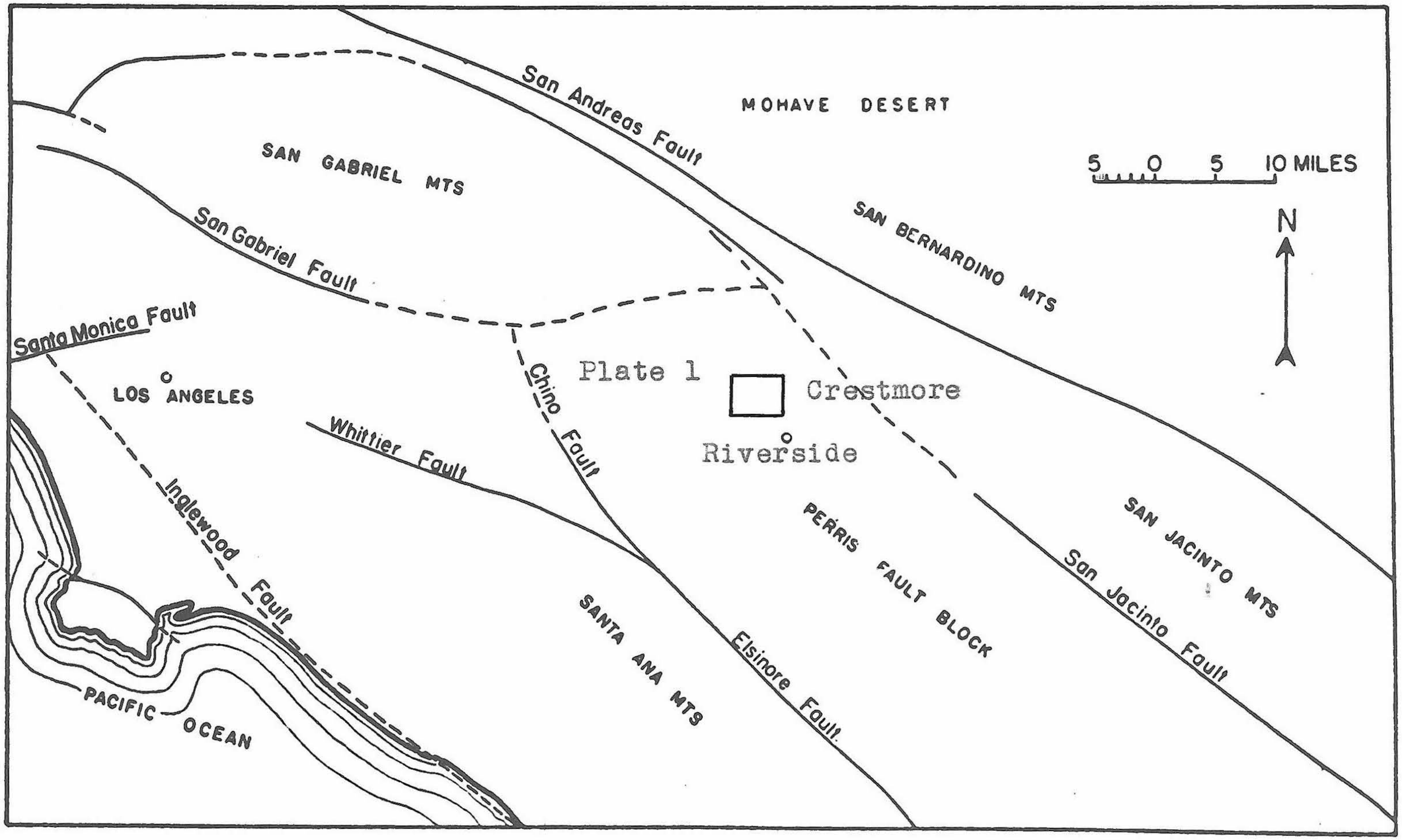

FIGURE 1.— Index map showing location of Crestmore District

(From map prepared by W. A. English, 1926, U. S. Geol. Survey, Bull. 768) the limestone is too coarse grained for the usual petrofabric analysis using the universal stage, a method was devised whereby the optic axes of the crystals could be measured under the binocular microscope. The results of fifteen analyses from Crestmore and three from Jensen quarries have been plotted.

Acknowledgments

The writer wishes to thank the Riverside Cement Company for quarry maps and sections. Garner A. Beckett, President of the Company and R. H. Wightman, Mine Superintendent, facilitated the work in every way possible. The project was under the supervision of Dr. Ian Campbell of the California Institute of Technology. The writer is indebted to Dr. Campbell for his help and guidance.

In describing the general geology of the area and the contact metamorphic assemblage at Crestmore, the writer has drawn freely on the published results of Daly (1935) and Woodford (1941).

GENERAL GEOLOGY

General Statement

Crestmore lies at the eastern end of the Jurupa Mountains, an east-west range paralleling the front of the San Gabriel Mountains. The district is part of a conspicuous topographic unit named by English (1926) the Perris Fault Block (Fig. 1). The block is about 20 miles wide and is bounded on the southwest by the Elsinore trough and on the northeast by the San Jacinto fault. It appears to have been down-faulted with respect to the higher San Gabriel and San Bernardino Mountains. The flood plain of the Santa Ana River and associated dune sands cover much of the area in the vicinity of Crestmore. The Jurupa Mountains represent higher portions of the block that rise above this plain.

The oldest rocks in the district are a series of metamorphosed sediments. These are intruded by five distinct plutonic rocks apparently related to the same general period of igneous activity.

Metamorphic Rocks

Daly (1935) proposed the name, Jurupa Series, for the metamorphosed sediments of the map area. The lower portion of the series consists of quartzites, quartz biotite schists and gneisses having a total thickness of over 3700 feet exposed. The base is cut off by intrusives. This portion of the series Daly called the Undifferentiated Complex.

Lying conformably on the complex are the limestones which are quarried and mined for cement manufacture. At Crestmore the commercial limestones occur at two horizons separated by 75-100 feet of quartzite and schist.

The lower horizon is known as the Chino limestone. This member is a white, bedded, coarsely granular marble. Graphitic beds believed to be derived from the metamorphism of carbonaceous beds are common near the base. Bands of yellowish calcite-brucite rock, predazzite, alternate with the white crystalline limestone. The Chino limestone lens is over 1500 feet long, dips at about 45° to the east and extends downdip at least 1200 feet. The maximum thickness found to date is about 300 feet. Most of the original outcrop and the Chino quarry floor as mapped by Daly (1931) have now been removed by mining. A glory hole some 200 feet deep marks the area now being removed by a block caving system (Wightman, 1944). The Chino limestone body is both underlain and overlain by quartz diorite.

Quartzites and schists some 75-100 feet thick lie between the two limestone horizons. These are similar to the underlying Undifferentiated Complex.

The upper limestone horizon is known as the Sky Blue limestone. It was quarried in the Lone Star, Wet Weather and Commercial quarries. The Sky Blue limestone differs from the Chino only in development of blue calcite and intense contact metamorphism near the intrusives. From this marble and the contact rock derived therefrom have come most of the rare minerals of the Crestmore assemblage. The blue color of the calcite is believed due to minute inclusions of graphite, carbonaceous matter or water. On heating the sample sputters and becomes white. The Sky Blue limestone has as first described by Woodford an arcuate outline. It forms an almost complete circle around the hill with the central portion occupied by intrusives and contact rock.

The age of the Jurupa series is not known definitely. The lower portion has been tentatively correlated with the Arrastre quartzite of Lower Cambrian Age (Daly, 1935), while the upper limestone portion is probably the equivalent of the Furnace limestone of Upper Paleozoic (Mississippian?) age. (Woodford, 1941 p. 353). Elsewhere on the Perris block metasediments similar to Daly's Undifferentiated Complex have been called the Elsinore Metamorphic Series (Dudley, 1935), and correlated on the basis of lithology with the Triassic metamorphic series in the Santa Ana Mountains.

Igneous Rocks

<u>General Statement.</u> - A series of five or more related but distinct plutonic rock types are found in the area. The sequence of intrusions (Daly, 1935 p. 647) has followed the order - hypersthene diorite, granodiorite, quartz monzonite porphyry, granite porphyry and pegmatite dikes. The order and spatial relationships of the series suggest differentiation from the same parent magma and that the intrusives followed closely in point of time (Daly,1935 p. 647). Their age is known to be post Triassic and pre-Eocene (Dudley, 1935). They are probably of the same age as the Sierra Nevada intrusives i.e. Upper Jurassic.

<u>Hypersthene Diorite.</u> - The oldest rock of the series, a hypersthene diorite, outcrops on the hills southwest of Crestmore. Normally the rock contains zoned basic andesine, but near the border becomes porphyritic in texture with labradorite phenocrysts and andesine groundmass. The femic minerals are hypersthene, hornblende and biotite. Quartz is present but is much less abundant than in the quartz diorite, the second intrusive in the series. The rock shows in places a platy structure due to the alignment of femags and occasional inclusions.

Quartz Diorite. - The most widespread intrusive rock of the area is quartz diorite. On the basis of mapping by Dudley (1935) quartz diorite (tonalite) is believed to underlie an area of at least 150 square miles on the Perris block. This rock is the same as the granodiorite of Daly (1935) and the Val Verde tonalite of Ransome and Osborn (1939). It is a light grey medium grained intrusive. Most of the femic minerals are green pleochroic hornblende and biotite. Oligoclase-andesine with minor orthoclase are the feldspars present.

The tonalite clearly intrudes the hypersthene diorite. Along their common border, dikelets of quartz diorite are seen penetrating the older rock. Blocks of the diorite are numerous in the tonalite. The tonalite-schist contact relationships are not so clean cut. The quartz diorite intrudes the schist but some contacts are gradational and irregular, suggesting that assimilation may have been important during emplacement of the rock. Osborn (1939) found that in the Val Verde district "The tonalite grades into the schist through first a tonalitic gneiss containing bands high in quartz and biotite, and second a gneiss resembling the quartz biotite schist but containing bands high in feldspar. In the transitional zone the foliation of the tonalite is parallel to the bedding planes of the schist."

Basic inclusions are common in the Perris quartz diorite. The inclusions are xenoliths derived from the hypersthene diorite and the quartz biotite schist of the Jurupa Series. Osborn (1939) studied inclusions in the Val Verde tonalite petrographically and reached the same conclusion.

The quartz diorite has a gneissic structure due to the platy alignment of biotite, feldspars and inclusions. There is also a linear parallelism of elongated inclusions and hornblende. These flow structures are described in detail in a later section.

Quartz Monzonite Porphyry. - Occurring as dikes and pipe like masses a quartz monzonite porphyry cuts limestone and earlier intrusives. It is probably the equivalent of the Cajalco quartz monzonite described by Dudley (1935) and the granite of the Val Verde district (Osborn, 1939). It is a light brownish-grey massive rock with abundant quartz, nearly equal quantities of orthoclase and oligoclase, and scattered grains and aggregates of pale green pyroxene. Quartz occurs in micropegmatitic intergrowth with orthoclase.

Granite Porphyry. - In the western part of the Jurupa Mountains granite porphyry is quarried as a building stone. The occurrence is outside the map area but is of interest in the igneous sequence. It is chiefly microcline and quartz with oligoclase, orthoclase and biotite. It intrudes the Perris quartz diorite and is in turn cut by pegmatites.

Pegmatite. - An abundance of pegmatite dikes occur in the hills adjacent to the quarries. They range in width from a few inches to as much as 25 feet. Some can be traced for a mile or more. Many show banding parallel the walls (Daly, 1935). The outer bands are of thin layers (1/2"-1") composed of graphic intergrowths of quartz and albite. The inner zone having a width of about one-tenth of the total thickness of the dike is composed of extremely coarse feldspar (albite and microcline) and quartz with the occasional development of black tourmaline and biotite.

In the Crestmore quarries the pegmatites are more lensy in outline and variable in composition than is the case in the adjacent hills.

Contact Rock

The minerals for which Crestmore is famous occur in contact rock formed by the pneumatolytic alteration (contact metamorphism) of the Sky Blue limestone. Both Daly (1935) and Woodford (1941) concluded that the contact rock is related to the intrusion of the quartz monzonite porphyry. These authors have described the mineral assemblage in detail.

The porphyry is separated from the Sky Blue limestone by 5-100 feet of contact rock. The most widespread type, that occurring next to the porphyry, is composed primarily of grossularite garnet with or without grass green diopside. This garnet rock is a massive aggregate. On the limestone side of the garnet zone there is in places rapid gradation to rock composed mainly of pale green or brown idocrase. Outside the garnet and idocrase zones the rare minerals merwinite gehlenite and spurrite developed in the outer portion of the contact zone. A late pneumatolytic or early hydrothermal stage acting on the limestones and earlier contact rocks deposited various hydrous minerals e.g. epidote, clinzoisite, wilkeite, chondrodite. On further cooling zeolitic minerals such as crestmoresite, riversideite and foshagite formed probably as alterations of wilkeite. The sulfides, galena, sphalerite, chalcopyrite and pyrite occur sparingly in the contact rock and adjacent limestone.

The peripheries of the larger quartz monzonite intrusives show endomorphic effects such as (1) increase in amount and basicity of the plagioclase: (2) increase in percentage of femic minerals and change therein to diopside, diallage, augite and grossularite garnet: (3) often complete disappearance of the quartz.

The earlier quartz diorite intrusion effected recrystallization of the limestone and developed small contact metamorphic zones containing spinel grossularite and wollastonite. The later pegmatites also show limited contact zones containing such boro-silicates as tourmaline and axinite.

STRUCTURAL GEOLOGY

Structure in the Metamorphic Rocks

General Statement. - Most of the metamorphic rocks of the area trend west of north but the limestone bodies at Crestmore and Jensen quarries appear to be close folded along N.70°E. axes.

Quartz Biotite Schists and Quartzites. - The quartz biotite schists and quartzites of the lower portion of the Jurupa Series have in the area a relatively uniform trend. They strike north to northwest and dip at medium angles to the northeast. Schistosity parallels the original bedding in the metasediments. Planes of easy parting in these rocks are the schistosity and steeply dipping "cross" joints normal thereto, i.e. striking about N.70°E.

In contrast to apparent uniformity of structures in the Undifferentiated Complex are the rapid variations in trend found in the limestone bodies at Crestmore and Jensen quarries.

Limestone at Crestmore Quarries. - The outcrop of the Chino limestone trends northerly and dips 45° east. This is nearly parallel to the schists on the hill west of Crestmore. Within the Chino body in the central portion on the 660 level (Plate 3) the strike is N.30°E. At the south end both on the 660 level and on surface it is N.40°W. This suggests the development within this limestone of the same arcuate structure apparent in the overlying Chino quartzite and Sky Blue limestone.

Before the start of block caving operations the outcrop of the Sky Blue limestone outcrop continued south in an arc from the west end of the Lone Star quarry to the south end of the Commercial quarry. It probably connected with the limestone there thus closing the arc. The limestone in the Lone Star and Commercial quarries strikes northeast and dips southeast. That on southwest side of the arc strikes northwest and dips northeast. This suggests that the Sky Blue limestone is folded into a plunging syncline whose axial plane strikes northeast and dips southeast and whose axial line pitches east at about -50°.

The trough of the syncline (?) has been intruded by quartz diorite and quartz monzonite porphyry. Near the quartz monzonite much of the limestone has been altered to contact rock as described above.

Limestone at Jensen Quarry. - The limestone and schist area at the Jensen Quarry (Plate 4) is nearly surrounded by quartz diorite. Nearly 50% of the metasediments exposed consist of a mixture of impure limestone, quartz biotite schist, quartzite, and contact rock. Part of the schist may be similar to Osborn's "tonalitic gneiss."

The general trend of the formations is easterly with the average dip steeply to the south. At the southeastern corner of the limestone area the trend swings in an arc suggesting a tight fold plunging easterly as at Crestmore.

Structure in the Igneous Rocks

<u>General Statement.</u> - The plutonic rocks of the area show two main trends (Plate 1). The first, north to northwesterly, nearly parallels the schistosity of the intruded metasediments. The second, about N.65°E. parallels the cross joints in the Complex, and the tight folds at Crestmore and Jensen quarries.

<u>Hypersthene Diorite.</u> - Southwest of Crestmore outcrops of hypersthene diorite extend for two miles in a zone trending S.65°W. The greatest width exposed is about 1/2 mile.

<u>Quartz Diorite.</u> - The larger masses of quartz diorite appear to trend north to northwest parallel to the

Undifferentiated Complex. Apophyses and dikes of the tonalite strike about N.65°E. paralleling cross joints in the schists.

<u>Quartz Monzonite Porphyry.</u> - Dikes, small plugs, and irregular bodies of quartz monzonite porphyry, occur in the same S.65°W. trending zone as the hypersthene diorite. At Crestmore the porphyry bodies east of the Commercial quarry are arcuate masses in the enclosing contact rock. They appear to plunge northeast parallel to the axis of the syncline (?). To the southwest on the strike of the zone there was formerly exposed in the Chino limestone a small plug and an arcuate dike of the porphyry (Daly, 1935).

<u>Pegmatite Dikes.</u> - Most of the pegmatite dikes of the area trend about N.20°W. parallel to the trend of the quartz diorite. On the hill west of Crestmore the principal dikes dip westerly at 50° to 80°.

STRUCTURAL PETROLOGY

General Statement

Flow structures in the various igneous rocks of the area were mapped employing the technique developed by Hans Cloos and his co-workers. It was planned to add to the structural picture by a petrofabric study of the limestone using the universal stage. As most of the limestone is too coarsely crystalline to be suited to this technique, a method was devised whereby the poles of optic axes of the calcite crystals could be plotted accurately on the usual petrofabric diagram.

Because the orientation of the intrusives may have caused preferred orientations for the calcite in the limestone, the structures in the intrusives will be described first.

Flow Structures in the Intrusives

General Statement. - The flow layers and flow lines in the various intrusives show a distinct parallelism with the structures in the Jurupa Series (Plate 1). As described above the outlines and trend of the intrusives are in general concordant with these features. Adjacent to areas of Undifferentiated Complex flow layers nearly parallel either the schistosity or the cross joint direction in the Complex. At Crestmore and Jensen quarries the internal intrusive structures are arcuate paralleling the folding in the limestone. Flow lines have a general pitch easterly at medium angles.

<u>Hypersthene Diorite.</u> - A platy alignment of inclusions and femic minerals was mapped in the diorite. In the central portion of the large outcrop southwest of Crestmore the flow layers trend northerly and dip easterly at 25°. i.e., parallel to the general trend of the area and the eastern contact of the diorite. Along the southern margin of the body the layers strike N.65°E. paralleling the contact.

<u>Quartz Diorite.</u> - Throughout most of the area mapped (Plate 1) flow layers and flow lines are visible in the Perris quartz diorite. The intrusive contains numerous inclusions apparently derived from the Undifferentiated Complex and the hypersthene diorite. These inclusions are tabular, discoidal, ellipsoidal, or spindle shaped. Platy structure is shown by the alignment of inclusions and biotite; lineation, by the parallelism of elongated inclusions and hornblende crystals.

An unusual feature of the flow structures (Figure 2.) is the development of 2 sets of flow layers

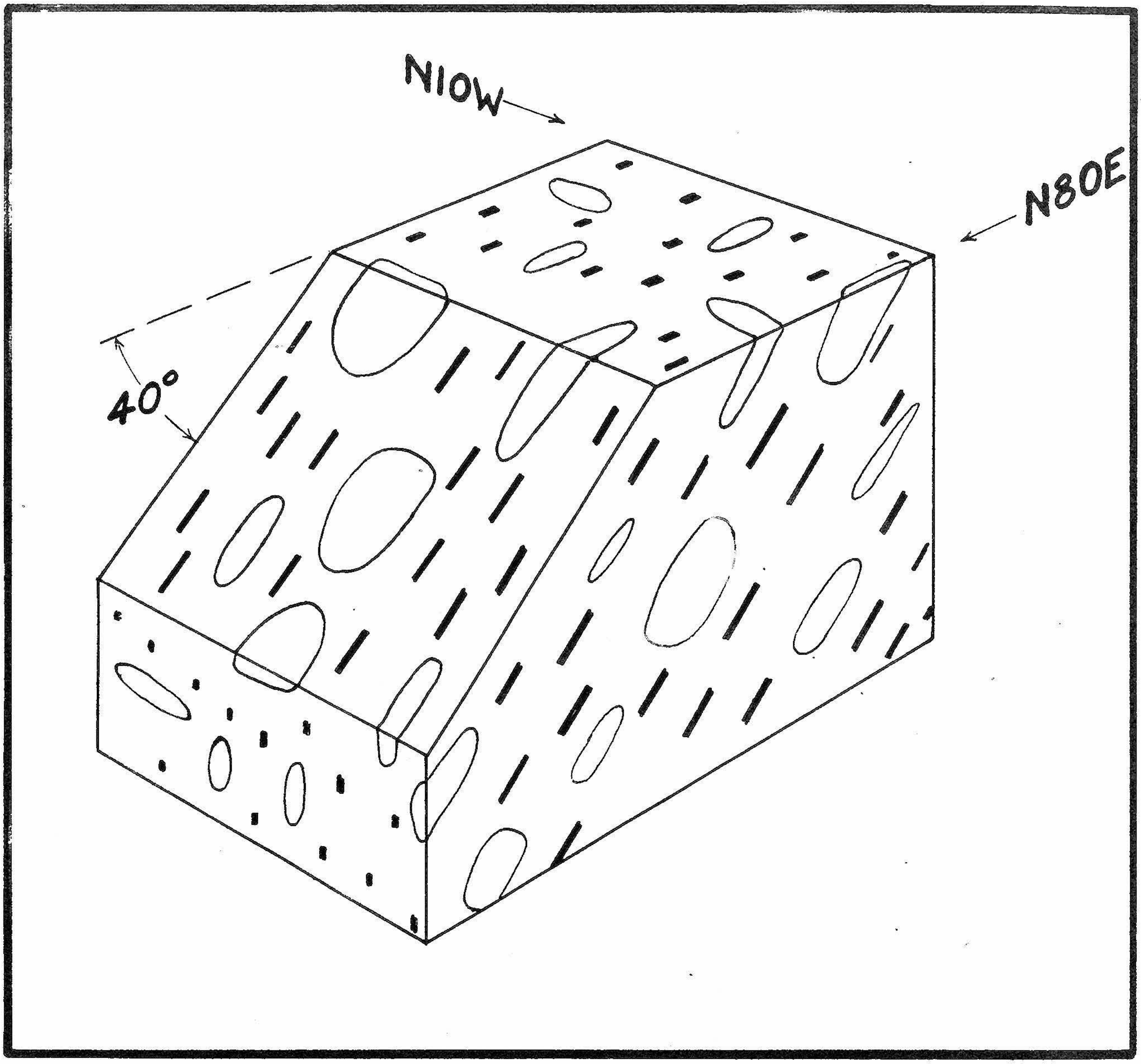

Figure 2. Diagram of flow structures in the Perris quartz diorite showing alignment of inclusions and hornblende. Flow layers show two preferred planes, N.10°W. dip 40°NE., and N.80°E. vertical.

with the flow lines paralleling their intersection. One set of layers has an average strike of N.10°W. and dips at about 40° easterly. The other set trends about N.80°E. and dips nearly vertical. The first set shows platy alignment of inclusions and some biotite; the second, only alignment of inclusions. The lineation of hornblende crystals and inclusions is common to both sets of layers.

This might be more clearly explained as follows - Let X, Y and Z be the greatest, mean and least geometric axes, respectively, of inclusions in the quartz diorite. In the small outcrop under consideration there are for example about 30 inclusions exposed. Nearly half of them show one orientation Type 1 and most of the balance show another preferred orientation Type 2. Their axes are oriented (direction and angle of pitch) as follows -

	Type 1	Type 2
X	N.80°E. -40°	N.80°E. -40°
Y	N.10°W. 0°	S.80°W. -50°
Z	S.80°W. -50°	N.10°W. 0°

The X Y planes of the inclusions are the planes of flow layers. The layers then have two orientations, Type 1. (N.10°W., dip 40°NE.), and Type 2. (N.80°E.,vertical). The flow line direction X (N.80°E. -40°) is common to both orientations of flow layers.

Along the eastern side of the hill between Hauser and Crestmore quarries, the flow layers and lines have a fairly uniform trend as described above. On the western slope southeast of Hauser quarry a reversal of dip of flow lines and layers suggests a local arch structure. However, this may result from the effect of the mass of hypersthene diorite.

North of Jensen quarry near the margin of the schists the lineation pitches easterly at small angles. Surrounding the Jensen quarry is an arc of steeply dipping flow layers. There is only a suggestion of a second preferred orientation of the inclusions on this arc. Flow lines where noted pitched at 70° or over. To the west of this arc inclusions are few and the flow structure faint.

At Crestmore (Plates 2 & 3) the flow layers in general parallel the contact with the older rock. Lineation is not so highly developed as to the west, but where determined it pitched easterly at low to medium angles. The flow layers in the quartz diorite adjoining Sky Blue limestone curve to parallel the limestone arc. On the 660 level (Plate 3) the flow layers in the tonalite dip parallel the limestone. On going west from the hanging wall of the Chino limestone the lineation flattens from 45° to 0° suggesting a flattening of the structure as the synclinal (?)

axis is approached.

The pegmatites dikes of the area (Plate 1) trend almost normal to the lineation in the quartz diorite. Between Crestmore and Hauser quarries the dip of the dikes where it could be measured increases from 50°W. to 70°W. suggesting that the dikes occupy a fan of cross joints related to the quartz diorite intrusion. However, the dikes cut the quartz monzonite porphyry without change of trend.

<u>Quartz Monzonite porphyry.</u> - In the outcrops of quartz monzonite porphyry southeast of Hauser quarry the flow layers strike northeast. At Crestmore (Plate 2.) the layers in the arcuate masses of porphyry dip northeast. Lineation is not conspicuous; it appears to pitch easterly.

<u>Interpretation.</u> - The general easterly trend of the lineation indicates that the direction of movement of the magmas was upward from the east at medium angles (Balk 1937 p. 7). Evidently there was a zone of folding or weakness striking N.65°E. through Crestmore. The trend of the hypersthene diorite and quartz monzonite porphyry along the extension of this zone suggests that this feature antedates the period of intrusion.

The presence of two preferred orientations for the platy alignment of inclusions in the tonalite may be difficult to explain. These orientations parallel the two principal contact planes for the intrusives. These planes are also planes of easy parting in the schists. The apparent anomaly might be explained by the hydromechanics of flow in magmas. An alternate explanation would be that the quartz diorite developed "in situ" by the palingenesis or assimilation of schist and hypersthene diorite, and, that the two preferred orientations for inclusions result from partial assimilation of blocks bounded by faces of the preferred orientations.

The axial line of the fold at Crestmore quarries and possibly that at the Jensen quarry parallels the lineation in the tonalite. Osborn (1939, p.929) found folds of similar orientation in the Val Verde district. Here in the schist, near the contact with the tonalite, the beds are commonly folded about an axis which parallels the dip of the schist. At Val Verde, too, lineation in the tonalite pitches easterly paralleling the dip of the schists. At Crestmore sharp folds plunging easterly occur on both hanging and footwall of the Chino limestone. This suggests that folding at Crestmore and Jensen quarries may be related to the mechanics of intrusion. There is also the possibility that the Jensen and Crestmore areas became engulfed in the tonalite magma and were oriented in the direction of lineation in the same manner as smaller inclusions.

Calcite Orientation in the Limestone

<u>General Statement.</u> - Thirty oriented hand specimens were taken from the Chino limestone on the 660 level at Crestmore and from the Jensen quarry. The orientation of the optic axes (c axes) of the calcite crystals were measured under the binocular microscope or reading glass. To do this a needle pointing in the c axis direction was attached to a calcite cleavage rhomb. This was used as a model and fitted on the calcite crystal in the hand specimen, with cleavages of model and crystal parallel. The orientation of the needle was measured giving the position of the optic axis of the crystal. The orientations were plotted on the usual lower hemisphere projection of the standard Schmidt equal area net. Only 14 of the oriented specimens were suited for study by this method. Contour density diagrams of these specimens are shown in Plates 5 and 6.

It was not possible to measure as many grains as in the usual petrofabric diagram using the universal stage. However, the crystals are large and are representative of the hand specimen. Some as large as 1/2" x 1" x 2" were present in a few specimens. Twinning is common. Crystals with 2 directions of twinning are common. In a few all three sets seemed present.

Crestmore Quarries. - Conventional density diagrams for a suite of specimens taken from the Chino limestone on the 660 level of the mine are shown on Plates 5 and 6. The location of the specimens are shown on Plate 3. The positions of the maxima and their variations across and along the limestone body are shown diagrammatically on Plate 3.

The diagrams show maxima lying in a complete or partial girdle. The girdle is common to all diagrams from Crestmore. It is not a simple great circle girdle as some maxima appear to be on two small circle girdles lying on either side of a common great circle girdle. This relation for calcite optic axes maxima is to be expected when the pole of the calcite twins lie on a great circle. This is discussed below. The pole or axis of this girdle would pitch about S.75°E. at -54°.

Specimens near the margin and contact with the quartz diorite show strong maxima nearly normal to the contact (see diagrams for specimens 38, 39, 43, 60 and 58). A composite diagram (Plate 6) for specimens 39, 60, 58, 56 located near the footwall shows strong maxima normal to the contact in a partially developed girdle.

A suite of 6 specimens (38, 39, 41, 42, 45, 43) taken across the limestone body show the same girdle. Strong E-45° maxima, normal to the contact, occur in those specimens near the contact and strong N.S. maxima show for the specimens (41, 42, 45) in the central portion of the body. A composite diagram of this suite is shown on Plate 6. The similarity of orientation of maxima and girdle in the central part of the body can be seen by comparison of diagrams for specimens 41 and 61.

Jensen Quarry. - The only specimens (62, 64, 65) taken at Jensen quarry and suitable for analysis by this method were close to quartz diorite contacts. Density diagrams and a composite for these specimens appear on Plate 6; their location and maxima diagrams, on Plate 4. The specimens show strong maxima of the optic (c) axes nearly normal to the contact, and partial girdles as at Crestmore. The composite shows a girdle striking north and dipping 50°W. The pole to the girdle pitches easterly at -40°.

Interpretation of orientation in calcite tectonites. - Some of most significant work in Structural petrology has been done in the study of calcite tectonites. Felkel (1929) and Sander (1930) determined the mechanism of grain deformation in such rocks. Their results are given by Knopf and Ingerson (1938 p.163). Fairbairn discusses the work clearly in his "Structural Petrology of Deformed Rocks", 1942. The plates used in the following outline are from this book.

Plate 7

Fabric diagrams of calcite orientation

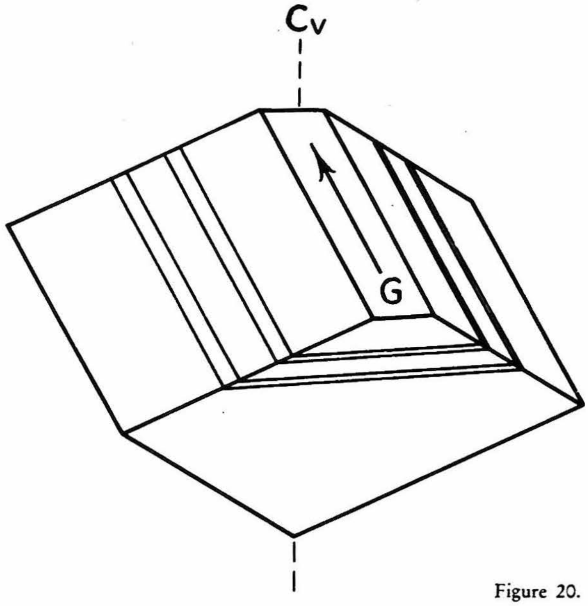

Figure 20.

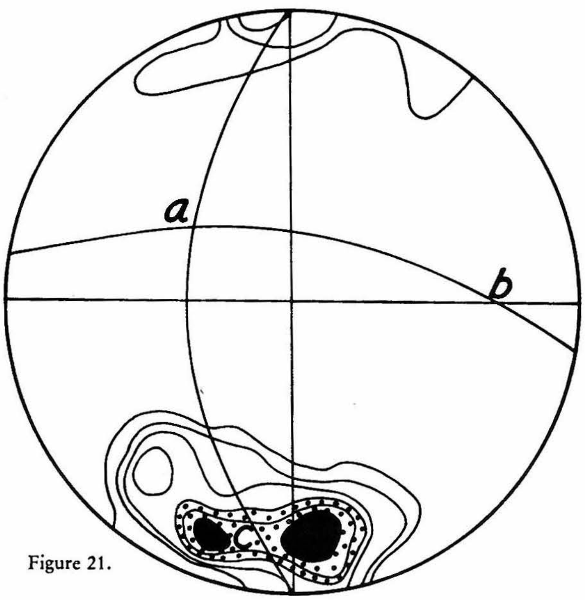

Figure 21.

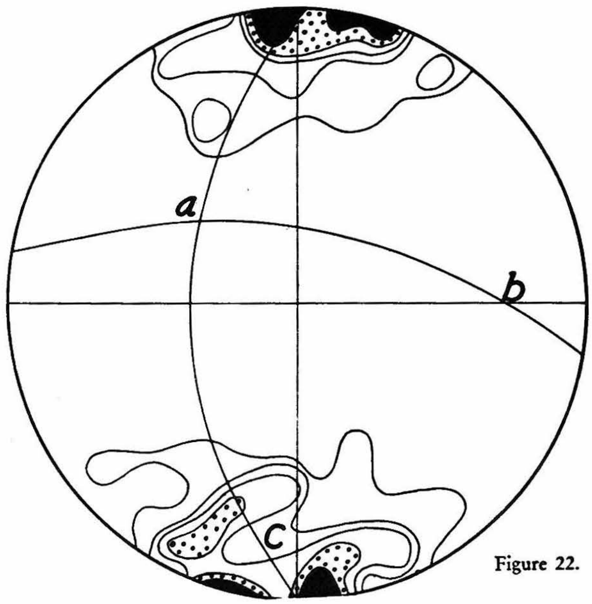

Figure 22.

Figure 20. Calcite cleavage rhomb showing orientation of one of the three sets of (01$\bar{1}$2) twins. Top part of the rhomb parallel to a twin is removed in order to show the slip direction and direction-sense (arrow at G). c_v = vertical crystal axis. After Fairbairn and Hawkes (39).

Figure 21. 206 poles to (01$\bar{1}$2) calcite twins from marble, Hochfeiler, North Tyrol. Contours 8-7-6-5-3-1%. Modified from Sander (105).

Figure 22. 186 axes of the twinned grains in Figure 21. Contours 7-6-4-2-1%. Modified from Sander (105).

Plate 8

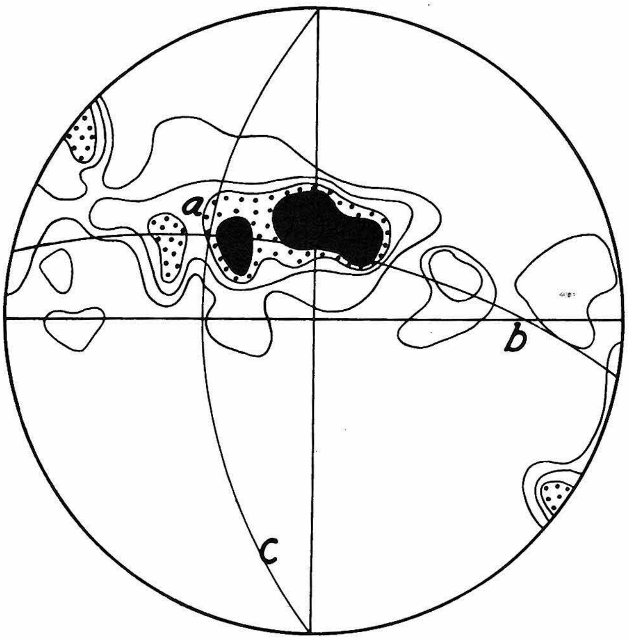

Figure 23. 201 "short diagonals" of the calcite twins of Figure 21. Contours 6-3-2-1%. Modified from Sander (105).

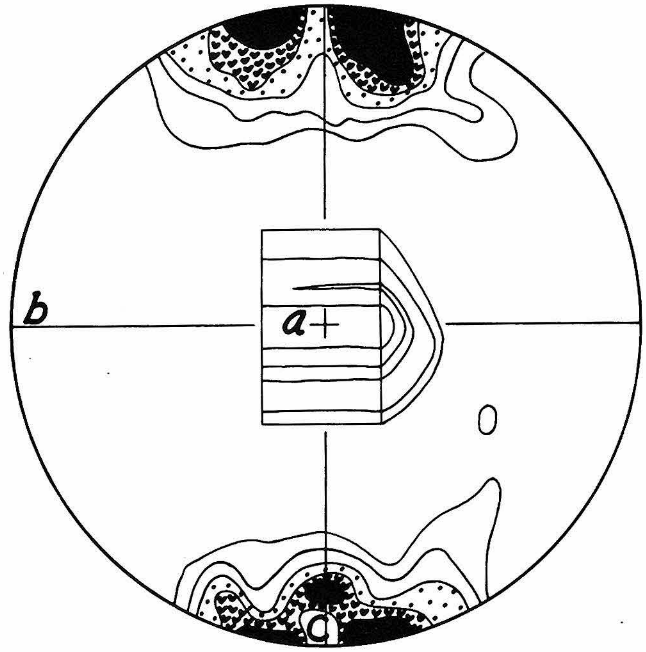

Figure 24. 330 poles to $(01\bar{1}2)$ calcite twins from calcareous phyllite-gneiss, near Mauls, South Tyrol. Contours 5-4-3-2-1%. Modified from Sander (105).

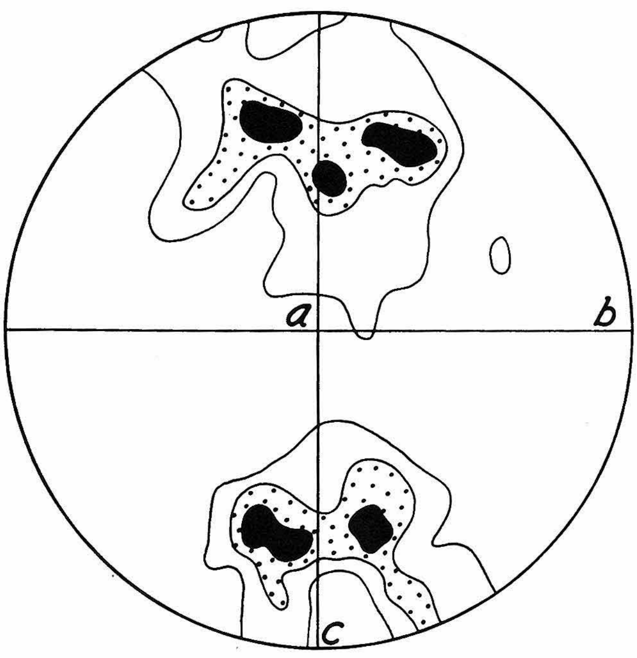

Figure 25. 416 axes of the twinned grains in Figure 24. Contours 4-2-1%. Modified from Sander (105).

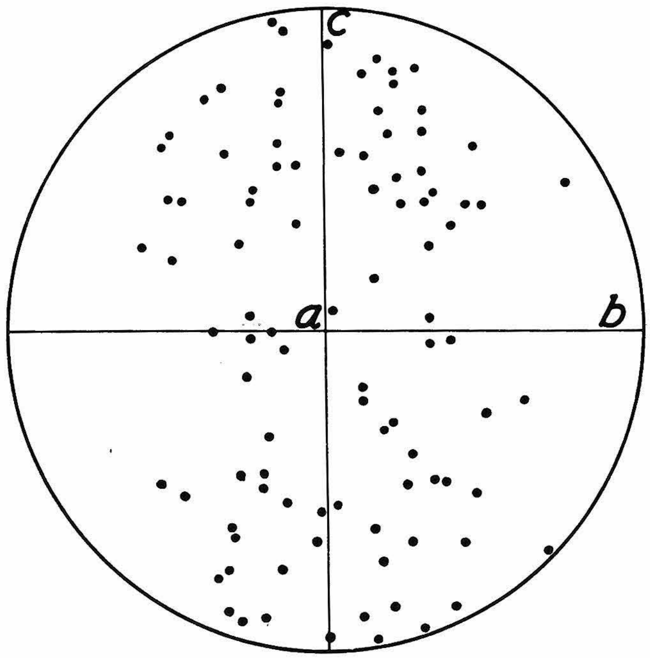

Figure 26. Collective diagram of the chief maxima of calcite axes from 7 selected tectonites. Modified from Sander (105).

Fabric diagrams of calcite orientation

late 9

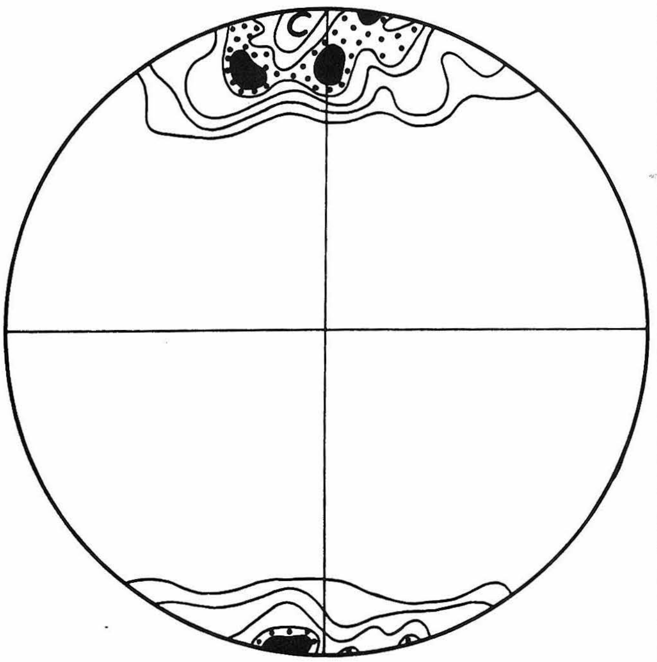

Figure 45. 246 calcite axes from marble, Brenner, Tyrol. Selection of large visibly deformed grains. Maximum contour 8%. Modified from Sander (105).

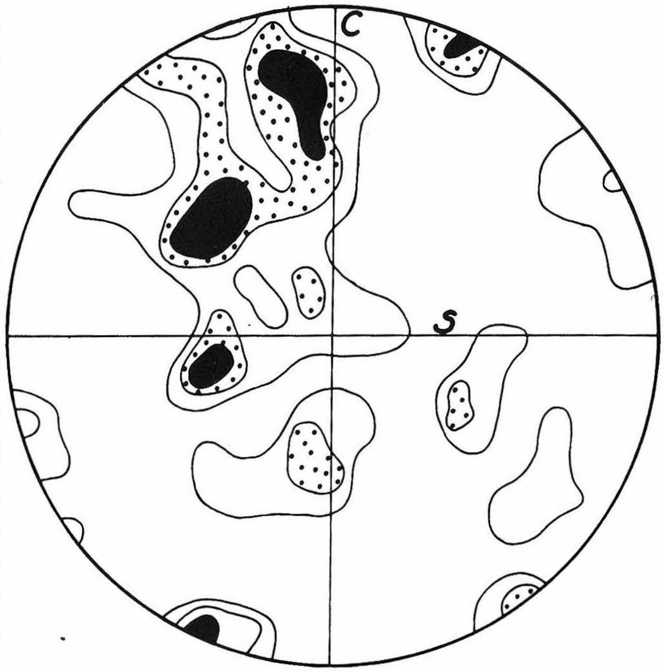

Figure 46. 224 calcite axes from the same marble as in Figure 45. Selection of small, "recrystallized" grains. Contours 5-2-1%. Modified from Sander (105).

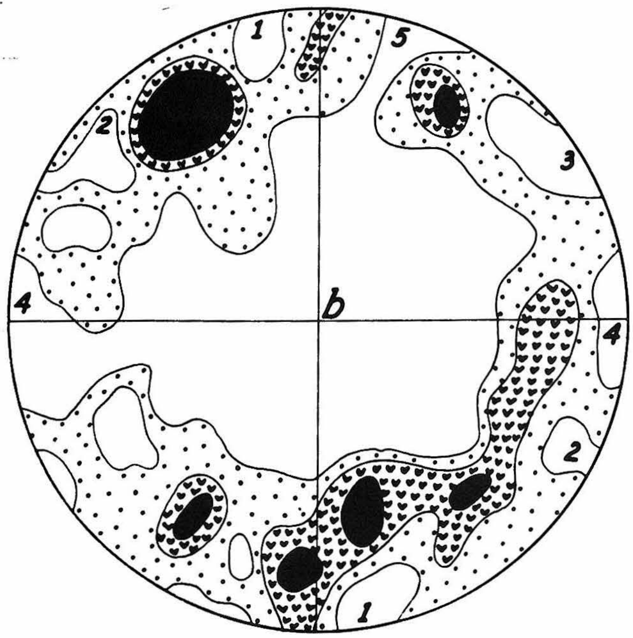

Figure 49. 263 calcite axes from lime phyllite, Brenner, Tyrol. The numbers refer to minima (areas in the main girdle of least concentration of axes). Contours 6-2-1%. Modified from Sander (105).

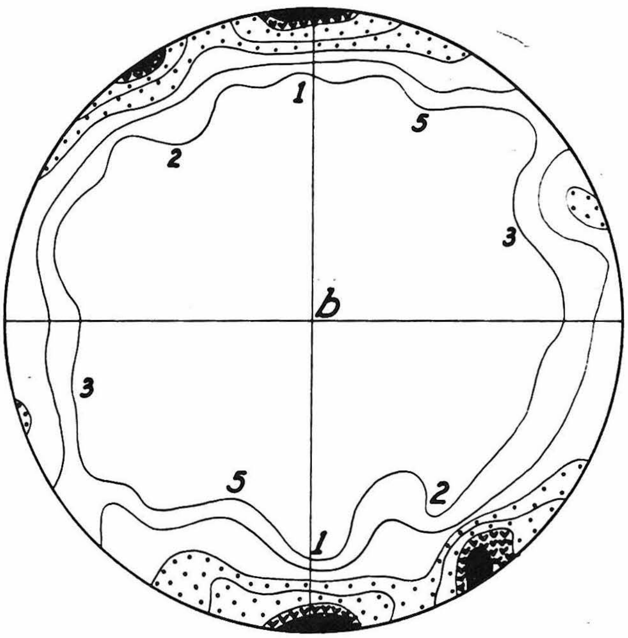

Figure 50. 117 poles to (01$\bar{1}$2) twins of calcite from the phyllite of Figure 49. The numbers have the same positions as in Figure 49 and are here related to the twin maxima. Contours 7-5-4-3-2-1%. Modified from Sander (105).

Fabric diagrams of calcite orientation

Plate 10

Fabric diagrams of calcite orientation

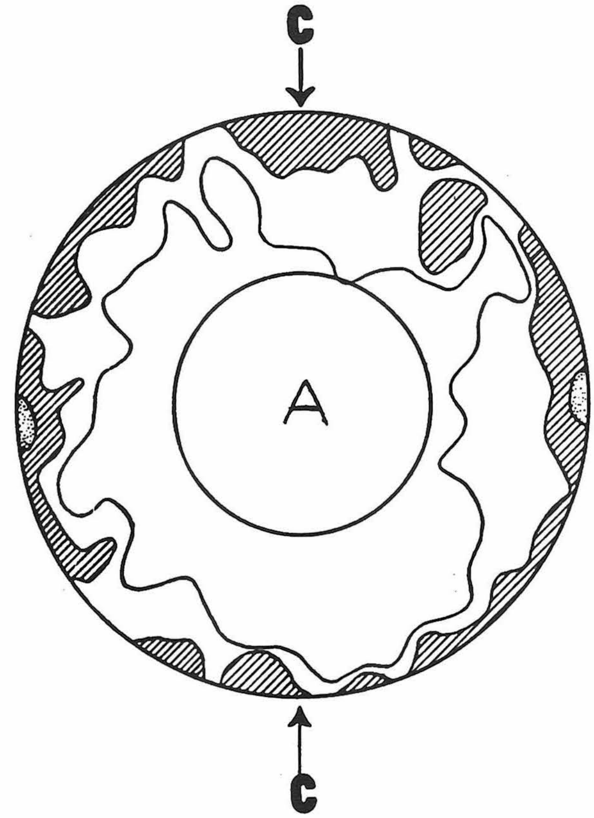

Figure 107. 200 poles to (01$\bar{1}$2) twin planes of calcite in marble, before deformation. No measurements in area marked A. Contours 4-2%. After Griggs (45).

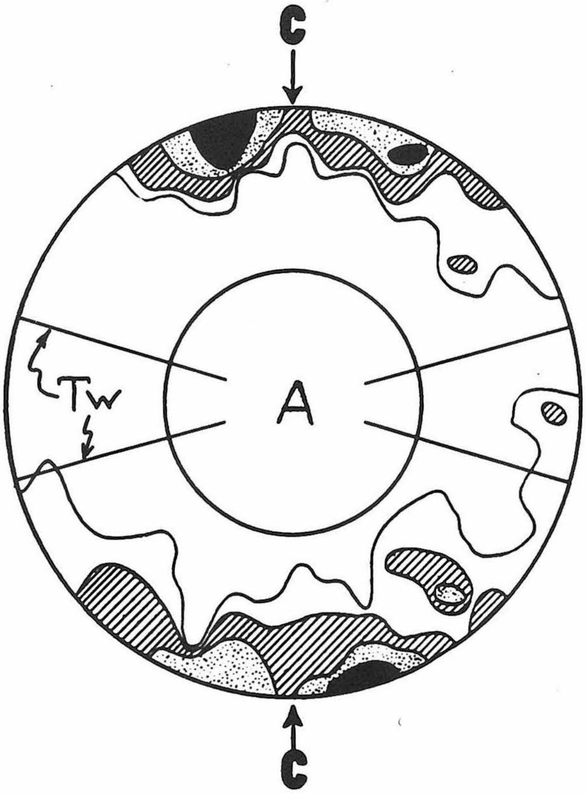

Figure 108. 200 poles to (01$\bar{1}$2) twin planes of calcite in marble, after deformation of 24% under confining pressure of 10,000 atmospheres, at room temperature. Maximum contour greater than 6%. C-C is the axis of compression, Tw represents the average twin plane positions. No measurements in area marked A. After Griggs (45).

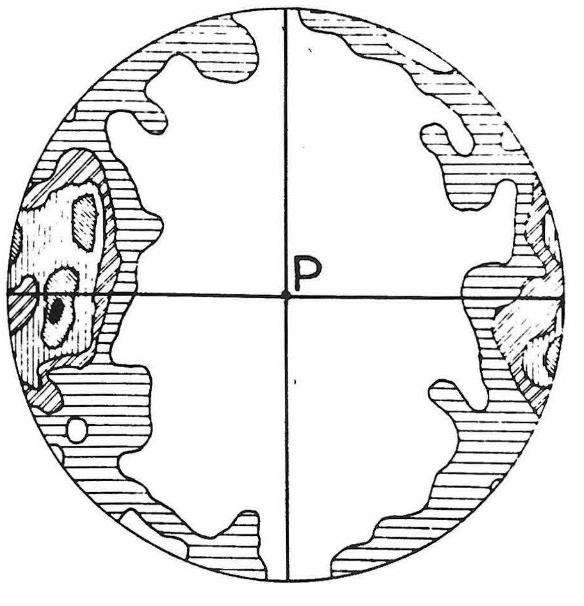

Figure 109. 209 calcite axes from Yule marble, before deformation. Contours 9-7-5-3-1%. After Griggs (49).

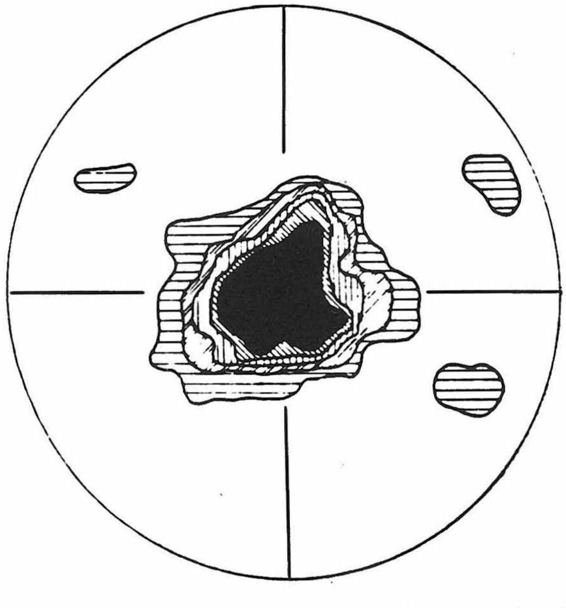

Figure 110. 163 calcite axes from Yule marble shortened 30% parallel to P in Figure 109, under 10,000 atmospheres confining pressure. Temperature 150°C., dry. Contours 9-7-5-3-1%. After Griggs (49).

Deformation twins are often found in calcite in tectonites. The composition plane of these twins is $(01\bar{1}2)$ and a maximum of three sets may develop in each crystal. The slip direction (glide line) and direction of movement on the composition plane is for twin gliding parallel to the short diagonal of the composition plane (Plate 7 Fig.2). This direction is the same as the line of intersection of any 2 adjacent cleavage faces. For translation gliding the twin plane acts as the translation plane without direction sense.

The deformation twin composition plane $(01\bar{1}2)$ commonly lies in the a b [x]tectonic plane. The poles of these twin planes in this case show a strong maximum at c (Plate 7 Fig.21); the poles the optic associated axes show a maximum about 26° from c (Plate 7 Fig.22). The "Short Diagonals" of the same specimen lie in a (Plate 8 Fig.23) the principal direction of movement. Fig. 24 shows the maximum concentration of poles to $(01\bar{1}2)$ calcite

[x] Sander's original terminology is used in this paper: b is fold axis, frequently parallel with lineation; a is perpendicular to b in the movement plane, and c is perpendicular to ab (Sander, 1930, p.119: ab = principal fabric plane; ac = symmetry plane; c = normal to ab, b (B) = principal axis).

twins at c while Fig. 25 shows the corresponding maxima for the optic axes. Figure 26 shows a collective diagram of the axes maxima of seven calcite tectonites compiled by Sander. They lie in a double symmetrical girdle zone about ac. The tectonic b axis is the pole of the girdles.

Sander found that the large deformed and twinned grains of a marble studied show a strong maximum near c while the small "recrystallized" grains show less orientation (Plate 9 Fig. 5, 45 & 46). In the study of a lime phyllite showing a concentration of calcite axes in a small circle about b, the poles to the $(01\bar{1}2)$ twins lay in a great circle normal to b (Plate 9 Figs.49 and 50). The maxima within the axes girdle lie 20º30° removed from the maxima within the twin pole girdle. According to Fairbairn (1942, p.28) this is statistical confirmation of the angular relation of 26° between the optic axis and the $(01\bar{1}2)$ poles of calcite. Griggs (1938) deformed marble under a confining pressure of 10,000 atmosphere and attained a shortening of 24% at room temperature. The orientation of the poles to the $(01\bar{1}2)$ twin planes before and after deformation are shown on (Plate 10 Figs.107 and 108). At 10,000 atmospheres and temperature 150° C the shortening was 30%. The optic axes reoriented under the deformation to parallel the direction of shortening (Plate 10 Fig.109 & 110).

Twinning was intensively developed. A similar experiment with carbonated water surrounding the marble specimen showed 30% shortening under only 1900 atmospheres. There was little development of twinning. Deformation might have proceeded by recrystallization flow. Bain (1940) found that "pressure reorients calcite of many fine-grained marbles with the basal plane perpendicular to the stress. This causes a high degree of orientation to the vertical or c axis."

In simplest terms the commonest preferred orientation for the optic axes of calcite in deformed rocks seem to be -

1. At or near the tectonic c axis, i.e. with the optic axes of calcite in the direction of the compressive stress.

2. As girdles normal to tectonic axis b.

b is the fold axis and in most cases the axis of rotation and the direction of lineation.

Interpretation of calcite orientation at Crestmore and Jensen quarries.-- All specimens taken from near the quartz diorite contact show strong optic axes maxima normal to the contact. This is thought to result from pressure normal to the contact exerted by the quartz diorite magma.

The girdle diagrams shown by specimens in the central portions of the Chino limestone are considered to result from rotation about the girdle axis. Considering the folds at Crestmore and Jensen quarries the girdle axis is the local b axis, but as discussed in the following section it appears to be the a axis in the regional pattern.

The girdle axis pitches easterly at -40° to 55° paralleling the axial line of the folds at Crestmore and Jensen quarries as determined by field mapping. This direction nearly parallels the dip of the schists and the lineation in the quartz diorite.

The similarity of girdles at Jensen and Crestmore and the fact that the maxima near the contacts fit into the girdle pattern suggests that the folding of the limestone might have been caused by the intrusion of the magma.

The data to hand is not sufficient to prove these conjectures. Similar patterns might have been developed in the marble in response to regional stresses long after the period of intrusion.

Tectonic Axes for the Area. - The general N.15°W. 40°NE., plane of schistosity and bedding is probably the ab or principal fabric plane of the area. If the prominent N.75°E. steeply dipping joints are cross joints they lie in the ac plane. This would make the a axis parallel the dip of the schists and the b axis almost horizontal in the ab plane, i.e., parallel the strike of the metasediments. These axes parallel those determined by Osborn for the Val Verde area.

If, however, axial line of the fold at Crestmore is taken as the b axis for the area then the positions of a and b are reversed.

The evidence appears to be more in favor of the first given orientation, b parallel the strike of the schists and a down dip. This fits in with the areal pattern. If b were down dip, i.e., pitching easterly at 40° there should be some evidence of large scale folding on E.-W. axes in the area. The pattern is more suggestive of regional folding along N.-S. axes.

If this is the case then the folds at Jensen and Crestmore quarries are examples of lineation and folding parallel to the a tectonic axis. These features are discussed by Cloos (1946 p. 25.31). Fold axes parallel to a are described from the metamorphic terranes in Scandanavia. Elongation of pebbles and stretching in the a direction are common. Folding in a (in the principal direction of movement) is a well known feature of ice flowage. This suggests an analogy for the origin of the folding in the easily deformed limestones.

The assignment of tectonic axes to the quartz diorite is subject to question. Genetically the lineation in magma flow should, in most cases, be the a tectonic axis, the direction of principal movement. The normal to the contact would be the c axis direction; b would then be horizontal parallel to the contact and flow layers. This would place the fabric axes parallel to those in the schist.

ECONOMIC CONSIDERATIONS

The outlook for large bodies of limestone that could be cheaply mined or quarried is not hopeful at Jensen quarry. The projection of the limestone fold to the east would be the most favorable place to explore but it is evidently deeply buried.

At Crestmore the Chino limestone body has evidently thickened in a E.W. direction parallel to the axial line of the fold. This thickening is largely by flowage. On the 660 level the flattening of the flow lines in the hanging wall quartz diorite may indicate the limestone is flattening rapidly as the axis of the fold is approached. Exploration to the east of the Commercial quarry might show up a similar thickening of the Chino limestone on the east limb of the fold.

Similarly the Commercial quarry limestone may, if not cut off by quartz diorite, steepen down dip and reverse in dip to connect with the east limb of the Sky Blue limestone.

The extensive development of contact rock in the trough of the syncline is an interesting example of structural control that may have parallels in pneumatolytic metalliferous deposits.

SUMMARY AND CONCLUSIONS

The general trend of the metamorphic rocks of the area is N.15°W. and dip about 40°NE. The limestone areas at Crestmore and Jensen quarries appear to be in folds whose axial planes strike N.70°E. and whose axial lines pitch easterly at -50°. The igneous rocks of the area show in their contacts and internal structures two main trends, one paralleling the N.15°W. 40°NE. attitude of the metasediments, and the other N.75°E. paralleling steep dipping cross joints in the sediments. Lineation in the Perris quartz diorite, the most extensive intrusive of the area, is easterly parallel the dip of the schists.

The poles to the optic axes of calcite in the limestone show a girdle pattern. The axis of the girdle pitches easterly at 50°. Strong optic axes maxima occur near the tonalite contact oriented normal to the contact. This indicates that the intrusive exerted pressure normal to its wall, i.e., the quartz diorite was forcibly intruded into the area.

The fold axis at Crestmore lies in a N.70°E. zone which was the locus of intrusions of hypersthene diorite and quartz monzonite porphyry. Structurally the contact rock may be related to these rocks or to the quartz diorite. The limestones at Crestmore may have been folded along this zone before intrusion of the quartz diorite but parallelism of the lineation in the tonalite and the girdle axis suggests that the folding was caused by the intrusion.

The fabric pattern at Crestmore is considered to be an example of folding and lineation parallel to the a tectonic axis.

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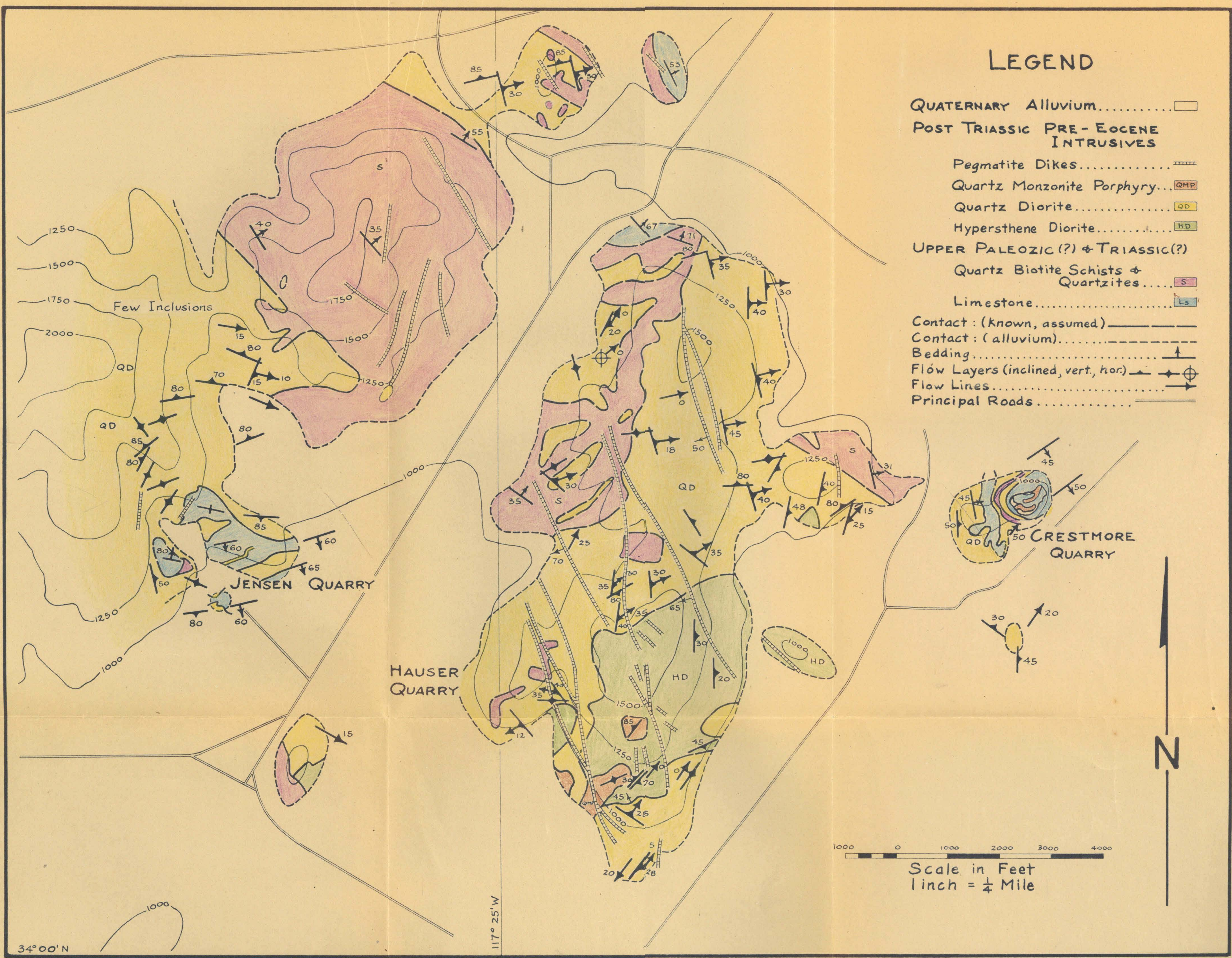
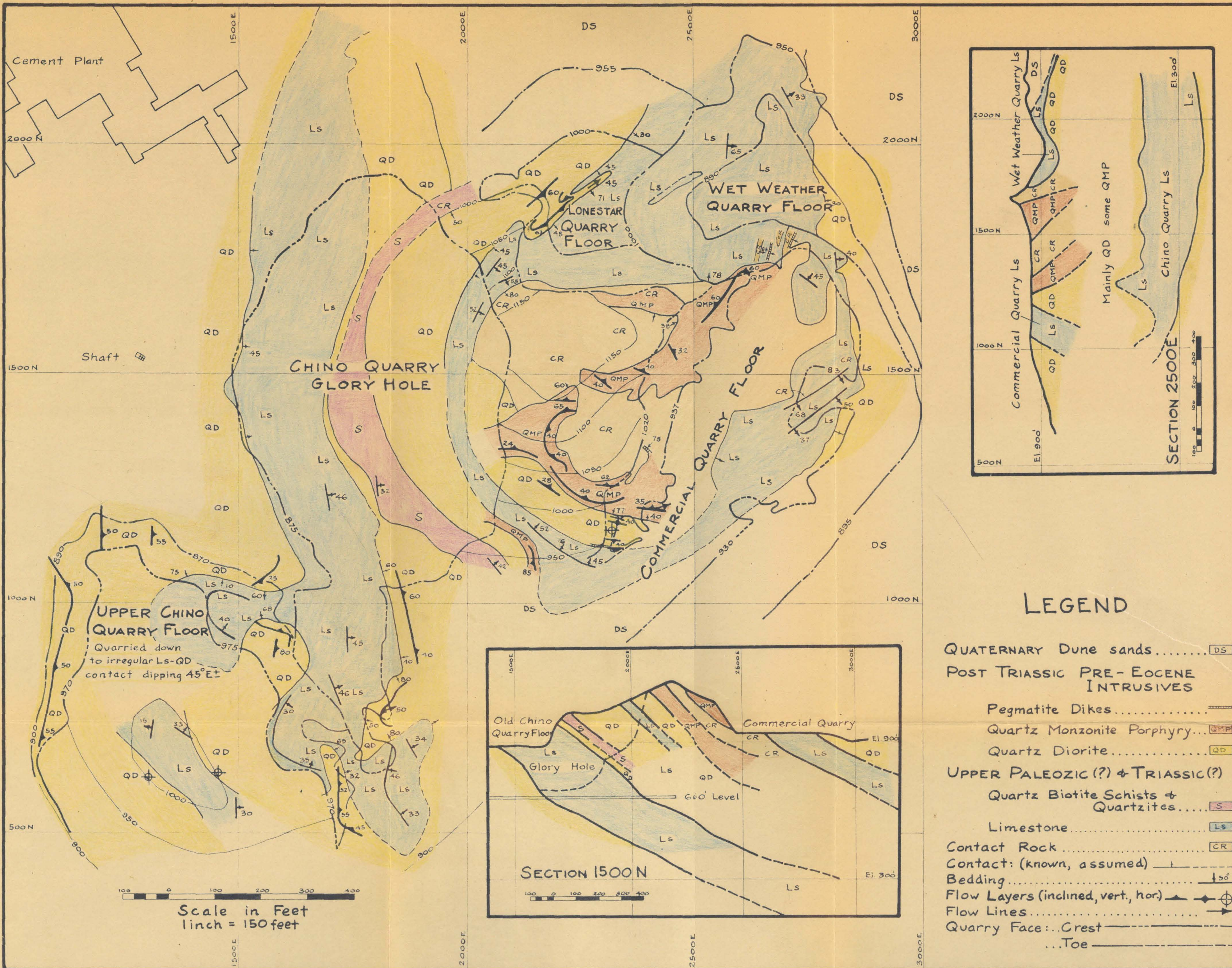
PLATE 1



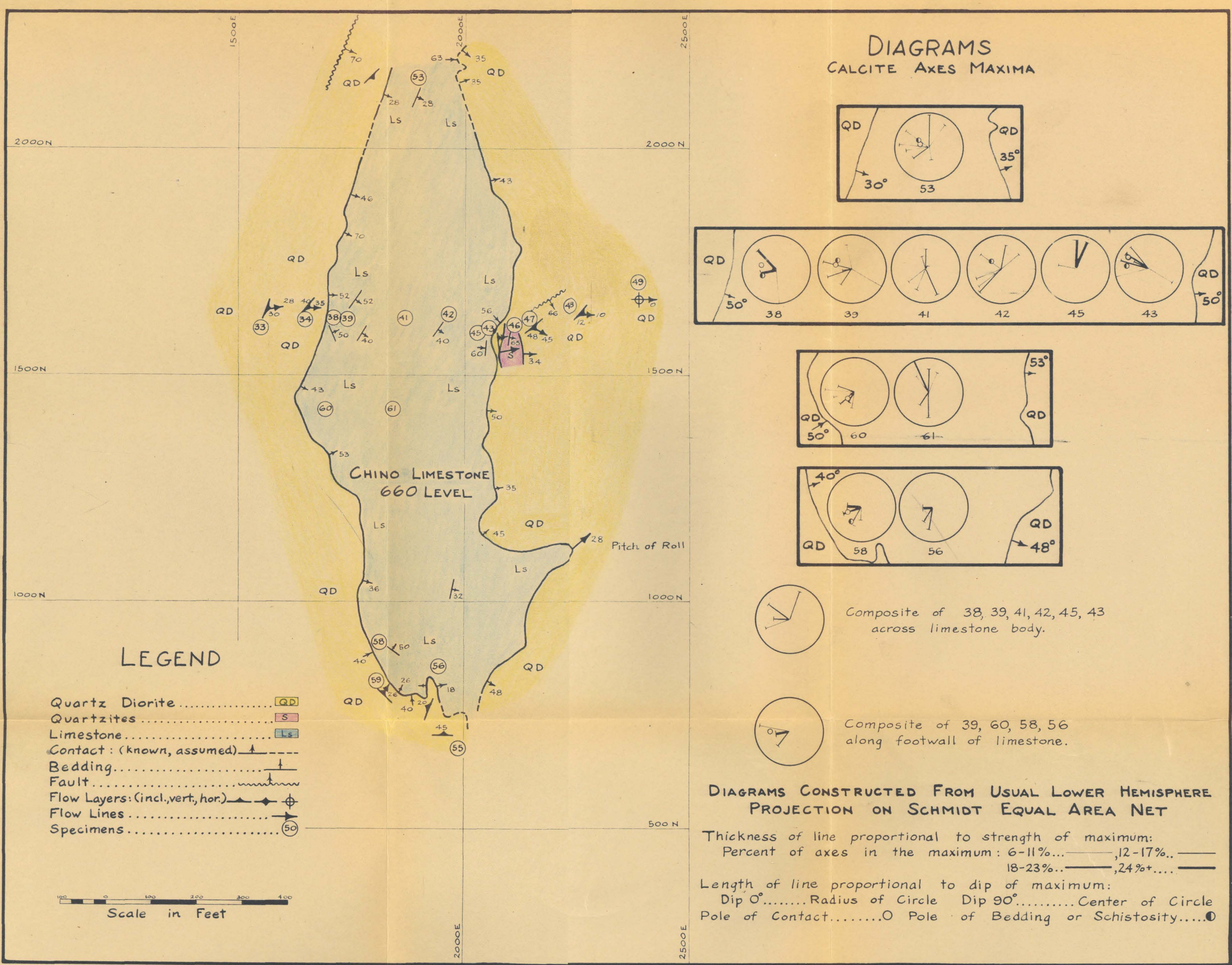
Structural Geology • East Portion of Jurupa Mountains
Riverside & San Bernardino Counties California 1941

PLATE 2



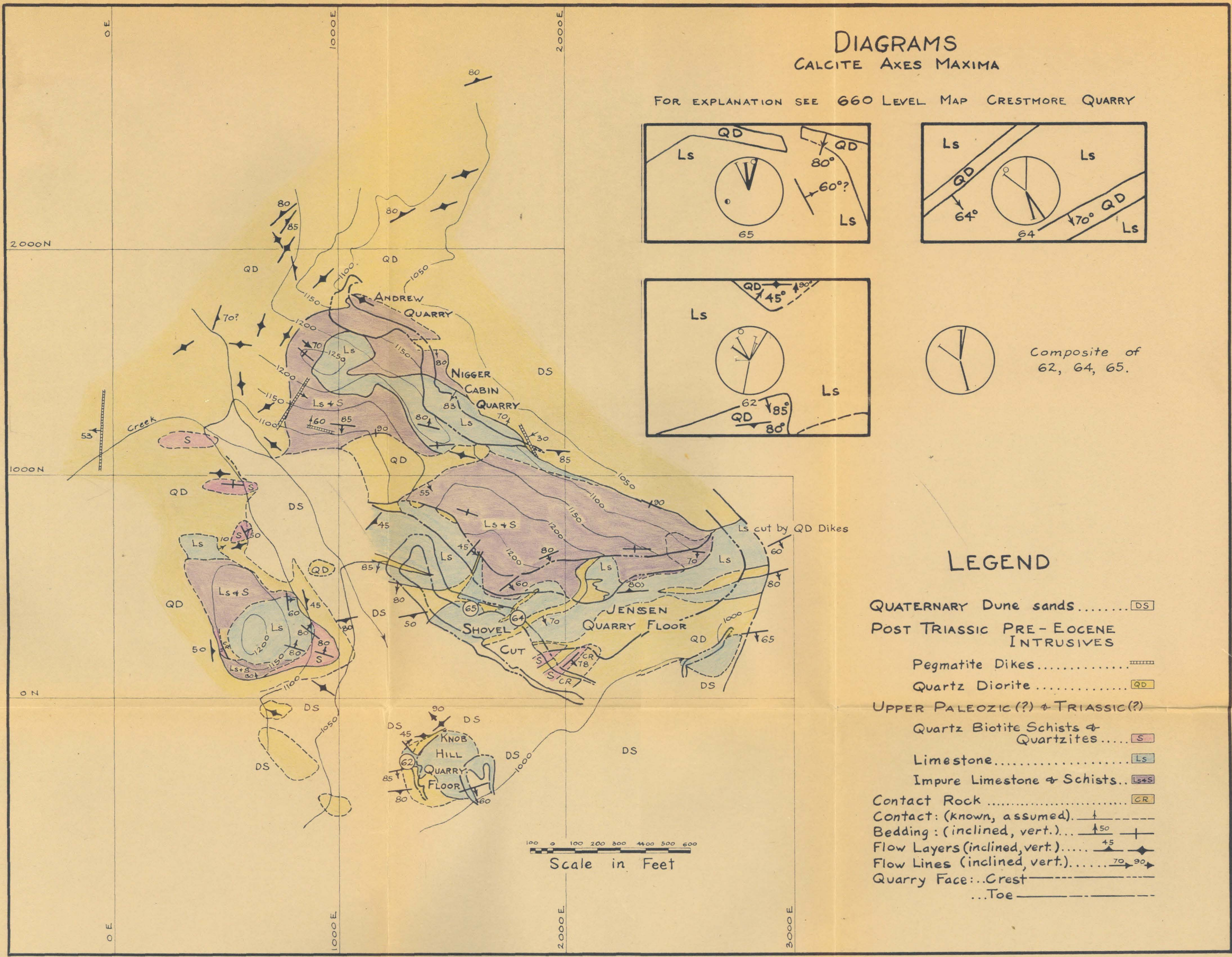
STRUCTURAL GEOLOGY · CRESTMORE QUARRIES
RIVERSIDE COUNTY CALIFORNIA 1941

PLATE 3



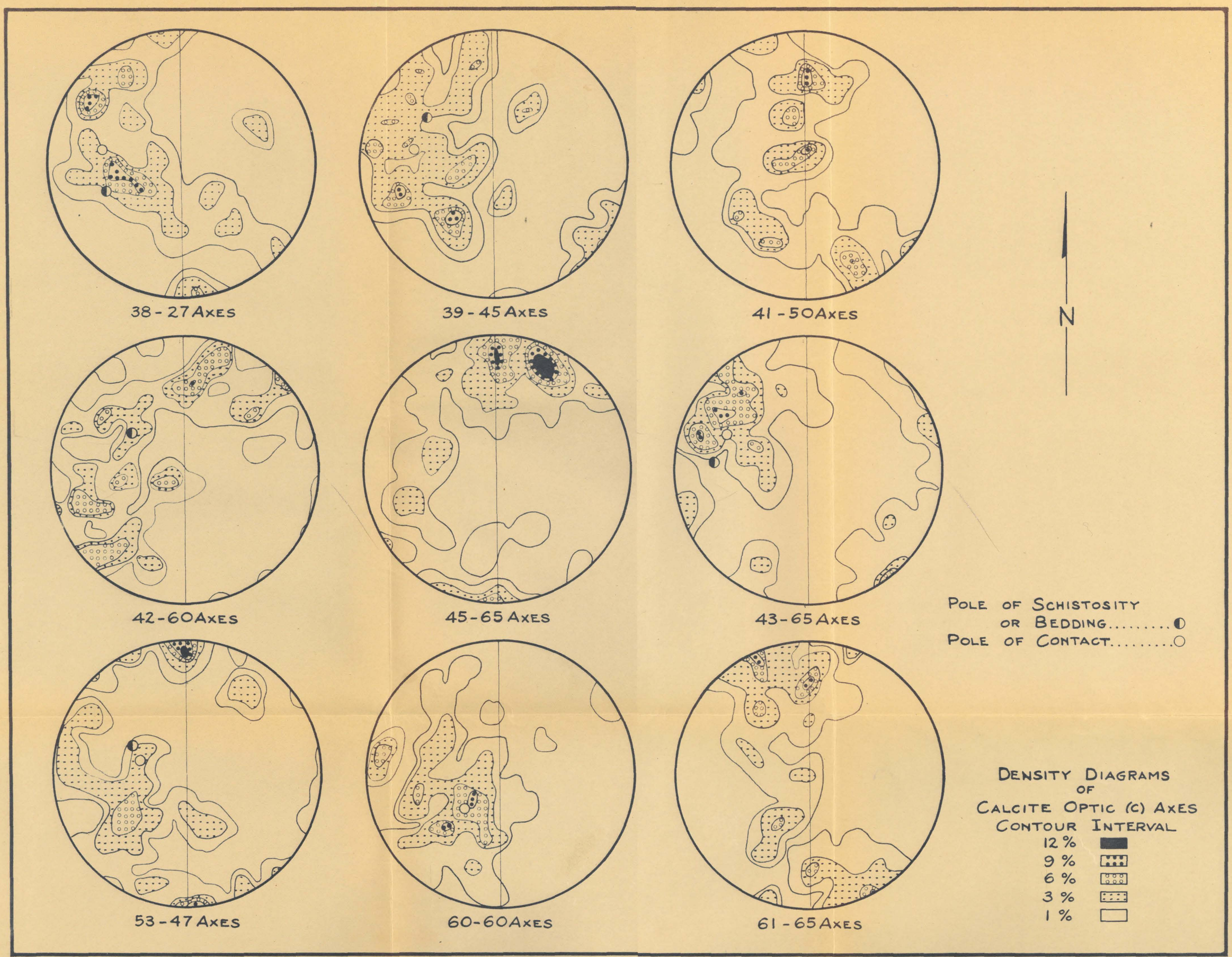
Structural Geology • Chino Limestone • 660 Level
Crestmore Quarries • Riverside County California

PLATE 4



Structural Geology • Jensen Quarries
Riverside County California 1941

PLATE 5



Petrofabric Diagrams
660 Level Crestmore Quarries

PLATE 6

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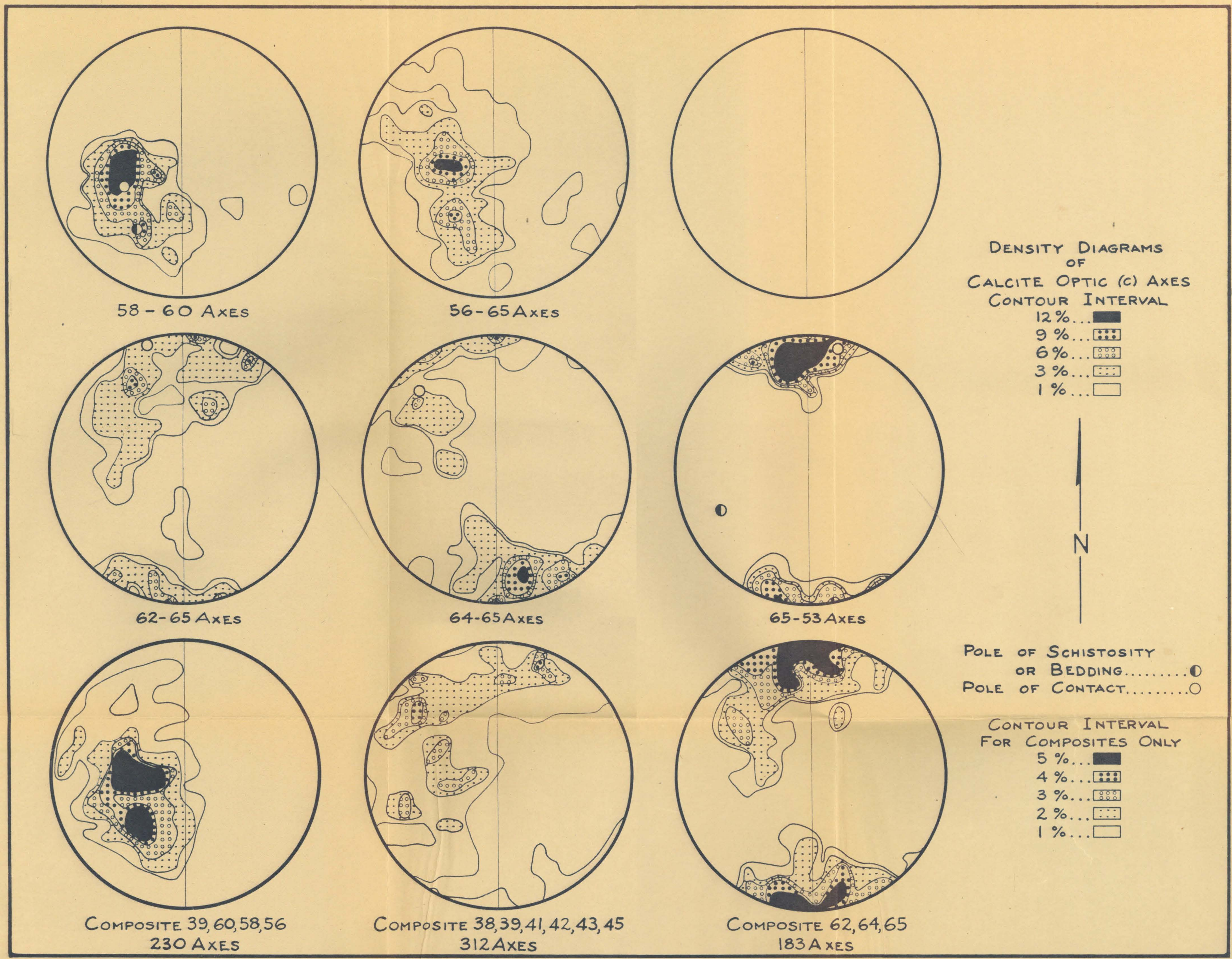

Petrofabric Diagrams
Crestmore & Jensen Quarries

MINOR THESIS

THE GEOCHEMISTRY AND PARAGENESIS OF THE ORES OF THE CACTUS MINE, KERN COUNTY, CALIFORNIA

Thesis

by

Alexander Smith

IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

CALIFORNIA INSTITUTE OF TECHNOLOGY

PASADENA, CALIFORNIA

1941

CONTENTS

THE GEOCHEMISTRY AND PARAGENESIS OF THE ORES OF THE CACTUS MINE, KERN COUNTY, CALIFORNIA

INTRODUCTION

This thesis embodies the results of a laboratory investigation of the ores and mill products of the Cactus mine. The primary purpose was a study of the association and distinction of the metallizing solutions as shown by the occurrence of the gangue and ore minerals.

This investigation has been correlated with geological and structural studies of the Cactus mine which are presented by Mr. John T. Jordan (Master's Thesis, California Institute of Technology, 1941).

Summary of Geology.

As the geology of the Cactus mine has been fully described in Mr. Jordan's thesis, only a very brief description of the ore deposits will be given here. The reader is referred to Mr. Jordan's thesis and accompanying maps for any details.

The Cactus mine is on the western slope of Middle Buttes in the Mojave desert about 9 miles northwest of the town of Rosamond. The mine, operated by the Cactus Mines Company, is comprised of three units, the Cactus or Cactus Queen mine, the Silver Prince mine, and the Cactus Hill pit. The deposits are epithermal gold-silver veins and replacement ores.

In the Cactus mine the vein occupies a faulted and brecciated zone on or near the contact between rhyolites of Tertiary age and older quartz monzonite. The vein strikes northeasterly and dips at a moderate angle to the southeast. The contact relations are structurally complex but in general the main mass of monzonite lies in the footwall and the main mass of rhyolite in the hangingwall.

The Silver Prince mine lies about 2400 feet N30E from the Cactus. The Cactus Hill pit workings are about 2200 feet N70E of the Cactus mine at an elevation 200 feet above the Cactus mine. This deposit is formed along a somewhat irregular altered zone, entirely within rhyolite.

Summary of Vein Structure and Mineralization.

The complex Cactus vein has been formed by several surges of hydrothermal solutions separated by periods of re-brecciation of the vein. The earliest solutions deposited barren bony white quartz. The succeeding transparent quartz carried common sulphide, gold, and ruby silver mineralization. Accompanying this quartz are minor amounts of an alunite-dickite gangue and mineralization of the following stage. The third main surge of solutions was rich in sulphates. The soft gangue consists of quartz, alunite and dickite. The accompanying mineralization is gold, argentite, and minor cinnabar, realgar and orpiment. Meteoric waters have had little effect on the hypogene mineralization although native silver may have been deposited by supergene solutions.

The deposit is very lightly mineralized. The total of the metallic minerals comprise less than 0.2% of the ore. The average grain size of the sulphides is of the order of 0.05 mm with a range of from 0.5 mm for a large grain down to blebs of a micron in diameter.

The Cactus Hill deposit has been formed by solutions of the third stage. The Silver Prince vein as exposed is intermediate in characteristics between the Cactus vein and the Cactus Hill deposits.

Methods and Technique.

Over 200 ore samples were taken at suitable intervals in representative areas throughout the mine workings. From these samples some 450 sawn surfaces were cut with a diamond saw and examined with a binocular microscope. This procedure was adopted with the particular purpose of studying the distribution of the various types of mineralization and their association with different types of gangue. The mineralogical details were determined from over 70 specimens which were selected from the sawn surfaces, mounted, polished and studied mineragraphically.

Special composite mill samples covering a seven day period (January 23-29, 1939) were run over a Haultain superpanner. The various products were weighed and assayed. The mill samples and the panner concentrates were studied under the binocular microscope and grains which could not be visually determined were identified by microchemical tests. In addition several of these products were mounted, polished and examined.

Location of Specimens.

Maps accompanying Mr. Jordan's thesis show the location of the specimens studied. They include suites taken in the following areas:

1.) CQ 105-145, down the shaft and adjacent stopes from the tunnel level to the 700 level, at 25 foot intervals.

2.) CQ 145-146, from the 500 levels native silver ores.

3.) CQ 132-139, from the N6-50 stope between the 500 and 600 levels.

4.) CQ 140-144 and 147, from the N7-230 stope between the 600 and 700 levels.

5.) CQ 45-104, from both along and across the three quartz bodies of N700 level.

6.) CQ 148-150, from the 800 level.

7.) CQ 192-224, from the Silver Prince 150 level.

8.) CQ 19-43, from Cactus Hill pit.

9.) CQ 151-181, alteration suite from 500 and 600 levels.

The specimen and polished section numbers (CQ 102) etc., appearing in the report, are given as references for the texture or mineralization being described and may be suitable for photo-micrographs or future correlation work.

Acknowledgments.

Earlier microscopic studies of selected specimens were carried out on the ore by Dr. Horace J. Fraser in 1936 and 1937. The present study by the writer was under the supervision of Dr. Fraser.

The writer wishes to express his sincere thanks to Dr. Fraser for his able supervision of the project and for his helpful and constructive criticism at all times. Mr. John T. Jordan worked together with the writer in the collecting of the samples. His knowledge of the geology of the deposit was especially helpful in correlating the laboratory and field investigations.

Particular thanks are due to Mr. Harvey S. Mudd and Mr. Roy W. Moore, not only for permission to personally collect samples and study the ore occurrence underground, but also for their continuing interest in the work and many helpful suggestions. The hospitality of the various mine officials was greatly appreciated.

Many of the ideas expressed in this thesis were reached independently by Dr. Fraser, Mr. Jordan and the writer, each using different modes of attack on the problem. Correlations not at first apparent to the writer, have been suggested by them and have been incorporated into this thesis.

MINERALOGY

In the ensuing discussion, the minerals present in the ores, as determined from polished sections and superpanner concentrates, have been divided into the following groups:

1. The common sulphides of the base metals.
2. The silver bearing minerals.
3. Gold.
4. Mercury and arsenic minerals.
5. The gangue minerals.
6. The supergene oxides.

1. Common Sulphides of the Base Metals.

The common sulphides include pyrite, marcasite, arsenopyrite, chalcopyrite, galena, sphalerite, chalcocite, covellite and bornite.

Pyrite. -- This is the most plentiful and widespread of the metallic minerals in the vein, but even so the total amount present is considerably less than 0.15% of the total volume of the ore. Moreover, it is the only sulphide characteristically present in altered wall rock adjacent to the veins.

In altered wall rock pyrite occurs alone (excepting minor arsenopyrite on 700 level Cactus and 150 level Silver Prince), but in the veins it is usually accompanied by other sulphides. It is found as isolated crystals or grains disseminated in transparent quartz, in dark grey quartz, and in alunite-dickite-quartz gangue.* It is rarely present in the barren white bony quartz. The grain size varies from minute blebs of 1-2 microns up to 0.7 mm, with the average about 0.05 mm. Although originally most of the pyrite in the veins may have had crystal outlines, these are now present in only about 30% of the grains. The crystals are corroded or replaced first by quartz in which they occur, then by later common sulphides and silver minerals, and finally by late soft gangue minerals. Even in the upper levels pyrite is rarely altered to limonite.

Marcasite. -- The contacts between pyrite and marcasite suggest that the two minerals crystallized at about the same time. The other common sulphides and the silver minerals are somewhat later although they are in the same transparent quartz and hence probably deposited from the same solutions. In some polished sections at least 40% of the FeS_2 is as marcasite occurring in units of several crystals or with pyrite. Marcasite is common in sections showing ruby silvers, sphalerite, galena and chalcopyrite.

Arsenopyrite. -- Though abundant locally, arsenopyrite is much more restricted in its distribution than pyrite or marcasite. A heavy dissemination of small needles of arsenopyrite is characteristic of a quartz vein on the 700 level of the Cactus Queen. In the

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*The alunite-dickite-quartz gangue is variable in composition. For the sake of brevity it is often referred to as the soft gangue in this thesis.

150 level ore shoot of the Silver Prince, arsenopyrite needles and rhombs reach a maximum size of 0.3 mm. Original arsenopyrite may be almost entirely replaced by covellite or silver minerals.

Arsenopyrite is found in the altered footwall monzonite between the 600 and 700 levels of the Cactus mine.

Chalcopyrite. -- In heavy sulphide mineralization, chalcopyrite occasionally comprises 40% of the sulphides present. Chalcopyrite, when abundant, is usually accompanied by sphalerite, galena, and/or a heavy silver mineralization. The early corroded pyrite is often surrounded and partially replaced by chalcopyrite.

In some places small blebs of chalcopyrite are found as replacement remnants of once larger crystals which have been corroded by soft gangue. These blebs can be distinguished only with difficulty from small gold grains which occur in a similar environment.

Galena. -- Galena is relatively uncommon and is found only where there is a heavy accompanying chalcopyrite-sphalerite mineralization. The galena has commonly been largely replaced by sphalerite or argentite.

Sphalerite. -- After the chalcopyrite and galena, sphalerite was deposited. It may make up as much as 65% of the opaque minerals present in some heavily mineralized specimens of the chalcopyrite-pyrite-silver mineral type of mineralization. Again, pyrite and sphalerite may be the only common sulphides found in a sample. Sphalerite is often rimmed with, or replaced by, argentite-stromeyerite or partly replaced by ruby silvers. It is of interest that no really minute blebs of sphalerite were found, but large grains up to 1 mm are common. Some complex grains containing sphalerite, chalcopyrite and ruby silvers reach a diameter of 1.5 mm.

Chalcocite. -- This is uncommon except in the arsenopyrite bearing ore on the 150 level of the Silver Prince. Here chalcocite occurs in isolated grains up to 0.4 mm and also as a rim around pyrite. Minor chalcocite occurs with covellite.

Covellite. -- Covellite is much more widespread and plentiful than chalcocite. It borders and replaces chalcopyrite, sphalerite, and occasionally pyrite. It also is a common associate of argentite-stromeyerite.

Bornite. -- This mineral occurs only as a reaction rim between covellite and chalcopyrite (CQ 144).

2. Silver-Bearing Minerals.

The common silver bearing minerals are argentite-stromeyerite, pyrargyrite and proustite. Less common are polybasite and pearceite. Native silver is abundant within its limited distribution. Freibergite is comparatively rare.

Argentite-Stromeyerite. -- The amount of argentite-stromeyerite present in the workings is about equal to that of the ruby silvers. It has a wide distribution and is the principal silver mineral of the "spotted" ores of above the 500 level. The ratio of stromeyerite to argentite varies; some relatively pure, sectile, isotropic argentite being found but ordinarily the mineral yields, on scratching, a black powder and is anisotropic. Together with covellite it borders and replaces the earlier common sulphides. Some grains of argentite show outlines of original galena crystals. It is generally accompanied by soft white non-calcareous gangue. The mineral often occurs in isolated blebs but occasionally shows a distribution controlled by fracturing. At times it is in contact with ruby silvers but evidently is later than any of them.

Vugs in the transparent quartz may contain small black sectile globules. Similar globules from the superpanner concentrate were proven microchemically to be argentite.

Pyrargyrite and Proustite. -- These ruby silver minerals, like argentite-stromeyerite, are widely distributed. They occur in isolated grains but commonly rim and replace the early common sulphides. They prefer to replace and associate with sphalerite, marcasite and chalcopyrite rather than pyrite. In the zoned mineralization of CQ 66 pyrite occurs only in the ruby silver zone. In specimens with heavy mineralization, ruby silvers may be intergrown with common sulphides to form complex grains of up to 3 mm in diameter. Narrow veinlets of proustite, occasionally with pyrargyrite, follow fractures cutting across several types of quartz.

Polybasite and Pearceite. -- They are much less common and less widespread than the ruby silvers and are found only in heavily mineralized specimens, containing the common sulphides and ruby silvers. Polybasite is commonly associated with chalcopyrite and pyrargyrite. Some large grains (CQ 130) show a "cracked porcelain" texture veined by argentite-stromeyerite. Pearceite occurs only where polybasite is present.

Freibergite. -- Freibergite occurs in small amounts in ore heavily mineralized with the common sulphides and silver minerals (CQ 38 and 82).

A few minute grains believed to be stephanite and miargyrite were noted.

Silver. -- Native silver occurs in isolated pockets on the 500 level (CQ 121), and on the south side of 7-100 stope at 635 feet (CQ 130). The rusty coating on the specimens containing native silver is dark brown in color. The silver occurs in plates, veinlets and blebs, principally along fractures, and is usually closely associated with limonite. There is some evidence that the silver is later than the limonite, as in CQ 4 it seems to follow fractures reopened along cracks filled with limonite (or hydrous hematite). In the rich native silver specimens, partly corroded pyrite and other sulphides may occur in typical isolated grains. These are not associated with the fractures followed by the limonite or silver.

3. Gold.

The gold occurs in several different forms and associations.

Gold with Common Sulphides and Ruby Silvers. -- The occurrence most easily distinguished is that in which the gold occurs in the complex units of the heavy common sulphide-ruby silver mineralization. In this association the gold is located on galena-chalcopyrite contacts or along the border of, or within, ruby silvers or sphalerite. The gold is later than the chalcopyrite and galena but earlier than the sphalerite. Grains in this association reach a maximum size of 0.08 mm.

Gold in Blebs of Soft Gangue. -- Fine gold occurs in blebs of soft gangue in the transparent quartz, in sugar quartz (CQ 99, 199, 144), and in calcite boxwork quartz (CQ 70). The blebs of gold are generally so minute (0.002 mm) that they are difficult to distinguish from chalcopyrite. Often they are apparently unaffected by KCN. In several specimens assaying over 2 ounces of gold per ton, these yellow specks were the only apparent source of the values.

Gold in Greenish Quartz. -- Coarse gold also occurs in greenish quartz and in transparent quartz intimately associated with the greenish quartz (CQ 54 and 202). Such gold may be accompanied by argentite. Fracturing has controlled the distribution of the greenish quartz, gold and argentite.

Gold in Late Soft Gangue. -- The late "soft" gangue of fine grained alunite, quartz and dickite, which veins the earlier quartz types, carries minute grains of gold. This gold is often tarnished (CQ 200). Specimens with this soft gangue often yield high gold values without any apparent mineralization. Accompanying this alunite-bearing gangue there may be a fine-grained silicification of porcelain or clay-like texture which occasionally carries a little cinnabar. This gold mineralization is characteristic of the upper or north end of the ore shoots on the 700 level and of the Silver Prince 150 level shoot, but is probably most extensively developed in the surface Cactus Hill pit.

Gold in Amalgam. -- On the superpanner a few globules of native mercury and amalgam were noted. This amalgam probably developed during the grinding of the ore. Some of the gold noted on the superpanner was actually electrum.

4. Mercury and Arsenic Minerals.

Cinnabar and Native Mercury. -- The presence of cinnabar and mercury were first determined in this ore from a study of the superpanner concentrates. This was confirmed by a chemical analysis (Smith-Emery Company) of the mill concentrates which showed 0.27% mercury present. This amount equalled that of the lead, and was two times that of the copper present.

In polished sections of the ore, cinnabar is apparently less readily identified since a much lower proportion of cinnabar to the other sulphides was found than in the panner concentrates.

Cinnabar occurs in fine grained porcellaneous alunite-dickite-quartz gangue (CQ 101), in the greenish quartz (CQ 76), or glassy sugar quartz. Vugs in a sugar quartz (CQ 75) with greenish cast contain grape-like clusters of black and silvery globules. Both give microchemical tests for mercury. The black globules may be cinnabar as the streak is red, the others may be amalgam.

Realgar and Orpiment. -- These minerals occur as minute grains in cavities filled with alunite and in specimens containing barite and alunite (CQ 101). These minerals appear to be associated with cinnabar.

5. Gangue and Non-Opaque Minerals.

Quartz. -- Quartz of several different types forms the bulk (probably over 90%) of the vein material but locally alunite, jarosites, barite and dickite may be of importance.

Carbonates. -- The complete absence of calcite or other carbonate minerals, except minor siderite, is noteworthy. The former presence of calcite in the veins is indicated by the so-called box-work quartz (CQ 62) which forms as the result of a replacement of calcite by fine-grained white quartz in which the cleavage pattern and outline of the former calcite crystals are preserved.

Siderite is found locally on the N700 level in botryoidal banding around fragments of vein quartz and altered wall rock (CQ 230).

Minor Gangue Minerals. -- A few grains of talc and sericite, occupying what are probably the "ghosts" of former feldspar phenocrysts in replaced wall rock, were noted. Zircon and rutile were abundant in the superpanner concentrate and probably were derived from fragments of country rocks in the ore.

Barite. -- Barite formed up to 3% of the gangue minerals in some of the superpanner determinations. It occurs with or near the alunite type of gangue as large crystals lining vugs in quartz (CQ 51) and on late fracture planes (CQ 102).

Alunite.-- This is a common gangue mineral. Its usual associates are dickite and a fine grained silica. It occurs in the soft white gangue filling blebs in quartz, corroding early sulphides, or veining or coating brecciated quartz. The alunite often has a slightly higher index than that given for pure alunite. This and the fact that some of the alunite turns rusty brown in KOH, indicates isomorphism with jarosite.

Dickite. -- The only clay mineral noted was dickite. It is associated with the alunite and fine grained silica. The dickite-alunite-quartz type of gangue reaches its highest degree of development and shows the most marked separation into distinct alteration zones in the Cactus Hill pit..

Jarosites. -- Minerals of this group were common in the superpanner middlings product. A spectrographic analysis and microchemical tests indicate that it is mainly jarosite with some plumbojarosite. The low silver value of the product shows that argento-jarosite is not common. The jarosites were not distinguished in the sawn and polished sections. They are probably to be found in the alunite-dickite-silica association. Some of the so-called brown limonite gangue may be jarosite.

6. Supergene Oxide Minerals.

The supergene oxides of iron, limonite and hematite, coat the quartz fragments of the Cactus vein down to, and in some areas on, the 700 level. In the upper levels the coating is uniformly light brown. On the 500 levels and wherever native silver occurs, the coating is a dark brown, suggesting that manganese may be present in these spots. In the wide stope between the 500 and 700 levels, the above two types of rusty coatings are accompanied by one of bright brick red. On the 700 level the brown oxidized coatings grade through light yellow brown to yellow, then to the white of the alunite-dickite-silica coatings. No attempt has been made to determine the exact composition of these various coatings. In polished section limonite and hematite (hydrous anisotropic) follow fractures in the quartz. Limonite,replacing sulphide blebs in the upper levels, is much less common than would be expected. Replacement of early sulphides seem to have been mainly by the soft white gangue rather than by limonite. Tough anisotropic hydrous hematite with red internal reflection generally follows the same fractures as the native silver and was possibly earlier than the silver (CQ 4).

RESULTS OBTAINED FROM STUDY OF MILL PRODUCTS AND ORES USING THE HAULTAIN SUPERPANNER

Preceding the present study of the Cactus deposits by means of sawn surfaces and polished sections, considerable time was spent by the writer in preparing concentrate, middlings and tailing products of ore and mill products, using the Haultain superpanner.

This study was not carried to its conclusion because of the difficulty of separating and identifying many of the minute grains, and because, as the mill recovery is high and satisfactory, no useful purpose could be served by making a laborious quantitative study of the minerals present in the various products. These products are available for study should need arise.

In order to obtain satisfactorily clean separations on the superpanner, it was found necessary first to size the material using in a Rotap machine a set of screens ranging from 100 to 250 mesh in 20 mesh intervals. The best separations were obtained on the panner in the range 150 to 250 mesh. The following are the more interesting of the results obtained:

1. Even in the -250 mesh products there are still mixed grains of quartz and sulphide. At 150 mesh 20% of the sulphides were attached to quartz.

2. The minerals determined in the superpanner studies of the ore, correspond with those determined in polished section.

The superpanner however emphasized clearly the presence in the ore of considerable cinnabar and some native mercury.

3. The gold, as observed in the concentrates of the ores and mill heads, occurred in several different forms, - rough bright electrum-like gold, gold with bronzy and rusty stains, nodular gold, crystalline gold, and amalgam balls. The last may have developed in the ball mill from the native mercury and gold of the ore.

4. The middlings products of ore, mill heads, and flotation and cyanide tails, contained considerable jarosites and limonite. A spectrographic analysis of the product showed only low values in silver, so probably the jarosites are principally jarosite and plumbojarosite, while argentojarosite occurs in only small amounts.

5. In the cyanide tails the following minerals were found: Chalcopyrite, ruby silver, sphalerite, electrum, cinnabar, and minor native mercury. These minerals are usually coarser than the average grain size of the tailings. The tailings losses are probably mostly in silver and gold values enclosed in the common sulphides and in blebs still surrounded by quartz. Because of the relatively large volume of jarosites in the tails, there may be some silver losses as argentojarosite.

TYPES OF GANGUE

The principal gangue types in approximately their order of deposition are: 1. White and grey replacement quartz, 2. Bony white quartz, 3. Coarsely crystalline euhedral glassy quartz, 4. Transparent quartz, 5. Dark grey quartz (disseminated mineralization), 6. Calcite boxwork quartz, 7. White and transparent sugar quartz, 8. Greenish quartz, 9. Alunite-dickite-silica gangue, 10. Silica associated with limonite.

The writer has not studied these various gangues petrographically. The following notes are from study of the sawn or polished surfaces under reflected light and the descriptions are of the various gangue types as seen under those conditions.

As some of these gangues characteristically carry high values while others are notably barren, the relationships and distribution of the gangues is of prime importance. Indeed, the distribution of the values seems to depend more on the relative amounts of the various gangues present than on zoning within the vein as a whole.

The deposition of the various gangues is subdivided by several periods of fracturing and brecciation. Each successive fracture pattern was the dominant control in the distribution of the succeeding gangue. Typical epithermal banding is developed only locally, presumably mainly around fragments and in isolated vugs. This repeated fracturing and brecciation was so intense that five or more separate and distinct gangues may be present in a single polished section.

Sufficient detailed underground mapping and study has not been completed to satisfactorily correlate intermineral fractures and the vein pattern with the distribution of assay values. However, the work completed does suggest a very definite correlation and one which may be of decided economic importance.

1. White and Grey Replacement Quartz.

White and grey replacement quartz is low grade and poorly mineralized (CQ 81 and 51). This replacement quartz grades into altered wall rock. In this altered wall rock occur euhedral pyrite crystals. These may have been deposited from the same solutions as the replacement quartz.

2. Bony White Quartz.

The bony white quartz also appears devoid of any mineralization. It is tough, dense, and uniformly fine grained. Under the microscope the quartz grains are anhedral with interlocking boundaries. No evidence that this is a replacement quartz was noted in the thin section examined. However, much of this bony quartz might be a replacement. Dr. Fraser has evidence indicating that a bony quartz from the upper levels is a replacement of gouge.

The bony quartz is characterized by a lack of the small blebs either of mineral or of soft gangue such as occur in the later transparent quartz. The low grade of much of the upper portions of the Cactus vein is clearly due to the relative abundance of this bony quartz. In richer portions of the vein this quartz is generally brecciated, veined, and surrounded by the ore-bearing later gangues.

3. Coarsely Crystalline Euhedral Glassy Quartz.

The coarsely crystalline euhedral glassy quartz occurs in well shaped crystals up to three-fourths inches in length. It is earlier than the transparent mineralized quartz into which it sometimes seems to grade. Generally its boundaries with the transparent quartz are clean cut. In the narrow, high grade silver veins containing abundant ruby silvers this coarsely crystalline quartz is often amythestine (CQ 147). Although these quartz crystals are unmineralized except for mineralization originating in the transparent quartz, they are always associated with the transparent quartz and might possibly be an earlier coarsely crystalline phase of the transparent quartz.

4. Transparent Quartz.

The transparent quartz is the host gangue of the common sulfide mineralization, the ruby silvers, the bulk of the argentite and some of the gold mineralization. It commonly veins the earlier brecciated white bony and replacement quartz and is itself brecciated and veined by the later gangues. It is colorless to white and under the microscope, light penetrates the quartz to a considerable depth hence the name transparent quartz. In contrast, the barren white bony quartz has little transparency and appears a "dead" white. The distribution of this quartz seems to be controlled largely by refracturing and reopening of the vein.

5. Dark Grey Quartz (Disseminated Mineralization).

The dark grey disseminated quartz is a variety of the transparent quartz so filled with very fine sulfides as to appear dark grey. These sulfides are often needles of arsenopyrite or ruby silvers and covellite replacing arsenopyrite (CQ 216 and 193).

6. Calcite Boxwork Quartz.

Calcite boxwork quartz is a white to transparent, fine grained, almost sugary quartz (CQ 62) which has completely replaced the coarsely crystalline calcite once present in the vein. The cleavage faces of the calcite are preserved as ghost structures in the quartz. Vugs in this quartz may be lined with small quartz crystals and filled with the soft gangue. When this soft gangue is present, values may be high (CQ 65) but no mineralization occurs within the boxwork quartz itself.

7. White and Transparent Sugar Quartz.

The white and the transparent sugar quartz both have a characteristic sugary texture on a sawn surface but they are not at all friable. The relationships of the sugar quartz to the other gangues are not as apparent as they are in the case of many of the other gangue types. As mentioned above the calcite boxwork quartz is usually a white sugar quartz. In general the sugar quartz seems to be more closely associated with the transparent quartz than with the earlier gangues. They, however, are much more lightly mineralized. The common sulfides are rare. The silver minerals are found in blebs in or near crystal-lined cavities (CQ 138). Blebs of gold occur in the cavities filled with soft gangue (CQ 99) in a manner similar to the occurrence in the transparent quartz. Often specimens apparently unmineralized yield good values (CQ 70 and 75).

8. Greenish Quartz.

The greenish quartz is of much more restricted occurrence than the above types. It occurs as narrow tapering veinlets cutting the earlier quartz types. It is localized around areas characterized by the alunite type of gangue. The characteristic mineralization in this quartz is coarse and fine gold and argentite (CQ 54) but occasionally minor common sulfides occur (CQ 202). The gold may occur in cavities lined with quartz crystals. This greenish quartz may be an early phase of the succeeding alunite-type gangue.

9. Alunite-Dickite-Silica Gangue.

The alunite-dickite-silica gangue varies in the relative proportions of each of these minerals. It is found on the northern or upper end of the three quartz lenses or segments on the 700 level, on the 150 level of the Silver Prince, and attains its maximum development in the Cactus Hill pit workings. In the Cactus Hill pit it is separated into areas of alunitization, kaolinization (dickite?) and silicification. The extensive and strong alteration of the area may indicate that deposition took place very close to the surface. The effects on the 150 level Silver Prince are intermediate between those seen in the Cactus Hill pit and those on the 700 level of the Cactus Queen. On both hanging and footwalls of the Silver Prince vein there is a wide zone (15' ±) of silicification accompanied by alunite and dickite. A greater proportion of the gold-silver values seem to be closely related to the greenish quartz and alunite bearing gangues. On the 700 level the alunite bearing gangue veins the transparent and other earlier quartzes, and coats the fractured quartz of the vein. The principal values associated with this gangue are as gold which occurs in or near it (CQ 201). All of the cinnabar, realgar, orpiment (CQ 101), barite (CQ 102) and some jarosites are associated with this gangue.

The soft gangue which occurs in blebs in the transparent quartz is thought to be of similar alunite-dickite-quartz composition. It corrodes the early pyrite (CQ 109), seems to have been responsible for some of the covellite, stromeyerite replacement of the common sulfides (CQ 48), and contains minute blebs (0.001 mm) of gold (CQ 99).

10. Silica Associated with Limonite.

The silica, associated with the limonite along fractures and coating the specimens, is sometimes tough and springy. This may be supergene. The amount is small and there has been very little of any cementation of the vein fragments by silica carried by descending waters.

TEXTURES AND PARAGENESIS OF THE METALLIC MINERALS

Fine grain and light mineralization are the outstanding characteristics of the Cactus ores. It is difficult to determine in many cases the textural and paragenetic relationships of the minerals present. Approximately 85% of the mineralization in the deposit occurs as isolated blebs or crystals, each separated from its neighbor by a relatively great distance of barren quartz and without any connecting fractures or veinlets. This results in the "spotted" appearance of most of the ore.

Below the 500 level in the Cactus mine there is locally a heavy sulphide mineralization with hand specimens showing 1% sulphides.

Percentage of Metallic Minerals in the Ore.

The ratio of concentration between mill heads and flotation concentrates is 1:200. These concentrates are two thirds gangue and one third metallic minerals. The metallic minerals then comprise 0.2% of the ore by weight. This value of 0.2% metallic minerals in the ore is only an approximation because the concentrates do not include the minerals carried over into the Flotation Tails (Cyanide Heads) but they do include some pyrite from altered wall rock.

In the "spotted" or blebby type of ore, the average percentage of metallic minerals is even lower than the average for the ore deposit as a whole. In hand specimen it is impossible to distinguish the minerals other than occasional large pyrite crystals. In good grade ore the balance of the minerals appears as "spots." The ore of the Cactus Hill pit seems devoid of mineralization but on crushing and panning yields abundant fine gold.

The heavy mineralization averages about 1% sulphides. The maximum noted was about 10% sulphide for a picked hand specimen but samples showing over 3% sulphide are rare.

Grain Size.

There is a wide range in grain size. The smallest mineral grains are below 0.001 mm in diameter, the largest grain noted, one composed of several minerals, was over 3 mm in diameter. The average grain size is of the order of 0.05 mm. This necessitates fine grinding in milling the ore.

In the "spotted" ores the blebs or crystals range in size from a few microns up to 0.5 mm, or larger in the case of pyrite. In general an increase in the amount of mineralization is accompanied by a corresponding increase in grain size.

The heavy sulphide ores show a marked increase in grain size over that of the blebby ore. In well mineralized specimens, grains up to 0.6 mm are common. Complex grains composed of the common sulphides and ruby silvers, occasionally attain a diameter of 1.5 mm. The maximum noted was 3 mm.

Paragenesis.

The heavily mineralized specimens have yielded more complete information on the paragenesis of the minerals, but the same textural and age relationships hold true for the "spotted" ores. In mineralization accompanying the transparent quartz, the paragenesis is:

1. Pyrite and marcasite
2. Arsenopyrite (not present in heavy sulphide types).
3. Chalcopyrite
4. Galena
5. Gold (associated with galena).
6. Sphalerite
7. Pyrargyrite and proustite
8. Polybasite and pearceite
9. Covellite and argentite-stromeyerite
10. Gold
11. Realgar, orpiment, cinnabar

9, 10 and 11 are associated with the late soft white alumite bearing gangue.

The above paragenesis gives the order of the periods of maximum deposition for each mineral. There is some overlap for example sphalerite in minor amounts seems to have ranged from earlier than the galena to later than the ruby silvers (CQ 144)

Textural and Paragenetic Relations for the Various Minerals.

Some of the textural relationships were discussed above under MINERALOGY in the descriptions of the individual minerals. The metallic minerals with the possible exception of native silver and some of the argentite, were deposited from hypogene solutions.

All the hypogene minerals formed both original grains and replacements of the earlier sulphides. Exceptions to this are the minute and isolated monomineralic blebs of gold, cinnabar, realgar and orpiment found in the soft gangue. The characteristics of each gangue are detailed in the following sections.

Minerals in Transparent Quartz.-- Approximately 98% of the common sulphide mineralization, 90% of the ruby silvers, 65% of the argentite and about 40% of the gold in the ore occurs in the transparent quartz or soft gangue blebs therein.

In the "spotted" ore of above the 500 level, pyrite and argentite-stromeyerite are the dominant minerals, while sphalerite and chalcopyrite are uncommon. This type of ore continues to the lowest levels but with increasing depth there is an increase in the relative amount of the heavy sulphide type of mineralization.

In the heavy sulphide type, the common sulphides, pyrite, chalcopyrite, sphalerite and a lesser amount of galena are present and comprise from 35% to 100% of the mineralization. The balance is principally ruby silvers, polybasite and pearceite, and lesser amounts of stromeyerite and gold.

The details of the paragenetic and textural relations for the minerals present in the transparent quartz gangue are as follows:

1. Pyrite, the earliest sulphide, may show crystal outlines, but where in contact with soft gangue or other sulphides it has been eaten into and replaced by them (CQ 131). Marcasite seems to have been more amenable to replacement by ruby silvers than was pyrite (CQ 95).

2. Arsenopyrite is not found in contact with pyrite or chalcopyrite but is earlier than sphalerite (CQ 196). Needles of arsenopyrite are commonly replaced by covellite and stromeyerite (CQ 216).

3. Chalcopyrite has replaced and veined the pyrite (CQ 47) and indeed some of the pyrite was corroded by quartz before attack by chalcopyrite (CQ 82).

4. Galena is nearly contemporaneous with chalcopyrite (CQ 66). Before the common replacement of galena by sphalerite (CQ 55) and stromeyerite (CQ 49) took place, there must have been considerably more galena. These minerals seem to have had a greater affinity for replacing galena when it was present than for replacing pyrite and chalcopyrite. The replacement of galena by ruby silvers (CQ 147) has been less common.

5. Relatively coarse gold occurs with the common sulphide mineralization and seems to favor galena-chalcopyrite contacts. Some of the anomalous relations such as blebs of gold in sphalerite (CQ 66) and pyrargyrite (CQ 147) might be explained by the post-gold replacement of chalcopyrite and galena by those minerals.

6. Sphalerite replaces pyrite, marcasite, chalcopyrite and galena. The commonest example is the replacement of galena where large crystals of galena have been so completely replaced by sphalerite that only small blebs of galena are left in the sphalerite (CQ 47)and 55). The arrangement of these blebs suggests control of the replacement by cleavage directions in the galena. As discussed above, specimens showing sphalerite apparently later than ruby

silvers and polybasite (CQ 144) may result from a partial replacement of galena by sphalerite followed by a replacement of the balance of the galena by later minerals.

7. Pyrargyrite and proustite replace the earlier common sulphides. Proustite seems to favor the replacement of marcasite, and pyrargyrite that of chalcopyrite. Pyrargyrite replaces sphalerite (CQ 147). Veinlets of proustite, following hair-like fractures, cut across several earlier types of gangue (CQ 150). These veinlets seem to have originated near centers of heavy ruby silver mineralization. They are not of supergene origin. The pyrargyrite in places contains blebs of chalcopyrite (CQ 10) and gold (CQ 147).

8. Polybasite and pearceite occur only in specimens with heavy common sulphide-ruby silver mineralization. Polybasite is associated with the chalcopyrite (CQ 82 and 147). The time relationships between the ruby silvers and these minerals are not clear but from their occurrence and associations it appears that they were nearly contemporaneous. The ruby silvers are probably a little earlier.

9. Covellite and argentite-stromeyerite are closely associated. Soft gangue is nearly always present where blebs of these minerals occur in the transparent quartz, or where they are found replacing earlier sulphides. Complex grains of covellite and stromeyerite are common in the "spotted" type of ore (CQ 54 and 122). In the replacement of chalcopyrite by covellite a reaction rim of bornite may be developed (CQ 48). The sphalerite is often beautifully rimmed by covellite (CQ 47) and soft gangue. Many grains of

argentite have outlines and textures suggesting replacement of earlier galena by argentite (CQ 49). Large crystals of polybasite and pyrargyrite occasionally show a "cracked porcelain" texture veined by stromeyerite (CQ 130).

10. When gold occurs in the blebs of soft gangue (CQ 202) within transparent quartz, other minerals are usually absent in the bleb. These gold grains are extremely fine grained, probably averaging only a few microns in diameter.

11. Realgar, orpiment and cinnabar rarely occur in the transparent quartz but are associated with the later gangues (CQ 101).

The foregoing observations cover the textural and paragenetic relationships of the minerals in the transparent quartz.

Minerals in the Post-Transparent Quartz Gangues. -- The mineralization associated with the later gangues is much sparser but the gold and silver content is generally high. This mineralization is similar in type to that found in the blebs of "soft" gangue in the transparent quartz. In sugar quartz and boxwork quartz, gold (CQ 99) and a little argentite (CQ 138) occur in the soft gangue blebs and cavities. In the greenish quartz the gold may be quite coarse (0.10 mm) and argentite and gold may occur along fractures (CQ 54 and 218).

The "soft" gangue of quartz, alunite, dickite, jarosite and barite contains less argentite relative to the gold and minor amounts of realgar, orpiment and cinnabar. Since these minerals are seen only in minute isolated grains, there is little chance to determine the paragenesis.

<u>Minerals Associated with Supergene Oxides of Iron.</u> -- The native silver mineralization which is associated with the rusty brown "limonitic" veinlets and coatings is probably later than the hard "limonitic"(hydrous hematite) veinlets and coatings (CQ 4 and 145). Some of the native silver occurs along fractures with a soft, brown to white gangue and these fractures cut the hard limonite veinlets. Argentite occurs along the same fractures as native silver (CQ 145).

The occurrence of native silver and associated argentite can be considered as the result of supergene processes unless the present limonitic veinlets were jarosites at the time of deposition of the native silver, and subsequently were oxidized by supergene waters after the deposition of the silver, or unless oxidation of the original vein took place before the influx of a late hypogene silver-bearing soft gangue. Both these possibilities at present seem less acceptable than a supergene origin for the native silver and associated argentite. A petrographic study would have to be made in order to arrive at a definite conclusion.

SUMMARY OF VEIN HISTORY

The following table divides the history of the vein into four principal phases of gangue and mineral deposition, each separated by a period of brecciation and faulting. The control of these periods of reopening has played a large part in the distribution of the succeeding generation of gangue and metallic minerals.

Major and Minor Gangues	Mineralization and Paragenesis
Brecciation and Faulting	
(a) white and grey replacement quartz	Pyrite in wall rock ?
1. White bony quartz	Barren, no mineralization.
Brecciation and Faulting	
(a) coarse glassy euhedral quartz	Barren except where bordered and fractured by the mineralization accompanying later transparent quartz.
2. Transparent quartz	1. Pyrite, marcasite, arsenopyrite 2. Chalcopyrite 3. Galena 4. Gold 5. Sphalerite 6. Pyrargyrite and proustite 7. Polybasite and pearceite
In blebs of soft gangue (alunite, dickite etc.) within transparent quartz	8. Covellite and chalcocite 9. Argentite-stromeyerite 10. Gold
(b) dark grey (disseminated) quartz	
(c) calcite boxwork quartz (d) sugar quartz	9. Argentite) in blebs of soft 10. Gold) gangue

Brecciation and Faulting	
(a) greenish quartz	- Very minor common sulphides 9. Argentite 10. Gold 11. Realgar, orpiment and cinnabar
3. "Soft" gangue of quartz, alunite, dickite and barite	9. Argentite 10. Gold 11. Realgar, orpiment and cinnabar
(b) separation of soft gangue in Cactus Hill pit into areas of silicification and vein quartz	10. Gold
Alunitization	Barren
Kaolinization (dickite)	Barren
Brecciation and Faulting	
4. Supergene development of limonite, hematite, etc.	
Late soft gangue ?	12. Native Silver and argentite

This table emphasizes the relationship of the various gangues to the type of mineralization.

In Stage 2 the transparent quartz accompanied the deposition of the common sulphides, gold and ruby silvers. But the transparent quartz solutions evidently contained a small proportion of the constituents of the soft gangue of Stage 3, since the final stage of crystallization of the transparent quartz gangue produced small patches of the soft gangue within the quartz. These blebs of soft gangue contain covellite, argentite and gold as filling in the blebs, and as replacements of earlier sulphides in transparent quartz.

The greenish quartz represents a further increase in the percentage of the soft gangue minerals. Its mineralization was argentite, gold and realgar, orpiment and cinnabar. The soft gangue had a similar mineralization. In Cactus Hill pit the components of the soft gangue have separated into areas of silicification, carrying good values in fine gold and barren areas of alunitization and kaolinization.

In Stage 4, with limonite and other rusty coatings of supergene origin, there is associated the native silver and a very small proportion of the total argentite.

SUPERGENE EFFECTS AND SECONDARY ENRICHMENT

As described above, the fragments of vein quartz above the 700 level have been coated with limonite and other rusty products. On and below the 700 level this coating changes to a light yellow to white coating of quartz, alunite, dickite and barite. The alunite probably contains some jarosite because in an alkaline solution (KOH) it turns to a brown color similar to the so-called limonite coating of the upper levels. In other words, the rusty coatings, typical of fragments of the upper levels, may have resulted from the oxidation by meteoric waters of the iron already in situ, as the alunite-jarosite gangue coating, rather than from the descent of solutions rich in iron. The other alternative would be that the alunite coatings are a supergene effect lying below the limonite coated zone. There is no factual or mineralogical data favoring this latter alternative and there is strong evidence to the contrary.

These rusty coatings when on quartz are purely surface features. There is little if any penetration of the rust into the quartz except in native silver specimens. Of course, where the soft gangue, gouge, or altered country rock are present on the surface of the fragment, penetration is much deeper.

To have effected much in the way of supergene enrichment of original silver mineralization in the quartz of the vein, the descending surface waters would have had to accomplish the following:

1) A leached zone low in silver near the surface in which original mineral grains would be represented by empty cavities or limonite filled blebs.

2) A partially leached zone in which the mineralization bordering the surface of quartz fragments would be leached or replaced by limonite, while that towards the center would be unaffected.

3) A secondarily enriched zone just above and at the water table where there would be supergene silver minerals deposited along fractures or replacing other sulphides. Accompanying secondary copper minerals should be present at least in minor amounts.

These effects are not present in the vein. The leached or limonite-filled cavities are not common. Limonite replacing pyrite is rare. An upper leached and lower secondarily enriched silver zone would show the upper zone to be high in gold relative to silver and the lower zone high in silver relative to gold. The sulphides throughout are remarkably fresh and free from oxidation.

The native silver specimens (CQ 145) show some of these supergene effects, namely a deep penetration of the rusty iron oxides into the quartz and a control of mineralization by fracturing.

Assuming the soft alunite gangue of Stage 3, and the soft gangue blebs in the transparent quartz, to be supergene, the covellite and argentite would be supergene, the realgar, orpiment and cinnabar supergene, and the gold would also have to be either supergene or residual. Mineralogically the chances that the gold, realgar, orpiment and cinnabar could be supergene are very remote. Mineralogically the possibilities of the covellite and argentite being supergene are much better but texturally they are poor. In order to have supergene argentite in the spotted ore of the upper levels it would be necessary for the mineral bearing solutions to diffuse throughout the dense quartz without any preference for channelways, and deposit the soft white gangue and covellite and argentite in empty blebs, or replace earlier sulphides. A supergene origin for covellite and argentite in the spotted ores is extremely unlikely.

Supergene enrichment probably exists in the deposit to a limited extent. The native silver mineralization is more likely supergene than hypogene. Coatings of the soft gangue of Stage 3 probably were formed on the quartz fragments of some parts of the upper levels in a manner similar to the coatings on the north ends of the quartz lenses on the 700 level. These coatings would have been easily oxidized by descending waters so that there is the possibility that the rusty coatings and fillings between the quartz fragments were secondarily enriched near the water table. Such action may account for the origin and distribution of the native silver.

A sample showing a heavy rusty coating or gouge surrounding fractured vein fragments was washed. The rusty coating assayed $8.00 as against $15.00 for the shattered quartz. This indicates that these coatings in places carry a small but appreciable fraction of the total values. They would be susceptible to supergene leaching and enrichment.

ZONING IN THE ORE DEPOSITS

Imperfect but distinct zoning occurs on scales ranging from that seen in polished section, through zoning of individual quartz lenses, zoning of mineralization in the transparent quartz, to zoning of the various gangue and mineralization types in the deposit as a whole.

In hand specimen or polished section zoning or banding of the mineralization is seen only in the heavy sulphide type of mineralization and then only in the narrow hangingwall, ruby silver rich vein (CQ 147) and in some balls of heavily mineralized quartz (CQ 66). In these specimens the crude bands are of concentrations of 1) pyrite, 2) chalcopyrite, galena, sphalerite, 3) ruby silvers.

In a vertical section of an idealized vein with the mineralogy and gangue associations as shown in the table on page 33, one would expect the vein to be zoned up the dip with the maximum concentrations of the early minerals at the bottom of the vein, and on going up the dip to pass through zones relatively rich in the succeeding minerals.

This is true in a general way in transparent quartz. When compared with the other minerals present, the maximum relative concentrations of pyrite and chalcopyrite occur below the 700 level; of galena and sphalerite at the 700 level; of ruby silvers between the 700 and 550 levels; of argentite and covellite above the 500 level.

Above the 500 level the ore is typically of the "spotted" type, below this there is a zone relatively rich in coarser ruby silvers, while the heavy common sulphide ores with silver minerals occur below the 650 level.

Each of the three large quartz lenses of the 700 level north, show a similar zoning. Cross-faults form the north end of each lens. The lower or southern end of each of the three complex bodies carries a heavy common sulphide and ruby silver mineralization; the upper central part shows good values in a much lighter mineralization, mainly argentite and gold; while the northerly portion shows an abundance of the soft gangue of Stage 3 with gold, cinnabar, realgar and orpiment. This is true in a general way for each of the three bodies. The abundance of soft gangue at the northern end under the fault is probably due however to reopening of the vein by inter-mineralization movement along the fault. The late soft gangue solutions travelled up in the vein in the reopened portions under the fault.

The Cactus Hill pit represents the final and highest development of Stage 3. The 700 and 800 levels Cactus represent the earliest exposed part of Stage 2. The Silver Prince shows characteristics of the latter part of Stage 2 and earlier part of Stage 3. The bony quartz of Stage 1 is present in the Cactus veins from the lowest level (800) to the surface. The high proportion of this bony quartz, relative to the later mineralized quartz, in parts of the upper levels accounts for the low values there.

In the control of the distribution and localization of ore, zoning is of much less importance than the repeated inter-mineralization brecciation and faulting. Zoning however indicates for the Cactus vein a probable gradual diminution of silver values within several hundred feet below the lowest present level even if the vein goes down. Again it may indicate possibilities of a change with depth in the type of mineralization of the Cactus Hill pit.

POSSIBLE ECONOMIC APPLICATIONS OF THIS STUDY

It has been shown that a large proportion of the gold and silver values throughout the deposit are of primary and hypogene origin. Hence the relationships of the present surface and water table can have little control over the ore shoots.

The distribution of the ore bearing gangues of Stage 2 and 3 was controlled by the intermineralization brecciation and reopening of portions of the vein. This resulted from movements expressed mainly as N-S cross-faulting but possibly accompanied by movements on the vein itself. Thorough mapping of the structure, both in the veins and wall rocks, is needed to supply the details for this area. This data could then be applied in the search for ore on known veins and in the exploration for new veins.

Outcrops of barren quartz on the surface should be carefully examined along their strike for possible intersection with cross-faults of the age and type that could produce ore shoots. Also the mineralogy of such veins and their texture should be examined with the purpose of determining their favorability at horizons other than that exposed.

Veins or portions of veins with only bony white quartz are unfavorable. There had to be re-brecciation of this bony quartz to allow access of the transparent quartz and later ore-bearing gangues. Transparent quartz, if present, even although locally barren may indicate ore near by. Alunite alteration should be followed up under the controlling fault. In the mine the projection of inter-mineralization cross-faults might indicate possibilities of ore shoots ahead of faces which were stopped in barren zones.

Because the dominant control of the ore is structural rather than by either supergene or hypogene zoning, detailed mapping of the structural picture would be a valuable aid in the further exploration of the deposits.