GEOLOGY OF THE NORTHERN PART OF THE OSGOOD MOUNTAINS, HUMBOLDT COUNTY, NEVADA.

by

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[U.S. Geological Survey -

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ABSTRACT

The Osgood Mountains, located in north central Nevada near the eastern edge of Humboldt County, are typical of the numerous fault-block mountains of the Basin and Range province of the western United States. Although smaller than most, the mountains are rugged and stand at altitudes of between 3,000 and 4,000 feet above the broad valley flats on each side.

The range is dissected by steep-sided, V-shaped canyons and has reached a stage of full maturity in its physiographic development. The presence of headwater basins containing alluvium, and of topographic unconformities on the interstream ridges suggests at least two stages in the erosional history of the mountains separated by renewed uplift of the mountain block.

The sedimentary rocks of the Osgood Mountains are separated into six groups, each of which contains one or more lithologic types and is found in a block which is separated from the other blocks by faults. Consequently, the relative age relationships are not known, but it is believed that the older rocks occur at the south end and the younger ones toward the north. The oldest rocks, designated as Rock groups A and B and tentatively called Cambrian, comprise shale, limestone, and quartzite. Rock group C is composed of sandstone, chert, and metavolcanic rock, and interbedded hornfels and chert. Rock group D forms the core of the range and comprises argillaceous hornfels and marble. A coarse fanglomerate of very distinctive characteristics is found in two localities and is believed to be equivalent to the fanglomerate in the Battle Mountain district to the south. Rock group E, the youngest sedimentary group in the mountains, overlies the fanglomerate and comprises limestone, metavolcanic rocks, quartzite, and some interbedded hornfels and chert. Rock groups C to E and the fanglomerate are considered, on meager fossil evidence, to be upper Paleozoic.

Igneous rocks, aside from the metavolcanic material described above with the sediments, are of seven types. The principal intrusive rock is granodiorite which forms a double stock in the shape of a crude dumbbell. Associated with the granodiorite are numerous dikes of dacite porphyry, a few dikes of aplite, and a small amount of pegmatite. Andesite dikes cut the sedimentary rocks and the granodiorite and are considered to be somewhat younger than the dacite, aplite, and pegmatite. Basalt, as dikes and flows, is much younger and caps portions of the mountain range on the west side. One small area of rhyolite tuff, the most recent igneous rock, occurs at the east foot of the range.

The structure of the Osgood Mountains is dominated by the occurrence of structural blocks that are bounded by faults. The rocks within each block are essentially monoclinal, and no major fold axes were found. An angular unconformity occurs at the base of the fanglomerate which is also tilted, thus indicating at least two periods of major deformation. The numerous faults in the area are divided into two groups: those formed before the intrusion of the granodiorite and those formed subsequent to its intrusion. Pre-intrusive faults include both steeply dipping faults and thrust faults. Post-intrusive faults are mainly steeply dipping. The principal one follows the east foot of the range and is well exposed in numerous mine workings.

Igneous metamorphism, induced by the granodiorite stock, has affected nearly all the rocks in the northern part of the range. It is described under two main headings: thermal metamorphism and additive metamorphism. Thermal metamorphism has changed the mudstone and shale into hornfels, the sandstone into quartzite, the limestone into marble. Some impure limestone has been changed to tremolite rock or diopside hornfels. Additive metamorphism is slight in the argillaceous or quartzitic rocks. In the limestones, however, it has had profound effects wherever such rock is in contact with the stock. Two zones of additive metamorphic rocks are observed at limestone contacts: the light-silicate zone composed of wollastonite, diopside, and minor amounts of other silicates; and tactite or dark-silicate zone which is composed of garnet, amphibole, some sulfides, scheelite, and minor amounts of other minerals. The light-silicate zone appears to form early and for a greater distance out from the contact than the tactite. It is replaced in part by the tactite which is formed slightly later and is localized between the light-silicate zone and the igneous rock. The latest effect of the additive metamorphism is the introduction of silica along the contact between the tactite and the granodiorite. Locally the igneous rock is completely replaced by silica.

The restriction of most of the additive processes to contacts of granodiorite and limestone is interpreted to result from a channeling of solutions given off by the magma in its late stages of consolidation through the zones now occupied by tactite and light-colored silicates. It appears that the first effects of igneous metamorphism on limestones is to produce a general porosity in these rocks by means of the development of denser minerals. Such porosity affords a means of access for solutions carrying the material that was added to form the main volume of tactite. These same solutions brought in scheelite and, at a somewhat later stage, introduced sulfides into the contact zone.

INTRODUCTION

Location and accessibility

The Osgood Mountains are located in north central Nevada near the eastern edge of Humboldt County. (See fig. 1.) The mountains extend northeast for a distance of about 25 miles from Golconda, the nearest settlement; Winnemucca, the nearest trading center and County Seat, is but 18 miles west of Golconda.

The most direct access to the Osgood Mountains area is by way of graveled roads which branch off from U. S. Highway No. 40 near Golconda and extend northward up the broad valleys which flank the range. One road starts from U. S. 40 about a mile east of Golconda and passes through the Humboldt River Canyon and thence northeast along the east foot of the range past the junction of the roads to Red House and Kelley Creek and terminates at the Getchell mine within 3 miles of the north end of the range. Access to the west side is by dirt roads north from Golconda which lead into Eden Valley and connect beyond the north end of the range with roads following the course of the Little Humboldt River. A private road over the range, locally called the Burma Road, connects the Getchell mine with Anderson Canyon and Eden Valley. Numerous side roads extend for short distances up many of the creeks and to mines and prospects.

The Western Pacific and Union Pacific railroads follow the valley of the Humboldt River across the south end of the Osgood Mountains area and afford railheads for the immediate region at Golconda and Red House.

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PRELIMINARY MAP FIG. I

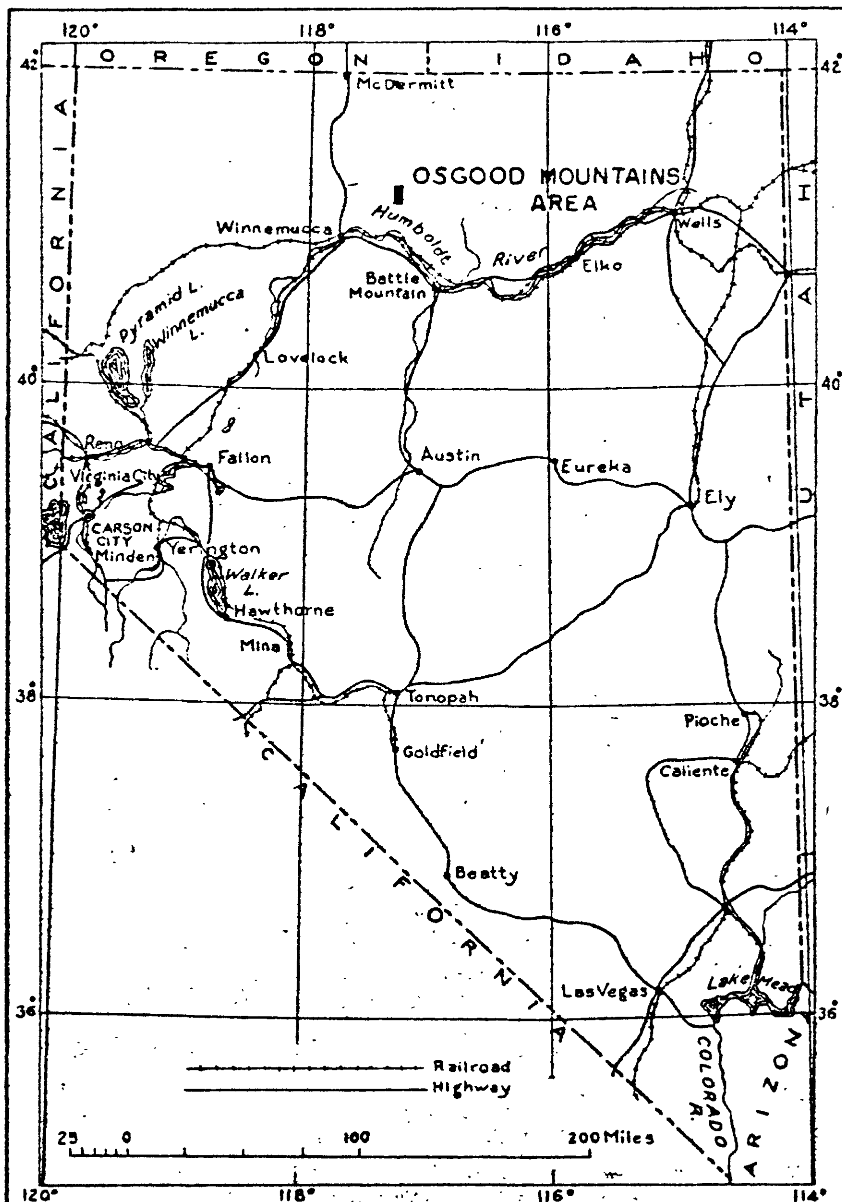

FIG. I INDEX MAP OF NEVADA SHOWING LOCATION OF THE OSGOOD MOUNTAINS AREA

Geography

In many respects the Osgood Mountains are typical of the numerous mountain groups of the Basin and Range province of the central part of the western United States. Smaller than most, it nevertheless has rugged relief and stands as an imposing range of mountains above the flat reaches of the surrounding basin areas. (See pls. 1 and 10, A.) From its south end at the valley of the Humboldt River, the range extends northeasterly for about 24 miles to its northern termination, where it narrows and gradually plunges beneath the broad alluvial flats which border the Little Humboldt River. The width of the mountain group ranges from less than a mile at its ends to a maximum of 7 miles about two thirds of the way north along its length. A group of semi-detached hills, the Dry Hills, lying to the west of the main backbone of the mountains, are included in the width of the mountains at this point. The highest point in the mountains, Adam Peak, with an altitude of 8,678 feet, is located slightly east of center in this area of greatest width and stands approximately 3,700 feet above the floors of the basins on each side. From Adam Peak the range crest declines gradually to the north end. The south half of the mountains has a general altitude of about 6,000 feet, and the floor of the Humboldt River Valley approximately 4,400 feet, thereby giving a general relief of some 1,600 feet.

On the east, the Osgood Mountains are bordered for most of their length by the broad expanse of the basin-like valley of Kelley Creek. Toward the south the Kelley Creek Basin merges with the broad east-west valley of the Humboldt River. At the south end of the Osgood Mountains, the Humboldt River is constricted in a narrow canyon which separates the Osgood Mountains from the Edna Mountains to the southeast. At the north end a series of low hills extend eastward from the Osgood Mountains into the basin and form a divide between the drainage which joins Kelley Creek and flows south parallel to the east side of the mountains and the drainage into the Little Humboldt to the north. On the southwest, the Osgood Mountains are bordered by the broad expanse of the Humboldt Valley and its junction with the lower end of the Paradise Valley. A narrow reentrant from this broad basin extends northeastward up the lower reaches of Goughs Canyon and connects over a low divide with Eden Valley, which borders the west side of the range toward the north. Lower Goughs Canyon and Eden Valley separate the Osgood Mountains from the small Hot Springs Range, west of which is the broad expanse of the main Paradise Valley. The drainage from the west slope of the Osgood Mountains is split at about the latitude of Adam Peak between that which flows south down Goughs Canyon and directly to the Humboldt River, and that which flows north through Eden Valley into the Little Humboldt River.

The climate of this part of Nevada is semiarid with a rainfall of between 10 and 15 inches. The summer months, from June to October, are dry and hot with temperatures frequently between 90 and 100, but the evenings and nights are cool and comfortable. Occasional summer thunder storms, some of near-cloudburst proportions, cross the range along narrow courses. The winter months are cold with considerable snow in the higher parts and temperatures which range down to zero and below. As a consequence of the generally low precipitation, the vegetation is of the semiarid type, consisting largely of sage brush, range grass, and other small dry-land plants. In the spring abundant wild flowers cover the hills. Lupin, arrow leaf, and indian paintbrush are especially abundant. Trees are restricted to a few deciduous types, principally alder, willow, cottonwood, and quaking aspen, all of which grow only in the stream valleys and in the small basin-like depressions at the valley heads.

In spite of the relatively low precipitation, many small streams have a year-round flow in the canyons, but all of this normal flow sinks into the gravel slope a short distance out from the mountain front. At times of heavy rain or cloudburst, water runs in sheetflood across the fan slopes and down the lower courses of the streams, which lead out across the basin floors where they empty into the main drainage of Kelley Creek, Eden Creek, or Goughs Canyon. A number of flowing springs occur throughout the range.

The main industries of the area center around mining and livestock. The Getchell mine, discovered in 1934 and placed in production in 1938, is the largest mining operation in the area. (See pl. 10, B.) When in full operation, it employs several hundred men and mines and mills from 800-1,000 tons of low-grade gold ore per day. Other mining centers around the contact-metamorphic tungsten deposits. Several of these are owned and were operated during the war by the Getchell Mine Company. Only the Riley tungsten mine, of the U. S. Vanadium Corporation, has operated since the end of the war. Several smaller mines and prospects have been opened by local people, but all these were dormant in 1947.

Stock raising, both cattle and sheep, is a big industry, and much of the mountain and surrounding plains area affords grazing land for the large stock companies who control grazing rights over much of the area. Small ranches flank the range near the mouths of the larger canyons where water for irrigation and domestic use is available. Several of these are still controlled and occupied by homesteaders, but many now serve as stake camps or summer camps for cattle companies.

Field work and acknowledgments

In the course of the studies of tungsten deposits of the United States by the Geological Survey during the recent war, the author, assisted by Mr. S. E. Clabaugh, spent a total of 3 months during the summers of 1943, 1944, and 1945 making detailed maps of the principal tungsten-producing areas in the northern Osgood Mountains. This work was based in part on a series of maps prepared in 1940 by Eugene Callaghan and C. J. Vitaliano. To expand this restricted work, with the objective of studying the regional setting of the tungsten deposit and mapping the areal geology of the northern Osgood Mountains, the author spent 3 1/2 months in the field during the summer and fall of 1946. Mapping was done on aerial photographs, and the geology was transferred to an enlarged copy of a part of the Osgood Mountains quadrangle. Some work was done at the Getchell mine, but no detailed geology of this important gold-producing property was attempted.

The officials of the Getchell mine, especially Mr. Roy Hardy and Mr. Frank de Mel, were very helpful in the project and furnished much information about the Getchell mine area. They were especially kind in affording living accomodations at the Getchell camp during all of the work. Especial thanks go likewise to Mr. Bill Hoskins, who acted as guide on many occasions over the Getchell properties. Officials of the U. S. Vanadium Corporation, operators of the Riley Mine, were very helpful in giving access to their property and information on their developments. Mr. Henry Ferguson and Mr. Ralph Roberts of the Geological Survey visited the area and contributed many ideas on the relationships of the stratigraphy to that in the Sonoma Range area to the south. The writer is deeply indebted to Professor Adolph Knopf who gave much help and encouragement during the field work and preparation of this report. Deepest thanks are extended to the members of the Geological Survey who made this report possible.

Previous work

The number of published reports that deal with the geology of any part of the Osgood Mountains is very few. Hess and Larsen (1)[a] very briefly studied the Osgood Mountains' tungsten deposits in the course of their country-wide coverage of contact-metamorphic tungsten deposits in 1917-18, and in their conclusions state, "Careful, systematic sampling and surface prospecting may disclose one or more large bodies of low-grade scheelite ore in the district". It is interesting to note that nearly 30 years later this prediction came true, when approximately 250,000 tons of ore containing an average of 0.53 percent of WO_3 was mined from these deposits during the war years of 1942 to 1945. A brief description of the Getchell mine and its vicinity was published by Hardy (2) in 1940, and in 1946 S. E. Clabaugh and the writer (3) published a short bulletin on the tungsten occurrences of the Osgood Range. The Battle Mountain, Golconda, and Sonoma Range areas, south of the Humboldt River, are those closest to the Osgood Mountains in which extensive geologic mapping has been done, but none of this work has yet been published.

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a/ Numbers in parentheses refer to the bibliography at the end of this report.

PHYSIOGRAPHY

No detailed study of the physiographic development of the Osgood Mountains was attempted in connection with this study, but a few observations were made, and the problems which they present will be outlined.

The northern end of the range has reached a stage of full maturity in its physiographic development. (See pl. 11, A.) It is thoroughly dissected and only a few remnants of its original surface remain. The valleys are all youthful with V-shaped cross sections at the mountain front. (See pl. 11, B.) The ridges have serrate crests with steep slopes from ridge crest to valley bottom. The east mountain front at the north end is fairly straight, and sub-triangular facets mark the truncated ends of ridges alined on the course of a prominent fault.

That the Osgood Mountains are a fault-block range is apparent from the geologic relationships, and their physiographic development dates from the inception of this faulting. The history of their development as a dissected fault-block range, however, is complicated by features that are anomalous to an orderly erosional history. The headwaters of many of the creeks which drain the east side of the range, especially north of Granite Creek, have open amphitheatre-like basins at altitudes of about 6,200 feet, some of which contain aggradational material. The interstream ridge crests show a marked flattening in longitudinal profile at about the same general elevation as the basins. At the mountain front, however, the interstream ridges slope sharply down to the upper ends of the pediment. The streams below these headwater basins are sharply incised and emerge from the mountain front in narrow V-shaped valleys only slightly incised below the present level of the pediments which skirt the mountains. Profiles of the streams leading from these headwater basins to the pediments show no marked break to correspond to the unconformity still evident on the interstream ridges.

The headwater basins together with the flatter reaches of the interstream divides suggest a still-stand in the erosional history of the mountain block at this elevation with the attendant cutting back of the mountain from its initial position along the line of range-front faults. Renewed uplift is in part responsible for a rejuvenation of erosion. Evidence of recent uplift is found in the form of a small scarp in alluvial material. However, it is possible that some of the rejuvenation of mountain erosion is related to the dissection of the pediment surfaces which flank the northeast slopes of the Osgood Mountains and extend out into the low hills which project far eastward from the Osgood Mountains. The complicated dissection of these pediment surfaces may be related to a mass excavation of material from the main Kelley Creek basin to the southeast, or to other regional factors not directly related to the Osgood Mountains block as such.

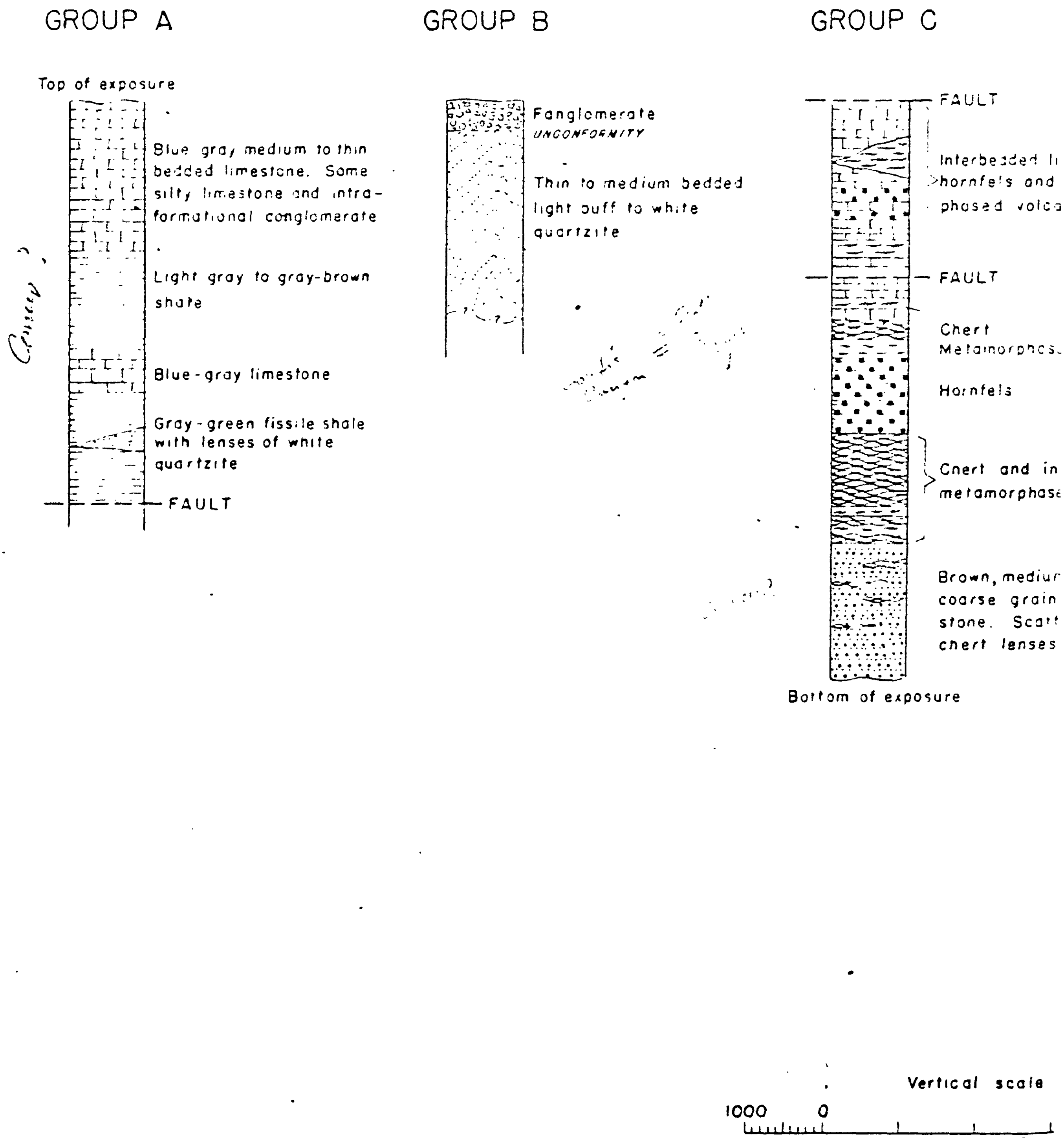
The relatively recent fault which offsets the alluvium extends from the very southeast corner of the mapped area southward for a distance of over three miles. The maximum vertical displacement on the fault occurs at about the latitude of the south edge of plate 2 and amounts to approximately 20 feet. The scarp has been rounded off, and several of the small streams which crossed the fault line and which were thrown out of adjustment by the displacement have built alluvial fans to the top of the raised block. This fault, located over one-half mile from the foot of the range, may give some indication of the distance the mountain front has retreated, although the possibility remains that it is merely one of many subsidiary faults which split from a zone of fracture closer to the main range.

GEOLOGIC FORMATIONS

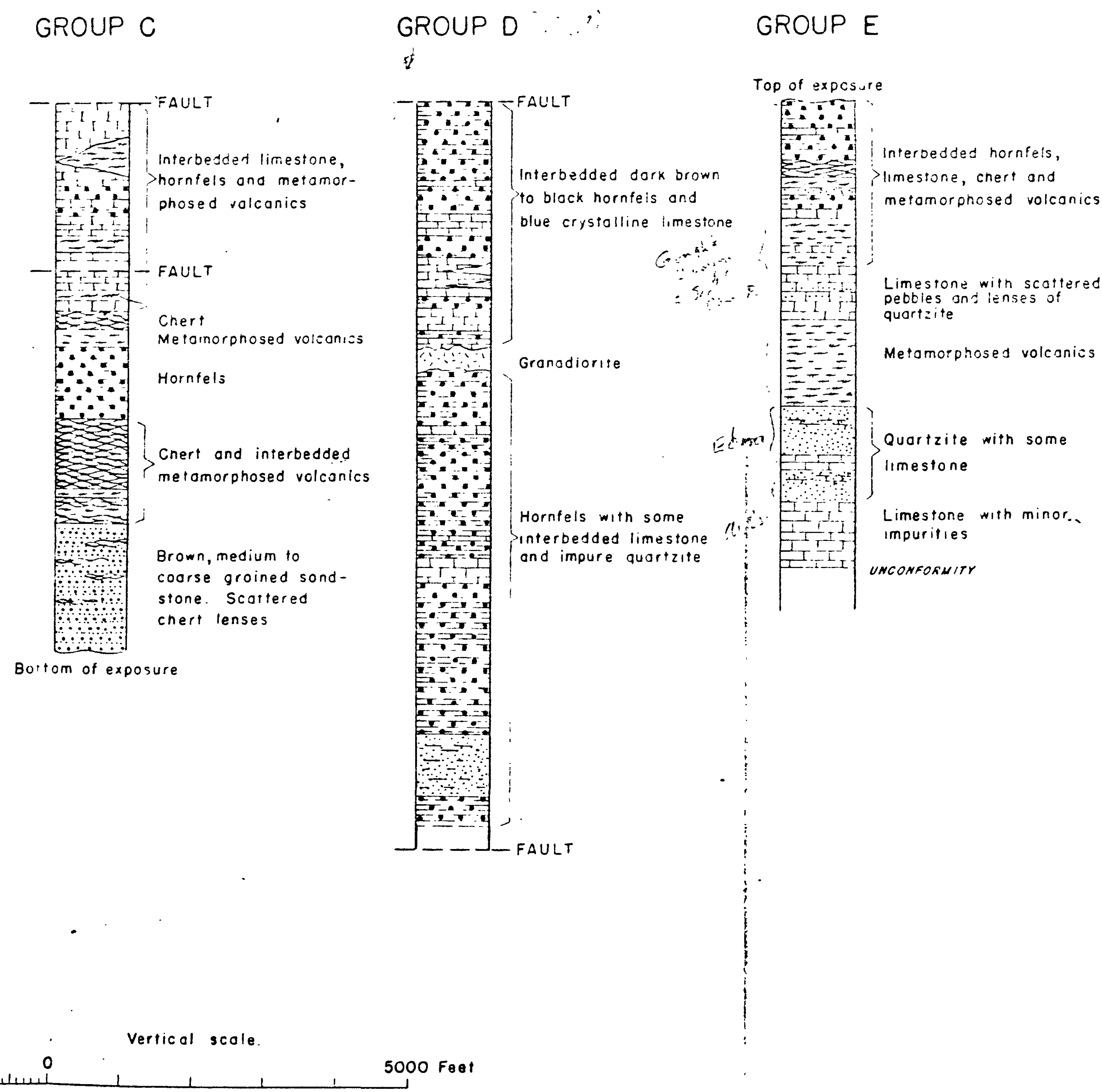
Introduction

The following descriptions of lithologies in the Osgood Mountains is not meant to follow strictly the usual sequence from oldest to youngest formations. The reason for this is twofold: the nearly complete lack of fossil and other evidence for age determinations, and the fact that most of the various distinctive rock groups occur as blocks bounded by faults, and as a consequence the pre-faulting relationships between them are unknown. All available evidence suggests that the oldest sedimentary rock occurs toward the south end of the range and the youngest at the north. In so far as this is true, the sequence of descriptions, which is from south to north, is in the usual order from oldest to youngest. The evidence bearing on the age of each group will be discussed in the description, and a summary of possible age relations and correlations will be given at the end of the description. To avoid confusion in geographical locations and facilitate references to the various rock groups, each group is given a letter designation which is shown on plate 2. One very distinctive formation, a fanglomerate, is mapped separately as such and is not included in any group. Plate 2 is essentially a lithologic map which attempts to show each group and the lithology within it, rather than age of rocks. Plate 9 shows a series of stratigraphic columns of the rock groups in the northern Osgood Mountains. Formation names have been avoided, pending eventual completion of the mapping of the quadrangle and possible correlation of the rocks with known formations to the south.

In the descriptions that follow, intercallated volcanic rocks are described with the sedimentary rock group in which they occur. All intrusive rocks, the basalt flows and the pyroclastic rocks at the Getchell mine, are described in the section on igneous rocks.



STRATIGRAPHIC COLUMNS OF THE ROCK GROU



THE ROCK GROUPS IN THE NORTHERN OSGOOD RANGE

Description of sedimentary rock groups

Rock group A

At the southeast corner of the map area is a series of sedimentary rocks which are separated by faults from those of the rest of the range. They are bounded on the north, east, and south by the covered pediment slopes which spread out into the basin and on the west by a fault of unknown displacement. The sedimentary rocks in this block are so badly faulted, folded, and contorted that an accurate measure of thickness is impossible, but at least 4,200 feet of beds are exposed. In general, these beds strike northeast essentially parallel to the front of the range and dip steeply southeast toward the basin.

The lowest member is composed predominantly of shale that has an exposed thickness of about 1,250 feet. Where it is least metamorphosed the rock is greenish gray, fissile, and locally has a well-developed fracturing which produces small pencil-like fragments. Toward the top, the shale includes interbedded thin, dark, blue-gray limestone, limy shale, and a hard, purplish, sandy shale. To the northeast, where the sequence approaches the granodiorite stock, the shale is slightly metamorphosed into a gray-black argillite, containing vaguely defined ovoid structures, which reach maximum dimensions of 4 by 7 millimeters. On exposed surfaces, these structures weather to a light-brown or buff color and give the rock a spotted appearance. The contact metamorphism also affects the interbedded mudstone and limestone of the upper part of the section by changing the mudstone and limy mudstone to low-grade hornfels and argillite and slightly recrystallizing the limestone layers. Some of the shale layers are transformed into low-grade phyllites.

A limestone member which averages 500 feet thick overlies the shale. It is composed of thin-bedded to platy blue-gray limestone, some of which is finely laminated. These beds range in thickness from 1 inch to 3 inches, and many are separated by one to ten inches of very thin,platy and brittle laminae of an impure light-buff limestone which splits along the bedding planes into paper-thin sheets. Many of the laminae in the purer blue-gray limestone beds weather out as slightly raised ribs with a buff color similar to the inter-limestone layers. Within this limestone member near the south end of its exposure is a narrow horizon of intraformational conglomerate. The basal contact of the limestone with the shale is gradational through about 100 feet of transition beds. Similarly, the upper 50-100 feet of the limestone contains some interbedded layers of dark impure limestone, argillite, shale, and thin local beds of chert, all of which represent a transition toward the overlying shale.

The shale above the limestone forms a relatively soft incompetent layer that ranges in apparent thickness between wide limits, very likely as the result of deformation. Because of the deformation that has affected the shale an accurate measure of its true thickness is impossible, but an estimate of between 800 and 1,000 feet is not unreasonable. Most of the rock in this zone is a light-gray to gray-brown fissile shale, in part phyllitic, and in many places having a well-developed fracturing so arranged as to produce needle- or pencil-shaped fragments in great abundance. Locally the shale is iron stained, and one zone, which is a hundred feet or more thick, is a purplish-black, fissile, sandy shale with an imperfectly developed slaty cleavage. A few zones of limy shale are interspersed in the section.

The uppermost-exposed member of this section is essentially a limestone but one composed of somewhat diverse beds. The principal rock type is a blue-gray medium- to thin-bedded limestone containing some thin chert layers and lenses. Near the base are a few horizons of silty limestone and calcareous silt. At several horizons, the upper limestone is characterized by layers and lenses of a well-developed intraformational conglomerate from one to over 10 feet thick. The conglomerate is composed of flat, angular to sub-rounded limestone fragments in an impure calcareous matrix and oriented semiparallel to the bedding. The occurrence of such a distinctive layer in different positions within the various fault blocks was at first interpreted as a result of the faulting of a single horizon. However, irreconcilable variations in the stratigraphy above and below the intraformational conglomerate layers in adjacent blocks, force the conclusion that there are several horizons of the conglomerate and that any one layer is continuous only for short distances.

Rock group B

The northern tip of an extensive area of quartzite is exposed at the southwest corner of the map area. This quartzite is exceptionally well displayed in the upper reaches of Hogshead Canyon, especially on the steep southern face of what is locally known as the Hogshead, a prominent prow-shaped peak about 1 1/2 miles due south of Adam Peak. It extends for a distance of at least several miles south of the area mapped.

No attempt was made to measure a section of the quartzite. Neither the base nor the top is exposed, and the series is folded, contorted, and faulted in such a fashion that any attempt to reconstruct the section would be futile. The quartzite is bounded on the east by a major, steeply dipping fault, and is overlain unconformably on the north and west by younger formations.

The quartzite is a medium- to thick-bedded, fine-grained, quite pure, light-buff to nearly white rock. For the most part it is uniform in general composition, although localized variations in color, grain size, and amount of impurities are evident. The rock is composed of quartz grains which were originally subrounded, but most of which have been recrystallized, at least along the borders, to irregular, more angular shapes. In many places the grains form a perfect mosaic texture. However, scattered grains of zircon, pyroxene, and apatite retain their rounded forms. The grain diameters rarely exceed 1 millimeter and, for the most part, are less than 0.5 millimeter. In the less-pure quartzite, the impurities have been reconstituted to form interstitial sericite, granules of iron oxide, and other minerals not definitely identifiable. Several zones of shaly quartzite and one of a dark-gray quartzite interbedded with shale are present in the section, but their stratigraphic relations are obscure.

The age of the quartzite has not been determined. Three prominent quartzite horizons are known to occur in the Paleozoic section in areas far to the east and south of the Osgood Mountains. These are the Prospect Mountain quartzite of Lower Cambrian age, the Eureka quartzite of Middle Ordovician, and the Diamond Peak quartzite of Pennsylvanian age. None of these horizons has been recognized in areas adjacent to the Osgood Mountains. Extensive work by H. G. Ferguson and R. J. Roberts in the Sonoma and Antler Peak quadrangles, south and southeast of the Osgood Mountains quadrangle, has disclosed no quartzite lithologies that can be definitely correlated with any of the above-mentioned zones. However, Ferguson (4) has tentatively assigned a Cambrian age to the rocks which comprise the southern end of the Osgood Mountains where they project into the Sonoma quadrangle. The dating is based, in part, on general lithology but mostly on the discovery of several specimens of the genus Lingula. The rocks tentatively called Cambrian by Ferguson comprise a sequence of phyllites and phyllitic shale, in part limy or sandy, and containing some quartzite. The quartzite occurs as large pods, lenses, and discontinuous beds which may locally attain a thickness of several hundred feet. The quartzite is relatively pure, light gray or brown in color and for the most part it contains small flakes of muscovite.

The quartzite of the central Osgood Mountains may represent an expansion of one or more of the Cambrian quartzite horizons, and, in the light of present knowledge, this is considered to be the most logical correlation. In view of the complex folding and faulting of these quartzites, the seemingly thick sequence of them may be more apparent than real, and the true thickness may be quite commensurate with the Cambrian quartzite lenses to the south.

Rock group C

The group of formations lying on the west side of the mountains and separated from the rocks to the east by a fault, bear many resemblances to the rocks of the central part of the mountains, but because of certain notable variations in their composition and the fact that their relation to the other rock groups is unknown, they are treated as a separate unit. This group has been mapped for a distance of over 4 miles along the western flank of the range in the north half of the map area. It is bounded on the east by a fault of unknown displacement, and on the west by the overlapping alluvium of Eden Valley and the basalt flows of Soldier Cap. At the north, a series of branching faults terminate it against younger limestones. These rocks are known to extend at least 2 miles beyond the point shown on the map (pl. 2). Rocks of similar lithology crop out east of the Getchell mine where they are unconformably overlain by the limestones of rock group E. It is probable that these similar rock groups are equivalent, but the structural pattern that explains their position is not understood.

The rocks which comprise group C include grits, argillite, some quartzite, metavolcanic flows, chert, and limestone. The occurrence of the grit, metavolcanic flows, and chert necessitates a separate category for this sequence, even though the remaining rock types are, in most ways, identical with others in rock group D. These rocks are predominantly vertical. Evidence bearing on the top and bottom of the series is not conclusive, but it is assumed that the base is to the west, and the series will be described from west to east in ascending order.

The lowest exposed member is a dark-brown, medium-grained grit composed of 80 percent of rounded quartz grains, which average 0.5 millimeter in diameter. Occasional grains of smoky-blue quartz, as much as 2 millimeters in diameter, are scattered through the rock. The remaining 20 percent of the rock is matrix and cement composed essentially of sericite, iron oxides, and a little carbonate. The grit is medium to thick bedded; the beds range in size from 2 inches to several feet; and the series has an over-all minimum exposed thickness of about 2,500 feet. Narrow layers of light-gray shale occur here and there between the grit layers, and one bed 2 feet thick was observed in Anderson Canyon. Toward the top of the section the grit includes lenses and somewhat discontinuous layers of chert which represent a transition into the predominantly chert and greenstone members above. The contact with the overlying rocks is essentially gradational but has been placed at the top of the grit, even though large lenses of chert occur within the grit as much as 500 feet from the contact.

Above the grit is a sequence of layers which aggregates approximately 1,500 feet and is composed of highly altered volcanic flows, thick layers and lenses of chert, minor amounts of blue crystalline limestone, and some impure argillite. This horizon is predominantly characterized by the chert and metavolcanic rocks. The chert, some of which was noted above as occurring in the grit series, is dark gray and flinty appearing on the fresh surface but attains a smooth deep-buff colored weathered surface. Because of its toughness, the chert projects usually as bold outcrops. The bedding of the chert is typically irregular; the individual layers, which are from 2 to 4 inches thick, display a marked pinching and swelling. Thin shaly interlayers weather more quickly, leaving the chert layers standing out in relief, and the larger outcrops thereby assume a ropy or sinuous complexion. Thin sections show the chert to be composed essentially of cryptocrystalline silica with irregular clusters and stringers of recrystallized quartz which occurs as small grains no more than .01 millimeter in diameter. The chert zones range in thickness from a few feet to more than 1,000 feet where measured in Anderson Canyon. There is, however, considerable variation in the thickness of any one zone, and some layers evidently pinch out completely along the strike.

Associated with the chert are rocks which are classed under the general field term of metavolcanic flows. These are dark, greenish-gray, generally nondescript rocks with a faint irregular mottling and dull cast on the fresh surface. Only in large exposures is a layered structure apparent. Many specimens weather to a rough, irregular, and frequently pitted surface, formed by the weathering of material from cavities which were undoubtedly vesicles. Under the microscope, these rocks are seen to be fine-grained volcanic rocks, extremely altered, which, in some cases, have been subjected to contact metamorphism. All of them are composed predominantly of plagioclase laths in a semi-trachytic arrangement, associated with a variety of alteration minerals derived, for the most part, from the break down of the original mafic constituents. In a number of the specimens the plagioclase was sufficiently fresh to retain albite twinning, and determinations on 5 specimens scattered over the area, gave a composition between An_{45} and An_{55}. From this it is concluded that the original flows were basic andesite or basalt near andesite in composition. The plagioclase is flecked through with small sheafs of clinozoisite, a little sericite, and, in some specimens, considerable carbonate. The original mafic minerals are completely destroyed, being replaced by irregular aggregates of low-iron hornblende in small needles and bunches of needles, chlorite, carbonate, some secondary feldspar in very small grains, and, in some cases, by fine-grained aggregates of a low-iron biotite. The biotite has a very light, but definite, pleochroism, X = colorless, Y = Z = light brown or greenish brown. Residual cores of amphibole in some of the biotite suggests that the biotite is an alteration product from secondary hornblende. The character and composition of the original mafic minerals are difficult to decipher. For the most part, every vestige of the mineral is destroyed even to the crystal outlines. The presence of secondary hornblende, biotite, and chlorite in separate and distinct patches suggests the possibility that several mafic minerals may have been present, each of which gave rise to a separate series of alteration products. The light pleochroism of both the secondary hornblende and the biotite suggests that they have a relatively low iron content and possibly suggests also that the original mafics and the rock in general may have been deficient in iron content. Very likely, the principal mafic was enstatite or an olivine, which, in combination with part of the plagioclase, has produced the nearly colorless small laths of hornblende.

The altered volcanics are intercallated throughout this unit and, from their general accordance with the bedding and their highly vesicular structures, are considered to be flow rocks in the sequence. South of Anderson Canyon, on the ridge between Farrel Canyon and Cave Canyon, however, some anomolous relationships are displayed between the aphanitic igneous rocks and the enclosing sediments. Highly altered basic lavas occur as bulbous and irregular masses which seem to pinch down or terminate to the south. In the saddle just east of the eminence known as Soldier Cap on the aforementioned ridge these same altered basic aphanites are intimately involved with brecciated limestones and include sub-rounded limestone fragments. The igneous contacts with the limestone and with the fragments are chilled and indicate either that the basic aphanites are intrusive and have brecciated and incorporated the limestone or that the aphanites flowed out on a surface of limestone accumulation, either submarine or barely subaerial, and disrupted and incorporated part of the limy muds within them. Evidence is not clear to demonstrate either hypothesis, but the preponderance of the evidence favors the occurrence of the basic aphanites as flows. They are highly vesicular (not conclusive of surface formation), are associated with chert—a common association elsewhere—and conform to the general bedding.

Above the predominantly chert and metavolcanic rock sequence of group C occurs a considerable thickness of dark-gray, black, and blue-gray argillite, hornfels, and impure calcareous argillite. These are interbedded with several thin metavolcanic flows. Toward the top of the exposed section, in the vicinity of Farrel Canyon and southward, are a series of blue-gray crystalline limestones which are interbedded with the argillites and the upper flows. The stratigraphic relations are not too clear, but it is believed that the limestones are in part a local facies change and are continuous along the strike with the argillites, chert, and greenstone to the north. A very small collection of poorly preserved fossils was assembled from these limestones on the ridge between Farrel and Cave Canyons and was sent to the Geological Survey for identification. Dr. James Steele Williams reports as follows:

> "This collection contains crinoid columnals, a poorly preserved impression of a horn coral, and fragments of several species of brachiopods all of which are so weathered or otherwise so incomplete that they cannot be specifically or generically identified. These brachiopods include a Chonetes-like form and an Ambocoelia-like form. Some of the crinoid columnals are preserved in what appears to be part of a basaltic lava flow.
>
> "Dr. Edwin Kirk has examined the specimens for age clews from the crinoid columnals. None of us is able to give an age determination other than late Paleozoic from the material at hand."

Rock group D

A group of rocks that forms a more or less distinct unit occupies the core of the northern Osgood Mountains and extends from near the northern end to beyond the southern limits of the area mapped. These are the rocks which have been intruded by the Osgood Mountains stock, and, as a consequence of metamorphism by the stock, are now largely altered to argillite, hornfels, and marble. Only near the north end of the mountains are the rocks sufficiently removed from the influence of the main intrusion to have retained some of their original characteristics. However, even among the least metamorphosed sections, there are small zones and areas of more intense alteration related to small stocks, dikes, or subjacent igneous masses.

At the northern end of the range, the series is composed essentially of fine-grained clastic rock types. For the most part, these rocks are well indurated, slightly recrystallized mudstone, siliceous siltstone, and impure fine-grained quartzites. A variable, but usually minor amount of carbonate is present in certain zones, and several layers of pure crystalline limestone occur on the west side of the range in the lower part of the series. Near the fault which bounds the series on the west, and in the latitude of cross-section A-A', plate 2, there are several large lenses of pure fine-grained massive quartzite. A portion of the argillaceous rocks have developed into low-grade phyllite instead of a massive argillite. The phyllite may represent the results of thermal metamorphism of a well-bedded shale.

The largest part of this group of rocks is composed of very fine-grained, siliceous mudstone, comprising silt, fine quartz granules, and carbonate in proportions which differ from place to place. For the most part the rocks are somber hued in shades of blue, black, dark gray, brownish gray, and brown. Bedding is usually distinct in the less metamorphosed areas and ranges from beds less than 1 inch thick up to massive layers of siliceous argillite 20 feet or more thick. In the more uniform argillaceous or impure quartzitic facies, the beds are faintly laminated, a feature that is especially well shown on weathered surfaces. As the carbonate content increases there is a tendency for the carbonate and the clastic constituents to occur in separate layers with the development of a distinctive, thin-bedded facies of alternate argillite and limestone layers, each usually less than one or two inches thick. (See pl. 14, B.) Such zones of interbedded, thin-bedded limestone and argillite are locally as much as 100 feet thick, but have no consistant lateral continuity. On weathering, the purer limestone is etched out, producing a ribbed outcrop. Southward, along the edges of the granodiorite stock, the argillite facies has been, for the most part, recrystallized into a cordierite hornfels which will be more fully discussed under the section on metamorphism.

Limestone beds in the series occur both as very pure layers having sharp contacts with the enclosing argillite and as pure layers which grade into the argillite through a zone of interbedded limestone and argillite. For the most part, the limestones are a dark to light blue-gray color, medium bedded, and medium grained, with minor impurities concentrated along the bedding planes. In general they are well recrystallized. A very minor amount of chert is associated with the limestone. A notable feature of the pure limestone layers is their lensy character. Although some layers of limestone no more than 50-100 feet thick may be traced for a mile or more, it is not unusual for a layer of similar thickness to pinch out along the strike within a few hundred yards. One layer at the north end thickens from one hundred feet to 900 feet in a distance of one mile. At the north end of the range limestone comprises only about 5 percent of the series. However, to the south, the limestones become progressively more abundant, and in the area between the two stocks comprise nearly 25 percent of the section. It is evident from the map (pl. 2) that individual limestone beds tend to thicken toward the south, and, furthermore, tend to coalesce to form thicker layers. This suggests a feathering out of the limestone facies from south to north and probably explains the lensy and discontinuous distribution of the limestones in Rock group D at the northern end of the mountains.

Under the microscope, the limestones are seen to be fine, even-grained recrystallized rocks composed essentially of $CaCO_3$ in a mosaic of grains which range from 0.1 to 0.6 millimeter in diameter. No dolomite was found. All gradations exist between pure limestones and pure sandstones and pure limestones and pure shales or siltstones.

The quantity of true quartzite in this series is relatively minor. For the most part, the quartzite occurs as discontinuous lenses no more than a few hundreds of feet long and 50 feet thick. The largest layer mapped is in the order of half a mile long and 150 feet thick, but this is exceptional. Only those quartzites are shown which are sufficiently large or continuous to be plotted on the map (pl. 2).

The quartzites are all fine grained, which is in keeping with the generally fine texture of the series. For the most part, the grain size rarely exceeds 1 millimeter and usually is between 0.05 and 0.5 millimeter. The purer layers are composed up to 95 percent of quartz, with a small proportion of apatite, zircon, amphibole, and pyroxene. The original cement appears to differ in different layers, with carbonates, iron oxides, and argillaceous material in various proportions as the most common cementing material. In some of the impure quartzites the proportion of these materials amounts to as much as 25 percent of the rock. The quartzites of this series have been recrystallized without exception. In the more extreme cases, the recrystallized rock comprises a mosaic of interlocking quartz grains with films and irregular segregations of the original cement along the boundaries. The original shape of the grain is lost, and only rarely is an outline of such a grain preserved as a faint line of inclusions in the enlarged crystal. In those rocks which comprise an appreciable amount of cement, the cementing material is reconstituted to form tremolite, sericite, and magnetite, and other new minerals. In some examples, the quartz of the grains is involved in the new combinations.

A number of anomalous zones of a siliceous, extremely hard, fine-grained flinty rock are considered to result from silicification of some other rock type. Several of these bodies occur at the northern end of the series, and others, less prominent, occur associated with the limestones in the reentrant between the two lobes of the granodiorite stock. A few of these can be directly related to silicification along faults or fractures, but others have no obvious structural control.

Fanglomerate

A period of marked diastrophism followed the deposition of the preceding formations and deformed and elevated the rocksinto a land mass which was subsequently eroded. Upon the beveled edges of the mudstones, shales, sandstones, limestones, volcanic rocks, and chert was deposited unconformably a sequence of rocks of widely different lithologies, which, from meager fossil evidence, are considered to be, at least in part, upper Carboniferous, possibly upper Pennsylvanian in age. This series has as its basal member a very striking, coarse-textured, unsorted clastic rock which fits the characteristics of a fanglomerate. (See pl. 13, B) It is exposed in two widely separated places in the map area—at the southwest corner where it rests unconformably upon the massive quartzites of Rock group B and about a mile northeast of the mouth of Anderson Canyon, where it forms the base of a synclinal trough which rests unconformably upon the cherts and metavolcanic rocks of Rock group C. It appears to be absent north of the Getchell mine where the horizon of its occurrence at the unconformity between rocks of Groups C and B is exposed. The fanglomerate ranges in thickness from an estimated 20 feet at the northern exposure to approximately 100 feet or more where it is exposed in the cliff face on the north side of the Hogshead Canyon. It comprises an assortment of angular to sub-rounded rock fragments which range in size from sand and pebbles to boulders one foot or more in diameter. For the most part, the constituents are unsorted and jumbled together in the general form of a breccia. Occasional lenses of sandstone or siltstone are interlayered with the fanglomerate, but for the most part the rock is a heterogeneous mixture of material of all sizes, well compacted and cemented. Fragments of all the underlying series occur in the fanglomerate, but quartzites predominate; where the fanglomerate overlies massive quartzites in the subjacent rocks, it is composed nearly 100 percent of quartzite fragments. The fanglomerate is overlain directly in apparent conformity by a thick series of rocks, the lower members of which are limestones with subordinate amounts of argillite and sandstones.

The fanglomerate of the Osgood Mountains is apparently a northward extension of the amazing fanglomerate originally described by A. C. Lawson (5, 6) near Battle Mountain, Nevada, and subsequently found to be of very wide extent in the Sonoma and Antler Peak quadrangles. Whether the formation was at one time continuous over the area enclosed within its outermost occurrences, is unknown, but it does make a continuous formation over extensive areas south of Battle Mountain, and the conditions which produced this type of rock were in operation over hundreds of square miles. The thinning of it from south to north in the Osgood Mountains and its absence north of the Getchell mine may imply that this area is near the northern limits of its occurrence. In the Antler Peak quadrangle, the fanglomerate is overlain by the Antler Peak limestone of upper Pennsylvanian age.

Rock group E

The sequence of rocks that rest directly on the fanglomerate at its two outcrops in the Osgood Mountains is incomplete, all but the basal few hundred feet having been eroded. Above the fanglomerate in the small synclinal fault segment exposed north of Anderson Canyon is a sequence of sandy limestone, limestone, and minor amounts of argillite. The limestone ranges from nearly pure white, fine-grained crystalline types to massive blue-gray limestone with thin hornfel layers. A meager collection of fossils was made from this locality and was examined by Dr. James Steele Williams, who reports: "This collection contains crinoid columnals, a rhomboporoid bryozoan, and brachiopods resembling species of Hustedia and Punctospirifer. The brachiopods are imperfectly preserved and so altered by silicification that minute structures, such as punctation, are not determinable. They cannot therefore be definitely identified. The most complete brachiopod specimen is a large Hustedia-like form that in general appearances resembles a Phosphoria species, Hustedia phosphorienses Branson. This species has been collected from Ferguson's area from a locality in the Edna Mountains where it is associated with Spirifer pseudocameratus and a varied fauna which I believe is of Phosphoria age. .... Although the present evidence does point to the Phosphoria age of the collection, I feel that it is too meager to be conclusive".

Non-fossiliferous limestone and argillite of characteristics similar to the fossiliferous ones described above overly the fanglomerate of Hogshead Canyon. They are, however, much metamorphosed and sheared and contain no evidence of fossil remains. Both of these series are probably related to the rock series at the northeast corner of the area which is next described.

Along the northeastern flank of the mountains and extending out for 8 to 10 miles in an easterly direction is a series of sedimentary rocks with interbedded volcanic material, the age of which appears to be slightly different from the other series in the range. The limestone and quartzite of this series are exceptionally well exposed in the low hills east of the north end of the range and outside of the map area. Because of their low dip, resistant characteristics, and white color, they form striking outcrops that are visible from the vicinity of the Getchell mine. In the area mapped, only the west end of this series is shown where it abuts against the Getchell fault.

A collection of fossils from some of the limestones in this series indicates that it is, at least in part, equivalent to the Antler Peak beds near Battle Mountain which lie directly above the fanglomerate in that area. These fossils were also examined by James Steele Williams, who reports on them as follows:

> "This collection contains productoid brachiopods of the subgenera Dictyoclostus and Linoproductus and bryozoans belonging to the genera 'Fenestella', Sulcoretepora? (Cystodictya of authors), Diploporaria?, Penniretepora, and also rhomboporoid bryozoans. In facies and age, the collections resemble the beds at Antler Peak and are thus upper Pennsylvanian (as against lower Pennsylvanian) in age. These beds might possibly extend up into the zone of disputed Pennsylvanian-Permian age, but we believe them to be equivalent in general to the Antler Peak limestone beds."

The series rests unconformably on greenstone, chert, and argillite that are believed to be equivalent to those of Rock group C on the west flank of the range. In this respect, they bear the same relation to the greenstone-chert series as the fanglomerate and its overlying limestone series. However, in this locality the fanglomerate is missing, and the limestones that directly overly the unconformity appear to be of an age more nearly equivalent to limestones that overly the fanglomerate in the Battle Mountain area than to the limestones that overly the fanglomerate on the west side of the Osgood Mountains. The meaning of this anomaly is not clear. The local absence of such a formation as the fanglomerate might be expectable, but the existance of approximately 4,000 feet of Antler Peak beds in this section and their apparent absence 2 miles to the west are less easily rationalized. In view of the meager fossil evidence and the general doubt as to the exact age of such fossils as were obtained, the limestone above the fanglomerate on the west is correlated with the basal limestones on the east.

The rocks of group E are distinguished by the interbedding of considerable thicknesses of crystalline limestone with impure, white quartzite, tuffaceous quartzite, metavolcanic rocks, and some argillite. Chert occurs in very minor amounts in the lower part of the section but in more abundance toward the top.

As with other series of formations in the range, this one is incomplete. Whereas the base is known, the top is buried, and faulting has caused repetition together with a certain amount of cutting out of beds in such a manner as to make exact measurement of thickness impossible.

The base of this section is exposed about 0.6 of a mile due north of the Getchell mine where a basal limestone, 900 feet thick, rests in marked unconformity upon the greenstone and chert of the older formations. The limestone is a crystalline, blue-gray, thick- to massive-bedded, nearly pure, limestone that is distinguished by the inclusion of widely scattered, but well-rounded, white quartzite pebbles and cobbles. At places, especially in the rocks exposed east of the map area, small lenses of quartzite pebbles and conglomeritic or sandy layers occur in the limestone. The association of limestone and quartzite in a sedimentary sequence is not uncommon, but the occurrence of scattered isolated pebbles and lenses of pure quartz conglomerate or sand in an otherwise pure limestone presents a situation not easily explained.

Above the basal limestone is a layer 1,000-1,200 feet thick of siliceous limestones and impure fine-grained quartzite. Small outcrops of granodiorite suggest the existence of a subjacent igneous rock which may account for the metamorphism of these rocks to fine-grained quartzite and tremolite-rich quartzite. Certain of the carbonate-rich portions of the series are dolomitic. Some magnesium may have been introduced from the igneous rock to form the tremolite.

Above the sandy limestone occurs a zone, approximately 1,200+ feet thick, which is composed primarily of metavolcanic material with some intermixed impure limestone. In weathered outcrop the metavolcanic rocks appear as brown dense rocks which have an irregular, contorted, ropy flowage pattern in cross section. On fresh surface, the rocks are gray brown in color, somewhat mottled and have a dense, almost flinty texture. If it were not for the structures shown on weathering surfaces, the rocks might easily be mistaken for light-colored hornfels. For the most part, there are no phenocrysts or other evidence of their volcanic nature. In Rock group E, the metavolcanic rocks, although ranging considerably in general appearance and composition, are all derived from more silicic types.

Under the microscope the metavolcanic rocks have a very fine-grained groundmass with little evidence of the former existence of phenocrysts, although some irregular patches of coarser-grained mineral aggregates may mark the locale of such crystals. Original textures have been largely destroyed by the metamorphism, which has been responsible for the production of the hornfels and quartzite from the mudstone and sandstone. Flow lines in the rock are preserved by swirling lines and narrow zones of a brown stain which is interpreted to be a partially devitrified and altered glass. (See pl. 23, B.) Some biotite has formed along these lines. The silicic lavas were apparently very susceptible to metamorphic changes. The groundmass is composed essentially of a granular mosaic of quartz and a clear, untwinned feldspar. The feldspar, which has an index well below balsam, is very likely orthoclase or albite or both, but the grains were too small for accurate identification. Scattered shreds of a white mica are present through this mosaic and are also segregated along certain lines and in irregular masses. A small amount of biotite is present along some of the brown flow lines of the rock. Some of the layers may have been tuffaceous, but the evidence for their original constitution has been completely destroyed. Small fractures are filled with secondary quartz, and small ovoid areas of similar quartz are interpreted to be vesicle fillings.

Above the metavolcanic rocks is more limestone similar in every respect to the limestone below the impure tuffaceous sandstone. This layer is approximately 700-800 feet thick. Above this is a zone of interbedded limestone and some tuffaceous beds, aggregating in all some 800 feet. The uppermost-exposed rocks of group E comprise 1,500 feet to 2,000 feet of interbedded brown cherts, fine-grained, thin-bedded quartzite, black siliceous hornfels, metavolcanic rocks, and a little limestone. This part of the series is very poorly exposed, and the relative amount of the various components was not determined.

Description of the igneous rocks

All of the igneous rocks of the northern part of the Osgood Mountains are described in this section with the exception of the meta-volcanic rocks interbedded with the sedimentary series, which were described under the lithology of the rock groups. Seven igneous rock types have been identified in the area.

Granodiorite

General features.—The granodiorite of the Osgood Mountains stock is the principal intrusive rock of the area. In general shape the granodiorite forms a double stock consisting of two roughly equidimensional masses on a north-south line which are joined by a short narrow dike-like septum of the same kind of rock. The southernmost of these two stocks is nearly circular in outline with a diameter of 2 miles; the northern is more irregular, being 3 miles long by nearly 2 1/2 miles wide. The general shape of the mapped area of the stocks may be likened to a crude dumbbell.

The relation of the contacts of the stock to the country rock changes from place to place. In general, the bedding of the sediments is parallel to the strike of the contact wherever this strike is not too different from the predominant north-south strike of the sediments. Such conformable contacts occur along parts of the eastern and western sides of the stock and at places on the ends where large sills split off from the main stock and protrude along bedding planes. As a result of this characteristic, the bedding of the range shows a tendency to wrap around the stocks and accomodate itself to the boundaries of the granodiorite. However, on the ends, the granodiorite sharply cuts across the bedding, and it is obvious that large volumes of the country rock have been eliminated from the space now occupied by the stocks.

The dip of the contact can be determined with assurance in several of the mining excavations on the periphery of the stock. At the Riley mine, on the east side of the north stock, exploration indicates that the granodiorite contact dips quite uniformly to the east at 40° parallel to the bedding. (See cross sections, pl. 4.) At the Pacific prospect on the east side of the south lobe of the stock it dips to the east at 60°. At the south end of the same lobe the contact in the Granite Creek mine dips 60° to the southeast. These three specific localities illustrate characteristic conditions which prevail along the eastern borders of the two stocks where the contact is controlled by and lies essentially parallel to the bedding of the sediments. At the Richmond mine, on the northwest side of the north stock, the contact cuts across the bedding and is vertical. The contact at the Porvenir mine dips steeply to the east, and the granodiorite thereby overlies the sedimentary rocks. Elsewhere on the western borders of the stocks, the configuration of the contact, its relation to topography, and, in a few places, direct measurement of the dip, indicate that the contact dips consistently to the east at a steep angle. Whereas the dip of the contact on the eastern side of the stock tends to follow the bedding of the sediments, it seems to be true generally that on the west, the contact, dipping to the east at an angle greater than the dip of the sediments, intersects the bedding.

Thus the Osgood Mountains stock is a downwardly enlarging body of igneous rock with an assymetrical cross-section in which both contacts dip eastward. (See section B-B', pl. 2.) The character of the southward termination with its steeply dipping contact as shown in the Granite

Creek mine and a general lack of dikes or outlying plugs very far from the main mass suggest an abrupt ending of the rock in this direction. The north end of the north lobe feathers out into several fairly large sills and dikes, which lead toward a number of other disconnected dikes as well as three small granodiorite plugs, the composition of which is similar to the stock. The occurrence of these small igneous rock bodies in the area north of the main outcrops of granodiorite suggests that the stock may have an underground extension in that direction. Evidence based on the degree of metamorphism also bears this out and is discussed under that heading.

The upwardly converging character of the contacts together with the apparent burial of the north end of the stock make it logical to infer that the stock is probably exposed near its crest, although it could have extended several thousand feet above its present elevation.

Petrography.—The granodiorite is an equigranular, medium coarse-grained light-colored rock, which, on weathered surface, assumes a buff or light-tan color. (See pl. 14, A.) Local areas contain abundant sulfides and upon weathering become stained a dark-reddish brown. Plagioclase, orthoclase, quartz, biotite, and amphibole can be recognized in all hand specimens, and, in some specimens, yellowish-brown titanite is visible. Detailed study of thin sections of rocks collected from all parts of the granodiorite has determined that the composition is remarkably uniform, with the exception of a very narrow border zone. An average composition is as follows: plagioclase 45 percent, orthoclase 25 percent, quartz 15 percent, biotite 10 percent, amphibole (common hornblende) 5 percent, plus minor amounts of titanite, apatite, zircon, and alteration products. The plagioclase is always very close to An_{40}

in composition, although much of it is zoned and varies in some measured specimens between An_{36} and An_{48}. Many of the plagioclase crystals show oscillatory zoning with evidence of corrosion between each sequence of zones, and most of them are corroded on the periphery by orthoclase. The principal mafic mineral is biotite, with an amphibole near common hornblende in composition as the second most abundant. Of the accessory minerals, sphene is the most abundant, and, in some sections, amounts to several percent.

The over-all uniformity of composition of the granodiorite is notable. An attempt to determine possible subtle variations that are not easily apparent was made by means of heavy residue studies of 6 samples which were collected from widely spaced localities in the stock, both near the contact and at the center. About 200 pounds of weathered-granitic grush, which was still in place, was gathered from each locality and panned. The magnetic fraction consisting essentially of magnetite was removed and the non-magnetic residues studied. These were found to consist almost entirely of different proportions of apatite, sphene, and zircon, with minor amounts of allanite in two samples. On the basis of so few samples, any generalizations are meaningless, but the following observations are given at their face value. The two samples from the center of the intrusive contain zircon in a great variety of crystal shapes, sizes, and color and in much greater abundance than in the other samples. Sphene is more abundant in samples near contacts than in the central part; and one sample on the contact at the Valley View mine contains a smoky lavender pleochroic apatite in sharp contrast to colorless apatite present in all other samples.

None of these observations is positive in the sense of indicating significant variations in composition of the granodiorite. A negative result, however, is the confirmation they give to the general conclusion that the granodiorite has been little affected by the contact action through assimilation of wall rock, by endomorphic alterations, or by incorporation of xenocrysts. For example, the lack of garnet in heavy mineral concentrates from granodiorite against tactite at both the Granite Creek mine and the Valley View mine illustrates this principle.

The exception to the general uniformity of composition of the granodiorite is a change in the mafic minerals within a few feet of the contact. This change consists of a diminution in the amount of biotite and the development of pargasite at its expense. At the immediate contact, biotite may be entirely replaced by the amphibole, and some of the amphibole, in turn, replaced by diopside. Paragenetic relations, based on the rimming of one mineral by another, are that of the Bowen reaction series in reverse. This change is apparent at all contacts regardless of the composition of the wall rock. Its significance, however, is not fully understood. From the occurrence of remnants of amphiboles and pyroxene in the silicified border facies of the granodiorite (a facies resulting from contact metasomatism and discussed under metamorphism), the implication is drawn that the production of the minerals predates the later phases of contact metasomatism with which the silicification is associated. This change in the mafic minerals may result from a slight contamination of the magma by the wall rock, or from the effects on the crystallization of the magma occasioned by the escape of volatiles from a zone at its borders into the country rock at the time of emplacement. This latter hypothesis might help explain the destruction of the biotite, through the removal of water which is essential in its composition, and the transfer of some material—notably iron—into the wall rocks from the outermost rind of the stock. Such a process might be a first step in additive metamorphism which is discussed at some length later in this paper.

Mode of emplacement.—The mode of emplacement of the stock is not easily deciphered. Five possible methods of emplacement are considered: (1) Invasion by pushing the country rock aside and making room between the sediments, (2) pushing of the displaced rock upward—a punching action, (3) metasomatic replacement, (4) stoping as championed by Daly, (5), a combination of two or more of the aforementioned processes.

As previously pointed out, there has been a certain amount of shoving aside of the country rock by the pressure of intrusion. This is not only illustrated in the regional pattern around the intrusive as shown on the map (pl. 2), but locally in several of the mine areas where crumpling of the beds occurs in reentrants or accompanies the edges of the ore bodies. (See pl. 5, section B-D and pl. 13, A.) However, the fact is obvious from a glance at the geologic map (pl. 2) that the generally predominant cross-cutting relations at the ends of the intrusive make it necessary to account for an embarrassingly large volume of hornfels and limestone which once occupied the space filled with granodiorite. For the main mode of emplacement, concordant intrusion is entirely inadequate.

The punching out of a block of the roof implies the production of boundary faults, a tearing off of large chunks of rock and the shoving of these upward or outward into a position from whence they have now been removed by erosion. For such a process to be sound mechanically the contacts would have to be nearly vertical, or at least parallel, and very probably flaring in the upper parts of the intrusive mass. Contrary to such expectations, the granodiorite contacts converge sharply upwards. A further expectation in such a hypothesis would be the dragging of the walls upwards around the periphery; this kind of intrusion being under great stress, such structures would be strong corroborative evidence of this mode of emplacement. None, however, was seen.

Emplacement by metasomatism or metasomatic replacement (recrystallization replacement) involves a process or series of processes which have been applied by various petrologists to explain the production in place of igneous-appearing rocks of all modes of occurrance where other mechanisms of introduction seem inadequate. The modus operandi and effectiveness of the process is interpreted variously by different workers. Some, such as Quirke and Collins (7), Sederholm (8), and others, apply the process in old Archean terranes under conditions of deep burial, high pressure, and temperatures sufficient to produce partial fusion of the rocks. Others, such as A. L. Anderson (9), Doris Reynolds (10), and C. E. Goodspeed (11), apply the process to the formation of igneous-appearing rocks in much later periods and under conditions of much less severe regional metamorphism, or even in the almost complete absence of excessive temperature and pressure. The process at lower temperature is visualized to be caused by a more or less tenuous, all-pervading solution which brings in the needed elements, removes excess or unusable elements, and promotes a recrystallization and reconstitution of the rock in place, thereby producing a rock whose mineral composition and texture simulates that of a true igneous rock. The source of the metasomatizing solutions is referred by most advocates of the process to some adjacent body of true magma, and, in such cases, the replacement rock forms only a rim or relatively small part of the whole. In some descriptions, however, large masses of country-rock sediments are said to have been transformed through the metasomatic activity of solutions which came from "below".

The criteria for distinguishing these igneous-appearing replacement rocks from true igneous rocks include the following: (a) Wall-rock units can be connected across an intervening area of igneous rock without offset; (b) inclusions or xenoliths which are completely separated from the country rock, but which maintain structural orientation with the structure of the country rock; (c) relicts of wall-rock structure which may be traced through or into the "igneous" rock—such things as ghost bedding, ghost pebbles or shadow pebbles of a conglomerate etc.; the so-called palimpsest structures of Sederholm may be included here in part; (d) the composition and texture of the metasomatized rock may change within short distances; this is especially true in the case of incomplete change or in areas of sediments of widely varying compositions; (e) coarse texture on borders—the lack of any fine-grained or glassy selvage; (f) gradational as well as sharp borders; (g) granulitic, granoblastic, and helicitic textures are common; (h) phenocrysts have features indicating porphyroblastic origin—turbidity due to included material, complex twinning, included minerals that are not pyrogenic; (i) inclusions in all stages of recrystallization may be locally abundant, and delicate relicts of the inclusions may be undisturbed; (j) wall-rock material at contacts extends into the "igneous" rock and is interstitial with respect to the crystals of the dike; crystalloblastic extension of dike minerals into the wall rock.

When applied to the Osgood Mountains stock, the criteria listed above fail to afford a convincing case for the metasomatic origin of the rock. There are no internal structures; the contacts are everywhere sharp and not controlled in any way by the lithology; the composition and texture of the granodiorite is very uniform to within a foot or two of the contact itself. There are very few inclusions within the granodiorite, even at the immediate contacts, and no examples of the orientation of inclusions with the wall rock.

The hypothesis of stoping presents a reasonably plausible mode of intrusion for the Osgood Mountains stock, but direct evidence for its operation is not available. The general lack of inclusions caught in the act of being stoped has been pointed out previously, but this can be rationalized as offering no argument against their former existence. The fact that the western contact dips under the granodiorite is not necessarily an argument against the stoping process, but such a dip is probably less to be expected than one that dips under the hornfels. Indirect evidence pointing to stoping as a possible mode of origin consists of two main lines of thought: (1) The nature of the contacts and their relation to the country rock, and (2) the relatively uniform composition of the intrusive mass.

In a number of the mine openings on the periphery of the stock, the contact can be seen in great detail and consists locally of a series of steps or nearly right-angle turns where the igneous rock cuts sharply across the bedding for a short distance before resuming a course more nearly parallel to the bedding. These jogs vary in size from 10 to 100 feet or more in depth. At the Riley mine, for instance, the course of the contact is determined essentially by the bedding of the sediments which dip 45° and a nearly vertical jointing at right angles to the bedding. (See pl. 4.) The vertical structures have been interpreted as cross joints or small faults, and the granodiorite has apparently made use of these structures at the time of its emplacement. In a process of block stoping chunks of rock would presumably break out along such lines of weakness, and the presence of this type of contact is suggestive of the mode of intrusion.

Dacite porphyry

Along the periphery of the granodiorite stock, notably at the north end but also at the south and in the area between the two lobes, are a series of dikes which are very closely related in composition to the granodiorite. The dikes are essentially offshoots from the main mass and are distinguished from it only by texture. In hand specimen, the rocks are light-gray to gray-tan colored porphyries composed of abundant phenocrysts of feldspar in an aphanitic matrix. A few scattered crystals of biotite and altered amphibole or pyroxene also are visible. In thin section, the rock is seen to be composed of zoned plagioclase phenocrysts (40-60 percent) having a composition of An_{33-45}, set in a matrix of fine-grained sanidine, pyroxene, and quartz. Scattered areas of chlorite represent alteration products of pyroxene. Accessory minerals include sphene and apatite. The plagioclase crystals show evidence of attack by the matrix with the formation of perthitic intergrowths on the periphery of some crystals.

Pegmatite and aplite

Pegmatite and aplite, both salic differentiates from the granodiorite, are grouped together because of their relative scarcity in the area. In fact, the most notable feature about them is the general paucity of such rock types either along the granodiorite contacts or within the granodiorite stocks. A few aplites have been mapped, but most of them are too small or discontinuous to show on the map. Pegmatite has been found at very few places and always against the contact. Wherever it is found in the Osgood area, the pegmatite is a simple mixture of quartz and feldspar with a little mica, but no rare minerals.

Relations along the contacts where aplite is to be observed indicate clearly that it was developed as an end product of consolidation of the granodiorite but was emplaced before the final phases of the contact metasomatism. These dikes tail out and disappear in the granodiorite, but in the contact zone appear to be replaced in part by solutions which produced the garnetization. (See fig. 2.)

Andesite

Dikes of andesitic composition are scattered rather widely over the Osgood Mountain area in the vicinity of the granodiorite stock. Most of them are relatively thin—rarely exceeding 10 feet wide—and are discontinuous along their strike. In a few instances, the dikes blossom out into small plugs and irregular masses. In hand specimen, the andesite is medium gray, fine grained to aphanitic and porphyritic. The phenocrysts comprise white milky plagioclase crystals, as much as 5 millimeters in diameter, and shiny black needles of hornblende. In thin section, the rock is seen to be composed of phenocrysts of plagioclase (An_{40})—zoned in an oscillatory sequence with much corrosion between the series—quartz, which occurs sparingly in well-rounded, large grains, biotite in large plates, and euhedral hornblende, all in a fine-grained groundmass of the same minerals. Some of the andesite is highly altered, and the phenocrysts of plagioclase are transformed into a mass of chlorite, carbonate, and epidote.

Andesite dikes cut all of the sedimentary rock groups in the area, the granodiorite, and the contact metasomatic rocks. They are definitely post-granodiorite, although they may be related to a much later phase of the same igneous activity. A notable feature of the series—granodiorite-dacite-andesite—is the uniform zonal character of the plagioclase. In all three rocks, the zoned plagioclase falls in the An_{35-50} range, the zoning is oscillatory, and corrosion occurs at intervals during growth of the mineral, ending with partial resorption of the outermost layer of the crystals.

Basalt

Considerable areas on the lower slopes of the west side of the Osgood Mountains are covered by basalt flows. The geologic map (pl. 2) shows a small portion of these rocks where they crop out on the ridge between Farrell and Cave Canyons and form a feature locally known as Soldier Cap. The rock is a dense dark-gray to black vesicular lava which contains scattered olive-green grains of olivine. In thin section, the rock is seen to have a fine-grained trachytic texture, due to the semi-parallel arrangement of plagioclase laths. The plagioclase laths, which average 0.2-0.3 millimeter long, enclose and surround scattered olivine grains which range in size from 0.6-1.1 millimeters. The olivine is always bordered by a thick rind of iddingsite, and many of the smaller grains are completely altered to this mineral. Plagioclase of a composition $Ab_{50}An_{50}$ comprises 75 percent of the rock, olivine 20 percent, and indeterminate interstitial material 5 percent.

Flows of the basalt cap the ridge, and dikes of the same basalt occur beneath the flows and are presumed to be feeders for them. The flows dip west at low to moderate angles, and, in all probability, extruded on an erosion surface produced on the site of the present range before its more recent elevation and tilting to the west.

Rhyolite tuff

Immediately north of the Getchell mine town site and extending to the vicinity of the new Getchell shaft is an ill-defined area of rhyolite tuff which is, for the most part, well covered and difficult to map. The area outlined on the map shows its general limits as nearly as could be determined from the few artificial exposures which uncover it. Were it not for several unusual features, the occurrence might be explained merely as an erosion remnant of a tuff fall that covered wide areas and had its source at some undisclosed vent. However, two exposures present evidence that strongly suggest its origin from a vent beneath the area of outcrop. One of these exposures is in the walls of a room excavated in the side of a hill for a powder magazine 2,000 feet northwest of the Getchell mill. Angular blocks of granodiorite, ranging in size from a few inches to several feet in diameter, are enclosed in a matrix of tuff, and most of these blocks are isolated one from the other by the tuff. The other exposure is in the new Getchell shaft which was sunk for a distance of nearly 300 feet in tuff. Hornfels was encountered at 296 feet from the collar, and surface exposures of hornfels surrounding the shaft at distances not exceeding 1,000 feet make it necessary to postulate a vent of some sort to account for the great local thickness of tuff.

To account for the relations outlined above, a local source of the tuff seems necessary and the nature of the material, and the enclosed blocks of granodiorite suggest an erruption sufficiently violent to tear off blocks of the wall rock and incorporate them in the debris.

Megascopically, the tuff is a light-buff, soft, porous rock of very fine grain, but it contains recognizable flakes of biotite and occasional grains of quartz and feldspar. In thin section, quartz, biotite, plagioclase, and orthoclase occur as recognizable crystals in a matrix of glass shards and pumice fragments.

GEOLOGIC STRUCTURE

The geologic structure of the northern part of the Osgood Mountains is complex, probably much more complex than is shown on the map and cross sections, and a complete unraveling of the structural history will have to await more extensive mapping to the south and southwest. The major structural feature of the northern part of the mountains is the occurrence of five groups of rocks each occurring in a structural block that is bounded by faults or by faults and alluvium. The lack of specific information on the relative ages of these rock groups makes an interpretation of the direction of movements on the faults very difficult, and a full understanding of the structure evasive.

Folds

Structural evidence suggests at least two periods of major folding and two others of somewhat lesser intensity. The predominant structural feature of the mountain block is the homoclinal eastward dip of the rocks of groups A, C, and D. All evidence suggests that the sequence is in normal stratigraphic relationship with tops of beds to the east. The dip to the east averages 60°, although it varies from place to place, and locally the beds are overturned. The regional structure to which this uniformly dipping series is related is unknown, but it is obvious that some major period of folding followed the deposition of the sequence of rocks in groups A, B, C, and D. If the tentative age of the youngest of these formations (Groups C and D) is correctly placed as late Paleozoic, it will be necessary to place the folding of them probably in the Pennsylvanian because these rocks are overlain unconformably by a series that has been tentatively correlated with the fanglomerate and the upper Pennsylvanian Antler Peak limestone of the Antler Peak quadrangle.

The fanglomerate and the Antler Peak limestone together with its succeeding formations, all of which lie above the unconformity, are also folded. This series, where exposed in the southwest part of the map area, has an inclination of 15 degrees to the north. Exposures of it in the northeast corner of the mountains dip between 20° southeast and 90°, and the small synclinal segment north of Anderson Canyon has dips on the limbs up to 70°. Such structure implies extensive folding in some period following upper Pennsylvanian time. Deformation of the upper Pennsylvanian series very likely affected the underlying rocks, but to what extent is hard to evaluate. The only place where such information might be obtained is beneath the synclinal remnant north of Anderson Canyon, but unfortunately the exposures at that place are not very revealing.

The quartzites of rock series B appear to be considerably more deformed than the rocks of series D to the east of them. Since these are tentatively correlated with the Cambrian sequence near Golconda, this more intense folding may reflect an early Paleozoic period of deformation. However, the deformation of these rocks may be more logically related to contortion and drag folding along the faults which bound this block.

Tilted lava flows on Soldier Cap must reflect a period of slight deformation subsequent to their formation and can, in all probability, be assigned to one of the later episodes in the structural history of the mountain mass.

Faults

Faulting has been one of the major processes in the structural development of the Osgood Mountains from early in their history to the very recent. The faults fall naturally into two major groups, those formed before the intrusion of the stock and those formed subsequent to its intrusion. The pre-intrusive faults include both steeply dipping normal faults and low-angle thrust faults. The post-intrusive faults are generally steep, and most of them are considered to have normal displacement, although some may have large horizontal components.

Pre-intrusive faults

The earliest faults of the pre-intrusive group are thought to be low-angle thrusts, two of which are represented in this part of the mountains. One of these is on the prow-shaped hill north of Hogshead Canyon and brings rocks of group D upon rocks of group E. The fault strikes nearly east and dips to the north at an angle of about 15 degrees. The other, in all probability related to the same period of thrusting, occurs at the north end of the map area. It also strikes east and dips gently to the north and thrusts rocks of group E onto those of group D. Both of these faults are delineated on the basis of discordant structures on opposite sides of a line of unusual contortion and occasional zones of silicification and silicified breccia. The southern thrust fault is cut off by the intrusion and thus is definitely dated as being pre-granodiorite. The other is cut by one of the steep-dipping faults that has been tentatively assigned to the pre-granodiorite group.

Several steeply inclined faults of major displacement are cut by the contact of the granodiorite and thus definitely pre-date the period of intrusion. The largest of these separates the rocks of group B from those of group D in the southwest corner of the area. At the one place where direct measurement could be made, the fault dips 80° to the east, and its topographic expression indicates that it maintains such a dip for most of its mapped course. Several faults of less magnitude strike into the contacts on either side of the stock and are cut off by the intrusion.

The large continuous fault on the west side of the range which separates rocks of group C from those of group D is thought to be also of pre-intrusive origin. This is based on the fact that it is very steeply dipping and near its north end is cut by a small plug of granodiorite that is correlated with the main stock.

The numerous cross faults that chop up the rocks of group A in the southeastern corner of the map may also be pre-intrusive. Notable amounts of secondary copper minerals, presumably derived from copper sulfides, are localized along them and at their intersections. The primary copper mineralization is presumed to be related to the intrusion of the granodiorite.

Post-intrusive faults

A major fault along the eastern edge of the mountains is one of the prominent structural features of the area. In detail, this structure is composed of a series of echelon segments, three of which have been mapped, and the south end of each overlaps the north end of the adjoining segment on its east side. The southern extension of each segment strikes out under the alluvial terraces on the flanks of the mountain where its extension cannot be traced. This series of fault segments is known collectively as the Getchell fault from the Getchell mine where one of the segments is exceptionally well exposed in the open-pit mine workings excavated in the fault zone. It is younger than the granodiorite, for it cuts across projections of the igneous mass. At the Getchell mine, the fault, actually a complex fault zone, dips to the east at an average angle of 55° and attains local thicknesses of as much as 100 feet. Much of the fault zone comprises closely spaced shears, but great pods of a blue gouge, which measure as much as 40 feet thick and hundreds of feet long, have been mined for their gold content. Numerous subsidiary faults split off from the main zone into the foot wall and hanging wall. The same fault segment so well exposed at the Getchell mine is also exposed at the Riley mine, both in the open-cut workings of the contact-metamorphic tungsten deposit and in diamond-drill holes put down in the course of the development of the tungsten ore. At this locality the fault zone is at least 200 feet wide (see pl. 4) and dips east at the relatively low angle of 40 degrees. In the Pacific prospect, north of the mouth of Granite Creek, another segment of the same fault is represented by about 500 feet of breccia, gouge, and sheared rock. Its average dip is estimated here to be about 60 degrees.

The Getchell fault shows evidence of a complex history. It is apparently one of several along which elevation of the Osgood Mountains has taken place, and, as such, has frequently been referred to as a range-front fault. It is evident, however, that movement on it alone may not have been sufficient to account for all of the uplift. In fact, the relationship of the formations on opposite sides are such as to discredit much downward displacement of the east side; limited exposures of limestone, hornfels, and granodiorite to the east of the fault appear to require a different form of movement. At the Getchell mine all visible flutings, slickensides, and linear elements are essentially horizontal, indicating that the latest movements were parallel to the strike. However, the production of such a wide zone of fracturing and brecciation seems to imply a long period of successive movements and very likely frequent reversals of direction of movement. Some direct evidence bears on the long-continued activity along this fault zone. Extensive underground workings at the Getchell mine have disclosed several andesite dikes which are badly sheared and altered but which seem to follow the trend of the fault zone. The original position of these dikes appears to have been controlled by an early structure which developed into the Getchell fault zone. The fault zone thus appears to date at least from the time of andesite intrusion. The most recent movement on the Getchell fault is not known, but a parallel break at the very southeast edge of the mapped area offsets alluvial fans and thus demonstrates the continuation of faulting to the very recent. Plate 12, A and B, shows the Getchell fault at the Getchell mine.

A prominent fault that separates rocks of group A from those of group D in the southeast corner of the map area is believed to be a split from the Getchell fault. It is poorly defined, but the topographic expression indicates a moderate dip to the east, and it joins the Getchell fault at an acute angle near the mouth of Granite Creek. A recent discovery of gold mineralization related to this fault is further indication of its relation to the Getchell fault zone, which contains gold at the Getchell mine.

IGNEOUS METAMORPHISM

Introduction

With the exception of a few localities in the north part of the mapped area, all of the rocks which comprise the northern part of the Osgood Mountains show effects of igneous metamorphism—metamorphism directly related to the Osgood Mountains granodiorite stock. The amount, distribution, and character of the metamorphic effects result from various combinations of four factors: the composition of original rock, the distance from the contact, the shape of the contact together with its relation to the structure, and the accession of solutions carrying heat and new material from the magma into the invaded rocks. Although the granodiorite stock was the cause of the metamorphism, it shows very few effects of the process, either in the form of assimilation and contamination from the invaded rock, or endomorphic alteration related to the solutions given off during the last stages of consolidation. On the other hand, the invaded rocks have been widely affected, the argillaceous members being changed to hornfels, the calcareous members to hornfels, tactite, or crystalline marble, and the sandstones to quartzites. In a few places it appears that the metavolcanic rocks also have been affected by the igneous metamorphism.

The contact-metamorphic aureole of the Osgood Mountains stock shows the effects of both thermal and additive processes. The exact line of separation between the two is often very difficult to define, and it is only in the purer carbonate rocks that conclusive evidence of metasomatism can be obtained. Very likely some material has been added to the argillaceous facies, but, from the standpoint of mineralogy, such addition is not essential to the development of the argillaceous hornfels.

Metamorphism has affected all the rocks in the map area to a greater or lesser extent, and consequently the distribution of the metamorphism is shown on the geologic map only by regular rock symbols. (See pl. 2.) In view of the widespread effects of the contact action and the inability in most instances to trace a single bed from the contact outward beyond the reach of metamorphic processes, it is difficult to evaluate the 4 factors listed above in order of their effectiveness. However, in this area, with its alternation of such diverse rock types as mudstone or siltstone and relatively pure limestones, the original composition of the rock appears to be the major controlling factor. Whether the control is the chemical difference between the clays and the carbonates or the physical differences in porosity and permeability between two such divergent rock types is for the moment not considered. The general fact remains that the metamorphic effects are vastly different in each of these two rock types. The effect of distance from the contact is somewhat hard to evaluate because of the unknown factor of the underground distribution of the igneous rock. Whereas distance from the contact is undoubtedly an important factor bearing on the intensity of metamorphism, other factors are more important in explaining the irregular and anomalous distribution of the contact effects. Structure and its relation to the contact is perhaps the next most important factor after original composition. Lasky (12) noted in the Little Hatchet Mountains that structures played a very important role in governing the distribution of metamorphism, and he laid great emphasis on the pre-supposed greater permeability of rocks to emanations passing along bedding planes than across bedding planes. It is not clear whether Lasky refers only to metasomatizing solutions or to any emanations that serve to transport heat, whether they carry material in solution or not. The effect of structure is difficult to demonstrate on a large scale in the Osgood Mountains, because of the geometry of the stock and its setting. Metamorphism extends out for distances of from one to two miles north and south from the stock along the strike of the beds. On the east side, there is only a narrow zone of rocks between the stock and the alluvium of the valley floor. On the west, the metamorphism extends for at least a mile out from the contact and apparently across the structure, but the dip of the beds is into the contact, and the spread of metamorphism may be explained as due to migration of heat along the bedding up the dip—a situation even more conducive to the flow of emanations than out from the igneous rock parallel to the strike. On a small scale, however, the effect of greater permeability and more extensive metamorphism along the strike than across it can be demonstrated at numerous localities around the edge of the stock.

Thermal metamorphism

In a subject which incorporates as many different factors as this one, a systematic and understandable description can only be achieved by reducing, so far as possible, the number of variables. Consequently, the descriptions in this section will deal with but one type of rock in turn, thus eliminating one of the more complicating variables and will be restricted to the effects on these rock types of thermal metamorphism without the addition of material from the magma.

Thermal metamorphism of the argillaceous rocks

Approximately 37 percent of the rocks of the Osgood Mountains were deposited as siltstones or mudstones containing scattered but minor amounts of sand and calcium carbonate. The original characteristics of these rocks have been destroyed for the most part by the metamorphism, but near the northern limits of exposure of rock group D a few outcrops of phyllitic shale are believed to represent the least metamorphosed equivalent of the original argillaceous rocks. The exposure of the phyllitic shale is nearly one and a half miles northwest from the nearest outcrop of the main intrusive. A few small dikes in the vicinity of the exposures probably have had little metamorphic effects. The rock is a hard, thin-bedded, fissile, phyllitic shale, dark gray in color with a surface sheen which results from the development of very minute sericite flakes. Whether the phyllitization resulted from a regional metamorphism before the intrusion of the stock or from the igneous metamorphism could not be definitely determined. In such a finely laminated argillaceous rock, the development of sericite oriented parallel to the bedding might result from mimetic crystallization, the orientation being controlled by minute flakes of kaolin or montmorillonite in the original shale, and the growth of the sericite could conceivably be initiated by heat from the intrusion. These rocks, however, have been subjected to considerable diastrophism, and consequently may have been phyllitized during deformation and before the intrusion of the stock.

The first definite metamorphic change that is without question related to the granodiorite stock is the development of a hard, dense rock, predominantly very dark in color and with only a very poorly developed foliation. Under the microscope, these rocks are seen to be composed of a very fine-grained, nearly unresolvable mass of feldspar, quartz, and sericite. Oval spots as much as 2 millimeters in diameter result from a slight local increase in grain size, together with an increase in amount of sericite over chlorite or biotite. (See pl. 18, A, B.) A further advancement of the process results in a rock which, on weathered surface, shows a distinct spotting (see pl. 15, A, B, C,), whereas on fresh surfaces a patchy resinous lustre is the only evidence of new mineral development. Microscopical examination of these slightly more spotted rocks shows that the earliest changes consist of the development of andalusite or cordierite or both as porphyroblasts in a very fine-grained matrix of clay mineral or alkali feldspar and quartz. The andalusite has developed most abundantly in the dark carbonaceous rocks and contains numerous inclusions, which in more advanced stages of metamorphism become oriented along crystal planes to form the variety known as chiastolite. Some of the beds in which andalusite is extensively developed are called andalusite hornfels. (See pl. 14, C.) The matrix comprises very fine-grained aggregates of a faintly pleochroic mica, which is probably an incipient biotite, sericite, alkali feldspar, and quartz; opaque inclusions, which are largely carbonaceous matter, include some magnetite powder and possibly ilmenite.

Cordierite predominates in the great bulk of the argillaceous hornfels, and because of its characteristically weak power of crystallization develops large, anhedral, irregularly ovoid crystals which have optical continuity but contain abundant inclusions of the groundmass. (See pl. 19, A, B.) In the incipient stages of metamorphism, cordierite crystals may attain considerable size but have little power to clear themselves of inclusions.

Rocks belonging to this preliminary stage of igneous metamorphism have been found as far as 5,000 feet from any exposed contact, but it is also true that rocks of similar grade are found within 1,500 feet of granodiorite.

Rocks of the same general composition somewhat closer to the contact—distances from exposed granodiorite of between 1,000-3,000 feet—show an increase in the amount and size of biotite grains. Cordierite porphyroblasts are prominent, but the inclusions within them are fewer in number and larger. Some of the rocks contain spots of three separate and distinct kinds: (1) Clusters of partly alined biotite crystals forming oval spots which extinguish more or less in unison, (2) cordierite porphyroblasts that have cleared rims but a central area of inclusions still alined with the foliation of the bedding, (3) large white spots of granular quartz and feldspar, which represent local areas of recrystallized groundmass essentially cleared of biotite. (See pls. 19, A, B, and 20, A.) The sequence of formation of the spots in one specimen, based on overlapping relationships, is the biotite segregations first, cordierite second, and cleared and recrystallized areas third. The horizons which are richer in carbonaceous matter have the characteristic development of andalusite (chiastolite), but in this zone somewhat closer to the contact most of the andalusite is altered to sericite and is recognizable only by virtue of the crystal shape and the arrangement of the inclusions. The completely sericitized core of the andalusite may be surrounded by a narrow margin of clear, optically continuous, muscovite. The significance of the sericitization is not clear but might represent the effects of metasomatic activity superposed on a previously thermal-metamorphosed rock.

Within 1,000 feet of the contact, a slight advance in the metamorphic grade is evidenced in the cordierite-biotite hornfels by the appearance of small needles and crystals of amphibole and pyroxene. Some specimens from this zone contain a small amount of hypersthene in small prisms in addition to biotite, cordierite, alkali feldspar, and quartz. The andalusite-biotite hornfels contains, in addition to the completely sericitized andalusite, incipient porphyroblasts of muscovite which have developed in the groundmass and contain abundant carbonaceous inclusions. Most of these appear to grow from a coalescence of the sericite so prevalent in the groundmass, but may, in part, be due to the addition of material—notably K and H_2O—from the granodiorite. Specimens 75 feet from the contact are essentially similar to the same rock 1,000 feet away, except for the appearance of well-developed, but small crystals of feldspar. The feldspar occurs as small well-formed crystals many of which show carlsbad twinning, and a few show zonal extinction. The optical signs and indices indicate that both alkali feldspar and a basic oligoclase are present in the rock. The presence of appreciable amounts of sodium-bearing feldspar is suggestive of the addition of material from the magma. None of the minerals formed in the early stages of reconstitution contains sodium, and this conforms to the generalization that clastic, sedimentary rocks are most everywhere notably deficient in this element. The general grain size is somewhat larger; cordierite porphyroblasts are as much as 2 millimeters long, and many of them are cleared except for a speckling of large well-formed biotite crystals. The groundmass contains an abundance of small incipient cordierites about 0.02 millimeter in diameter. There is still abundant dust of carbonaceous material—possibly graphite and iron oxides. A foliate arrangement of biotite and alinement of inclusions is still evident.

The most striking change in these rocks occurs within a very few feet of the contact. The rock loses its essentially foliate characteristics, and the average grain size increases to about 0.5 millimeter. The cordierite becomes more equi-granular and forms the principal groundmass, but it still contains abundant well-crystallized inclusions of quartz and biotite. (See pl. 21, A, B.) Some quartz has been introduced along old bedding planes or in cross fractures. (See pl. 20, B.) Biotite is well crystallized and locally attains a length of 5 millimeters. Some of the cordierite is altered to a sericite-like mica—most probably phlogopite—and this reaction is attributed to the effect of pneumatolytic solutions. It is evident, however, that the solutions, which pervaded the rocks at the time these changes were induced, were carrying no great quantity of elements which would react with the components of the hornfels. There is no evidence of the introduction of borates, fluorides, or chlorides, and the changes can be explained simply by the activity of water alone plus perhaps the addition of small amounts of potash and silica.

In general, the progressive changes which occur in the argillaceous rock upon approach to the contact are very gradual and, in the aggregate, not very profound. From the first appearance of cordierite, andalusite, biotite, and sericite at a distance at least 5,000 feet from the nearest exposure to within a few feet of the granodiorite contact itself, there are essentially no new minerals formed but merely a completion of the recrystallization already started. The local production of a little pyroxene may be attributable to a variation in original composition, and the alteration of andalusite and cordierite into micas may be attributed to pneumatolysis. The thermal metamorphism is essentially of low or low-medium grade. At the contact there is a very narrow zone, probably averaging less than 5 feet wide, in which feldspar appears as a new addition to the mineral assemblage. Notably missing are such minerals as garnet, sillimanite, and hypersthene in any appreciable quantity. Biotite is preserved up to the contact and is not destroyed to form feldspar, amphibole, or pyroxene.

Thermal metamorphism of the quartzites

Quartzites comprise over 20 percent of the rocks in the northern Osgood Mountains, but only in a few places do they approach the granodiorite, and only at one place do they contact the stock. The greatest thicknesses of quartzite occur in Rock groups B and C which are removed from the contact or barely adjoin it. Group D, the group of rocks which surrounds the main intrusion, contains only narrow beds or lenses of quartzite which are discontinuous. Susceptibility of quartzite to metamorphic change is intimately related to its purity. Under straight thermal, non-additive metamorphism, pure quartz can only recrystallize. However, the presence of a little carbonate or argillaceous material as cement or as impurities will facilitate reconstitution with the consequent production of new minerals. Many of the quartzites in the Osgood Mountains vary from place to place in purity and grade into the beds above and below. Consequently, a study of progressive changes in any one quartzitic layer as the contact with the granodiorite is approached is nearly impossible. However, generalizations about the thermal metamorphism of quartzite can be made on the basis of scattered data.

The gritty quartzites of Rock group C at a surface distance of 10,000 feet from the contact bear no evidence of igneous metamorphism. The quartz is in rounded grains showing no recrystallization; the cementing material is slightly changed, sericite having developed and a little carbonate having recrystallized, but no more than could be explained by normal diagenesis and slight regional metamorphism. At 6,000 feet from the contact an impure quartzite that was initially quite calcareous has been changed into a rock composed of 50 percent quartz grains scattered throughout a mat of fibrous pyroxene. That this rock was so intensely metamorphosed by granodiorite 6,000 distant is suspect, and the presence of underlying igneous rock is considered to be the reason for the change. Somewhat nearer the contact (4,700 feet) a narrow lens of very fine-grained quartzite has been slightly recrystallized to a mosaic of interlocking grains which average 0.05 millimeter in diameter. The recrystallization of the quartz is associated with the development of a few small clusters of tremolite and the recrystallization of residual carbonate. A pure quartzite at 3,700 feet from the contact has been completely recrystallized into a mosaic of quartz grains that range from 1 to 2 millimeters in diameter. Much of the quartz shows strain shadows. The massive, pure quartzite of Rock group B in the angle between the two faults on the back slope of Hogshead Peak has been much brecciated by pre-granodiorite deformation. This quartzite breccia has been recrystallized and recemented into a solid quartzite in which the original rock fragments are represented by a somewhat finer-grained mosaic than the recrystallized interstitial material. This complete recrystallization of the quartzite took place about 1,000 feet from the contact.

Cherts, which comprise about 5 percent of the total section, may be considered a special type of siliceous rock akin to quartzite. These rocks, originally chalcedony, were especially vulnerable to recrystallization, and even under mild regional metamorphism were transformed to a fine mosaic of quartz. One chert, at 5,000 feet from the stock, is composed of a mosaic of quartz grains 0.05-0.1 millimeter in diameter with some interstitial sericite and chlorite. A few larger euhedral quartz grains may be detrital but could just as readily result from recrystallization. Much of the rock contains an abundance of finely disseminated black impurities which are considered to be carbonaceous matter. A few areas of quartz mosaic are cleared of all impurities and are believed to represent areas of recrystallization under conditions of thermal metamorphism. Locally a small-scale brecciation is evident which could result from post-depositional, but pre-consolidational, displacements. This brecciation produces small-scale intraformational conglomerate.

An impure chert of similar position with regard to the contact shows, in addition to the features mentioned above, numerous small augen of clear quartz mosaic only 0.2 millimeter long, and many small veinlets of quartz which are contorted, folded, and often broken into small segments which overlap one another producing a structure which resembles ptygmatic folding. This structure also is attributed to general diagenetic processes. In contrast to the cherts which show metamorphic effects as far as 5,000 feet from the contact are several chert layers between 2,000 and 3,000 feet of the granodiorite that are essentially unrecrystallized cryptocrystalline silica with a grain size between 0.008 and 0.005 millimeter. They contain, in addition, a small amount of opaque carbonaceous material, sericite, a little clastic mica, and other very fine-grained minerals.

Thermal metamorphism of limestones

Limestones in the area comprise approximately 25 percent of the section. Their composition varies from nearly pure calcium carbonate to argillaceous, and arenaceous limestone. They grade into calcareous shale and sandstone through an increase in the amount of argillaceous or siliceous matter. Many of the limestone beds, however, are relatively pure. The carbonate is predominantly $CaCO_3$ with very little, if any, $MgCO_3$ and no true dolomites occur. The character and intensity of the thermal metamorphism of these rocks varies widely with the composition.

Pure limestone maintains its monomineral composition to within a few hundred feet of the contact, although the $CaCO_3$ is recrystallized to a mosaic of calcite grains for a distance of over 5,000 feet from the contact. Within a few hundred feet of the granodiorite the effect of additive metamorphism is evidenced by the development of new minerals in great abundance, but this phase of contact action will be dealt with in more detail in a later section. In contrast to the pure limestones, impure limestones are readily and obviously affected by the thermal metamorphism and show the development of new minerals at considerable distances from the intrusions. A rock comprising 50 percent quartz and 50 percent carbonate at a distance of 8,000 feet from any exposed igneous rocks is essentially unrecrystallized with no tendency to interaction of the two components. Within 5,000 feet of the granodiorite, impure calcareous rocks have been metamorphosed to hornfels composed of granular diopside, fine-grained quartz, and a small amount of fine garnet. However, the occurrence of a narrow veinlet of alkali feldspar in this hornfels is suggestive of the proximity to an underlying igneous rock. A rock layer which comprises 90 percent of fibrous, sheaf-like, colorless pyroxene, near diopside in composition, and 10 percent of quartz and carbonate is thought to result from the metamorphism of a tuffaceous limestone. The only evidence for this is its occurrence in a series of altered volcanic rocks and recrystallized limestones. Apparently the composition and proportions of the materials in the original rock were favorable to nearly complete reconstitution.

A somewhat more conclusive example of the effect of impurities in limestone under thermal metamorphism is to be found in chert-bearing carbonate rocks. A cherty limestone, comprising alternating beds of pure $CaCO_3$ and impure siliceous material each about one-half inch in thickness, has been slightly metamorphosed by the stock which is 4,000 feet distant. The carbonate layers are recrystallized to a coarser mosaic of calcite; the cherty layers are also slightly recrystallized but, in addition, contain small amounts of diopside, and at the contact of chert and limestone layers, considerable diopside is formed.

Effects such as described above are to be found in all limestones within a mile of the granodiorite stock except at the south end where the zone of metamorphism appears to be much more restricted. Around the intrusive, within a zone which varies widely in width, but which averages perhaps 200 feet or less, the limestone layers contain an abundance of the mineral wollastonite. Diopside occurs with the wollastonite in many places, and a small amount of garnet is also formed.

The occurrence of wollastonite suggests a general absence of magnesium and iron in the original rocks. Were these elements present, such minerals as tremolite and augite would develop. The development of wollastonite at distances of 100 or more feet from the contact is common, but in all such cases the mineral appears to be formed from the reconstitution of material in the original rock. The wollastonite follows bedding and develops most abundantly in siliceous layers. It shows no cross-cutting relations or control of development by fractures or other structures such as would indicate the addition of material from the magma. Nearer the contact, however, wollastonite has developed from limestone through the addition of silica. The details of this development are reserved for discussion under the section on additive metamorphism.

Thermal metamorphism of the volcanic rocks

The altered volcanic rocks of group C are, for the most part, little affected by the contact action of the granodiorite. The alteration to which they were subjected has produced retrograde minerals that are akin to those produced by the advancing metamorphism of the sediments. They thus show a tendency to reach a state of equilibrium with the environment at the time of igneous metamorphism. Furthermore, most of the volcanics are so far removed from the contact as to be within the zone of only limited thermal effects. However, in a few places a granoblastic mosaic texture appears to have been superposed by the thermal metamorphism upon the altered volcanic texture. No new mineral species were developed, but recrystallized forms of the old were produced, and the fine-grained alteration products were cleared from the larger crystals and concentrated in the interstitial spaces.

Additive metamorphism

The term additive metamorphism as used in this paper is synonymous with pneumatolytic contact metamorphism or pyrometasomatism. The workers who have made significant contributions toward an understanding of this process are too numerous to mention, but of special importance are the fundamental studies made by Barrell (13), Lindgren (14), Goldschmidt (15), and Eskola (16).

A very small proportion of the rocks surrounding the Osgood Mountains stock conclusively demonstrates the effects of additive contact action. For the most part, the addition of elements to the country rock is best shown in the limestones and impure limestones immediately adjacent to the igneous rocks. However, it seems probable that some material from the magma was introduced into all types of the country rock and possibly to considerable distances from the contact. Where emanations from the granodiorite penetrated the argillaceous rock, the amount of introduced material, most likely silica and alkalies, was generally small, and of such a nature as to leave no evidence of its magmatic origin. In the limestones, on the other hand, contact action has produced distinctive mineral assemblages whose composition implies the addition of considerable volumes of material from the magma. In fact, the very pronounced metasomatic effects in the limestone and the generally feeble evidence of such a process in other rocks suggest the existence of special conditions inherent at the limestone contact which localizes metasomatic activity. The possible reasons for such control will be discussed later.

Wherever limestone adjoins the granodiorite, a reaction zone has been formed that ranges in width from a few inches in some places to over 200 feet in others. In most places, the pneumatolytic contact zone

Magnetite, pyrite, chalcopyrite, and bismuthinite occur locally as grains or irregular patches. Scheelite is scattered throughout most of the tactite and at several localities occurs in sufficient abundance to make tungsten ore. The outer limit of the tactite zone may be irregular in outline, but the actual contact with the zone of light-colored silicates is nearly always very abrupt.

The light-silicate zone, located between the tactite and the unreplaced limestone, consists predominantly of the silicates wollastonite and diopside, together with recrystallized carbonate and quartz. Some introduced quartz in excess of the amount necessary to react with the original calcite is usually present. This zone, in contradistinction to the tactite zone, is called the light-silicate zone.

Prospecting and mining operations for tungsten ore have opened up the contact zone for inspection at ten or more localities around the periphery of the granodiorite stock. More detailed studies of the limestone-granodiorite contact phenomena have been made at several of these exposures, and a better understanding of the processes has been obtained therefrom. Several of the more important of these localities will be described in some detail.

The Richmond mine area is located at the northwest corner of the granodiorite stock near the crest of the Osgood Mountains and is localized along the contact between a series of limestone beds, which aggregate over 900 feet in thickness, and the granodiorite. The limestones have a steep dip to the east and strike directly into the contact of the granodiorite which is itself nearly vertical. The specific features of this deposit that are of value from the standpoint of contact studies produced against the granodiorite consists of two parts: an inner facies, which is composed predominantly of dark-colored silicates, with relatively sharp boundaries, and an outer facies composed of light-colored silicates which fades off gradually into unreplaced, but recrystallized, limestones. The dark-silicate zone is composed predominantly of garnet with lesser amounts of epidote, diopside, calcite, quartz, and small quantities of other minerals. Locally scattered grains of iron and copper sulfides and scheelite are present. This inner zone of dark silicates is thought to be the type of rock to which Hess (17) originally applied the term tactite, and, in this report, the term tactite is used synonymously with dark-silicate zone. The tactite is generally coarse or medium grained, but the grain size may vary much within short distances, both along the bedding and across it. Much of the tactite appears in hand specimen to be very massive, but under the microscope it is found to comprise a tightly interlocking mass of garnet grains which range from 0.2 millimeter to 2 millimeters in diameter. Zones of coarse-grained garnet are associated with coarsely crystalline white calcite, and individual garnet crystals may attain 1 centimeter in diameter and may develop nearly perfect crystal shape. The garnet ranges in color from a light honey-yellow to a deep reddish-brown and in composition from nearly pure grossularite to a type containing at least 50 percent almandite. All of it is birefringent and highly zoned. Epidote is abundant only locally but in some areas replaces the garnet as the predominant mineral. Diopside occurs sparingly in most of the tactite and in some has been altered to a fibrous mineral—probably diallage or fibrous amphibole. ACTINOLITE Orthoclase and small amounts of plagioclase occur sparingly in some of the tactite.

are the facts that the limestones strike directly into the contact and that they can be traced from unreplaced material directly into the contact-metamorphic zone.

Plate 3 shows the geological relationship at the contact and the distribution of the inner zone of tactite. The most obvious feature is the definite restriction of the tactite to contacts of limestone and granodiorite and its localization with regard to the contour of the contact and the restricting influence of non-limestone beds. Altogether approximately 1,000 feet of limestone adjoins the stock in the Richmond area, but the central 350 feet is covered by valley fill. The main mining operations were located at the east end of the contact. Here, the inner zone of tactite is a semi-tabular mass 210 feet long parallel to the granodiorite contact and nearly 35 feet wide. It is terminated on the east by argillaceous hornfels and on the west by a siliceous hornfels. The tactite on the west side is more extensive, irregular, and, in some respects, less easily studied because of poorer exposures.

The salient feature of the additive metamorphism in the Richmond mine area is the zonal arrangement of the metamorphism. The most prominent zone is the tactite, which locally attains a thickness of 175 feet and maintains an over-all uniformity that is remarkable. The rock comprises garnet, which makes up from 80-90 percent of the volume, residual carbonate, a fibrous pyroxene thought to be diallage, interstitial quartz in a very small amount, small irregularly distributed veinlets of an orthoclase with a small 2V, a few scattered grains of iron oxides, pyrite, chalcopyrite, and scheelite in amounts up to 1 percent by weight. The garnet forms massive aggregates of small interlocking grains with irregularly disposed areas of white calcite containing euhedral dark-brown garnet crystals as much as 1 centimeter in diameter. (See pl. 16, C.) In large exposures, the garnetite shows a layering of finer- and coarser-grained facies that corresponds to the bedding of the original limestone. The distribution of white carbonate-rich layers, in general, follows the same structure. Other minerals are distributed at random, with the possible exception of the scheelite which favors the massive finer-grained garnet aggregates over the coarser garnet facies of the garnet-calcite mixtures. Only in a few places is scheelite found in the calcite.

The contact of the tactite and granodiorite is a tightly welded junction marked by a relatively narrow zone of rather intense silicification. Masses of vein quartz 6 inches to a foot thick are irregularly disposed along the contact, and vugs containing quartz crystals up to a foot in length have been found. Some of the tactite is replaced by quartz for a few inches from the contact, and small veinlets of quartz cut into the granodiorite. The quartz is very evidently connected with a somewhat later phase of the contact activity and is not unique with the Richmond area, but the vein-like character and vuggy structure were found only here. No scheelite or sulfides are associated with the late quartz.

The outer limit of the garnetite zone is sharply defined. Completely developed tactite, similar in all respects to that adjacent to the granodiorite, occurs at the outer edge of the zone. Although the bedding at the Richmond mine strikes directly into the contact, and the beds show distinctive, even though small, differences in their characteristics, there is no evident bedding control which affects the outer limit of the tactite.

A zone of light-colored silicates and incompletely replaced carbonate adjoins the tactite on its outer edge and grades outward through a zone of variable width into normal recrystallized limestone which may contain occasional silicate porphyroblasts. The bedding control of replacement and reconstitution of the light-silicate zone is evident. At the Richmond mine the rocks immediately beyond the tactite are light gray and dark-blue gray, partly replaced, crystalline marbles interbedded with very white layers of wollastonite and fine, granular diopside. It is notable that blue-gray marble, completely recrystallized but not completely bleached, is interlayered with bleached marble and silicated marble. Most of the layers are of the order of 1 to 4 inches thick. In diopside-wollastonite layers the wollastonite occupies the center of the layer and grades into a narrow border of finely granular diopside. (See pl. 16, A.) Paragenetic relations indicate that wollastonite formed first, and that the diopside replaces both it and the crystalline carbonate. Wollastonite is the only silicate in the sequence of recrystallized limestones at greater distances from the contact. It seems probable that additive metamorphism accounts for the diopside through the introduction of magnesium, whereas the relatively sparse distribution of wollastonite in the marbles more remote from the granodiorite can be explained as simple reconstitution of material in the original rock.

The relationship of the tactite to the shape of the contact is noteworthy, especially with reference to reasons for the localization of the larger volumes of such rock and the concentration in it of the scheelite. Reference to the map (pl. 3) of the Richmond area shows two relations that may have significance in this regard. The east-side tactite body is bounded on each end by argillaceous hornfels which are dense, impervious, generally non-reactive rocks and as such serve to form, with the granodiorite on the south, a channel of localization. The tactite on the west side is formed in a reentrant in the granodiorite. In such a position the original limestone was partly enclosed by the igneous rock and subject to more intense metamorphism than if it were not so enclosed. A summation and evaluation of all such factors which might affect the formation of these metasomatic rocks will be given later.

The Riley mine, located on the east side of the northern lobe of the stock, affords some of the best exposures of rocks formed by additive metamorphism to be found anywhere in the district. In the course of mining and exploration operations, the contact has been exposed for a strike length of nearly 2,000 feet, and data on its position and character have been obtained from drill holes to a depth of 800 feet down the dip of the contact. In its large-scale features, this area conforms to the general pattern elsewhere in the district, but it contains certain distinctive features that add to an understanding of the mode of origin of this type of deposit.

Plate 4 is a map and cross sections of the Riley mine area and illustrates the general geology of the deposit. The feature of this deposit which contrasts most strongly with the Richmond mine area is the general parallelism of the bedding and the contact. Local contortions of the limestone and angles in the granodiorite contact produce variations that play an effective part in localizing the metamorphism. The country rock is essentially limestone with a few interbedded layers of argillite. The strike of the limestone-granodiorite contact is generally north, and the dip is from 30°-60° to the east. Thick-bedded, medium- to coarse-grained, blue-gray, pure limestone and thin-bedded, platy, fine-grained, impure limestones, are essentially parallel to the contact.

The two metamorphic zones, the tactite zone and the light-silicate zone, are developed in this locality, but the relationships of one to the other are somewhat more complex than at the Richmond mine. A band of tactite from 3 to 20 feet thick is present against the granodiorite along most of the contact. The hillsides slope gently in the same direction as the dip of the contact, and the outcrop width of the tactite zone is much greater than its true thickness. Topographic irregularities in combination with irregularities in the granodiorite contact give the tactite zone a sinuous outcrop pattern. As a general rule, the zone of tactite was formed against the granodiorite or very close to it. In some places, however, two prominent tactite layers occur, one against the granodiorite and another about 30 feet from the contact and separated from the first by unaltered limestone.

The tactite zone is somewhat more heterogeneous than that of the Richmond area and comprises zones, pods, and irregular areas of different mineral assemblages which are not interrelated in any systematic fashion. Red-brown, medium- to coarse-grained garnet forms the bulk of the tactite in much of the area, but even where it is most abundant, the garnet rock is interlayered with garnet-pyroxene layers which have an olive-drab hue and a finer texture. The garnet ranges in color from medium brown to very dark reddish-brown. It occurs as well formed interlocking grains and includes within some of the crystals small, scattered, individual grains of scheelite. Associated with the garnet-rich facies are scattered grains of pyrite and chalcopyrite. In some places, the sulfides may make up as much as 30 percent of the rock, and it is notable that such sulfide-rich areas contain a larger amount of the fine-grained scheelite. Large, somewhat localized areas of the tactite comprise a green pyroxene, somewhere between diopside and hedenbergite in composition, associated with a dark-gray very glassy quartz. The quartz occurs as large, clear, glassy grains which include numerous small and large pyroxene crystals. The whole rock has a poikilitic texture. The diopside-hedenbergite occurs both as small grains 0.2 millimeter in diameter and as large crystals as much as 3 or 4 millimeters long. Associated with these predominant minerals are irregular residual crystals of garnet, some carbonate, local concentrations of sphalerite, molybdenite, pyrite, bismuthinite, and scheelite. The scheelite occurs in crystals and groups of crystals that are considerably larger and better formed than those in the garnet-rich facies. Whereas small amounts of the quartz-pyroxene rock are to be found throughout the tactite, the larger concentrations of it are located against the contact. The textural relations of the minerals, the assemblages of coarse scheelite and sulfides, and the spacial relations of the material suggest that this type of rock originated by replacement and reconstitution of the previously formed garnet tactite by the action of mineralizing solutions subsequent to the development of the garnet. These relationships are somewhat analogous to the late stage influx of silica at the Richmond mine. Reasons for the greater spread of quartz replacement at the Riley mine as contrasted with the narrow zone of silication at the Richmond are open to speculation.

A unique feature of the Riley deposit is the nearly universal occurrence of a zone of schistose biotite hornfels between the tactite zone and the granodiorite. This zone ranges from less than a foot to over 10 or 15 feet in thickness. Where thin, the material is a relatively soft, platy or foliated rock containing fine biotite, quartz, and some feldspar.

Irregular tongues of the granodiorite project into this zone at some places. The contact with the tactite is usually quite sharp and parallel to the foliation in the schistose hornfels. Structural relations preclude the possibility that this layer is a definite bed in the sedimentary sequence. The contact has a number of sharp reentrant angles and locally cuts sharply across the bedding for some distance, and where this occurs the schistose hornfels follows the contact across the strike. None of the several hypotheses considered to explain this feature seems adequate. One possible explanation that fulfills more of the requirements than others, is for the schistose zone to be a metamorphosed shear zone or gouge produced by adjustments along the granodiorite contact before the completion of metamorphic activity.

The contact of the tactite and the light-silicate zone is locally as sharp as at the Richmond area, but in its larger expression, the line of separation is much more irregular. Aside from the main zone of tactite along the immediate contact of the stock, there are two, and in some places, three zones of tactite, usually parallel to the bedding, and separated from each other by zones of light silicates and unsilicated marble. These several zones strongly suggest a very pronounced bedding control of mineralization and will be discussed in more detail in the paragraphs on reasons for localization.

The light-silicate zone is extremely variable both in extent and degree of development. In the thin-bedded, impure limestones, the alternation of thin layers of nearly pure wollastonite with thin, unreplaced limestone beds suggests that the original composition of the beds was a major control in localizing the metamorphism. This control may have been in part compositional, and the wollastonite may have resulted from reconstitution of materials already in place. More likely the control was some such factor as permeability which gave the metasomatizing solutions easier access to certain layers than others. Associated with the wollastonite and residual carbonate is a small amount of diopside and a few other related minerals in very minor amounts. Locally, especially in the more massive, somewhat purer limestones, wholesale replacement of calcite by wollastonite has occurred, and interlocking wollastonite crystals as much as one foot long have formed. Some of these wollastonite masses are 15 to 20 feet wide and extend along the strike of the beds for considerable distances. In many places the wollastonite rock definitely cuts across the bedding, and this suggests that additive metamorphism has played an important part in its development.

The major factor controlling the location of the silicate zone is, of course, the juxtaposition of granodiorite and limestone. Plates 2 and 4 show the relatively small size of the wedge of limestone at the Riley mine. The mine area is bounded by the granodiorite on the west, by faults on the north and east, and wedges out against the Getchell fault to the south. The wide variations in the kind and amount of silicate formed depends on the character of the limestone and the relation of the structure of the limestone to the contact. Good tactite has developed where the rather massive, granular, pure limestone adjoins the granodiorite; little or no tactite was formed where the platy, thin-bedded, impure limestone is present at the contact. The granodiorite contact is nowhere precisely parallel with the bedding of the limestone for any great distance, and the tabular tactite bodies play out laterally or down dip where unfavorable beds are brought adjacent to the contact zone.

The structural control which has most effectively localized the large masses of tactite (the scheelite ore bodies) is the occurrence of right-angle turns in the granodiorite contact, where the igneous rock cuts sharply across the limestone bedding for a short distance before resuming a course more nearly parallel to the bedding. The sharp bends or jogs of the contact are always in the same direction, such that the main granodiorite contact lies farther east, south of the offset. These offsets create trough-like features which plunge at an angle of about 40° in the direction of the general dip of the contact. Tactite localized by the troughs tends to be relatively limited in surface outcrop, but it extends down the dip as elongate shoots. Where the granodiorite contact cuts across the bedding for considerable distances there is opportunity for several favorable limestone layers to strike into it, in which case more than one layer of tactite may form, with unreplaced limestone between them.

The Kirby mine, located between the two lobes of the granodiorite intrusive, illustrates another occurrence of the tactite zone in a place where it is well developed. (See pl. 5.) The structure of the sedimentary rocks in this area is complicated by much folding and crumpling of the limestones and argillites especially where they adjoin the contact. (See pl. 13, A.) Tactite occurs on the contact in roughly tabular bodies which are nearly parallel to the slope of the hillside. Most of the wide, prominent outcrops shown on the maps, therefore, represent only small volumes of material. The large tactite body, which was removed during mining, was a tapered, pendant-like mass of replaced limestone which projected downward into the granodiorite at the lower end of the tabular tactite layers. Granodiorite bounded the pendant on its sides and bottom and furthermore closed around one end.

Tactite at the Kirby deposit is in most respects very similar to that at the Richmond mine, and no special features of mineralization were noted. Of interest, however, are two features of the localization of the tactite. One is the major development of tactite in a trough-like structure in the granodiorite, and another is the highly crumpled character of the limestones in this trough and the fact that the development of tactite appears to be controlled by the bedding, even when crumpling is fairly intense. This latter feature is especially well shown at the outer limit of the tactite zone where the contact between the tactite and the light-silicate zone follows a highly folded layer.

Somewhat different metamorphic effects obtain in the vicinity of the Valley View mine. (See pl. 6.) In its broad aspects, the Valley View occurrence is similar to that at the Riley mine; the sediments are limestone, both pure and impure, with some interbedded argillite, and they are structurally nearly parallel to the contact. There are, however, no sharp irregularities in the contact, and the tactite zone is less continuous, generally much thinner and comprises a somewhat different mineralogy. A narrow zone of garnetiferous tactite occurs along much of the contact, but a zone of an unusual hybrid rock separates it from the granodiorite. This zone, generally but a few feet thick, spreads at one place into a mass nearly 150 feet square. The rock is primarily a dense diopside hornfels having a light gray-green color, and containing irregular specks, streaks, and large-scale segregations of a black amphibole. Much of the amphibole occurs in crystals 1-3 millimeters in diameter, but local segregations of pegmatitic aspect contain crystals of amphibole as much as 2 or 3 centimeters long. The coarser facies are associated with irregular stringers and blebs of granodiorite. Plate 17, A, shows a specimen taken at the contact of granodiorite and the diopside hornfels.

The amphibole was determined as pargasite, and its mode of origin is well exemplified in thin section where it is seen to be definitely porphyroblastic. Many pargasite crystals include myriads of small granules of diopside, quartz, and feldspar, which are to be found in the hornfels. Certain parts of the hornfels—perhaps more argillaceous than others—contain small crystals of biotite in place of diopside, and where pargasite has developed in these rocks, an area surrounding the porphyroblast has been cleared of biotite. (See pl. 23, A.) It is inferred that the components of the biotite were incorporated in the amphibole.

Accompanying the development of these unusual contact rocks, are certain extraordinary features within the granodiorite and at its immediate contact. In retrospect, it may be recalled that generally speaking the granodiorite boundaries are sharp and distinct; that few, if any, inclusions of country rock are to be seen; and that little change in the composition of the igneous rock is to be noted on approach to the borders. In the vicinity of the Valley View mine exceptions to these generalizations are the rule. The contact from granodiorite to hornfels is gradational, usually over but a few feet, but locally over several tens of feet. Diopside granules, interpreted to be residual from hornfels, are enclosed in feldspar in the granodiorite; porphyroblasts of zoned plagioclase (see pl. 24, A), quartz, and amphibole have developed in the diopside-feldspar hornfels for a distance of several feet from holocrystalline, hypidiomorphic granular granodiorite. Xenoliths of hornfels in all stages of replacement by granodiorite are to be found (see pl. 17, B), but these are restricted to within 10 feet of the contact. Leucocratic dikelets of granodiorite cut the hornfels and amphibole-rich zones and are distinctly later than the development of much of the contact metamorphism. The origin of the leucocratic dikelets by metasomatic processes is suggested by certain of their relationships to the wall rock. Further evidence of the effectiveness of metasomatizing solutions in changing the wall rocks into a composition similar to that of the granodiorite is the development in the partly recrystallized hornfels of sphene and apatite. Also of interest is the occurrence of radio-haloes in coarsely crystalline pargasite of the hybrid zone. These haloes are embryonic, poorly defined, and appear to surround a mineral that was included in the pargasite porphyroblast during its growth. Although evidence for the replacement of country rock hornfels by emanations from the magma is fairly positive at this locality, the extent of such activity is limited and the over-all effect is insignificant with respect to the emplacement of the stock.

The granodiorite likewise shows special features at this locality. Aside from containing inclusions of diopside, the igneous rock is deficient in the usually abundant biotite, and the remaining shreds of biotite have been partly altered to pyroxene. Pargasite is abundant, but it in turn is partly replaced by pyroxene. Such changes may result from the increasing basicity of the igneous rock upon incorporation within itself, by one process or another, of excess calcium and magnesium from the diopside hornfels. Such contamination appears to result in a reversal of the normal sequence of Bowen's reaction series. Late-phase solutions have produced some sericitization and some kaolinization of the feldspars.

The evidence at this locality suggests the following sequence of events: (1) Early production of diopside hornfels by granodiorite intrusion; (2) a rejuvenation of igneous activity, and the incorporation of part of the hornfels in the border zone of the intrusion with the concomitant production of the amphibole zone; (3) injection of leucocratic derivatives as veinlets and dikelets followed shortly by further contact action associated with addition of silica and some iron to produce the garnetiferous tactite zone with which is associated the sulfide and tungsten mineralization.

The Granite Creek mine, at the south end of the south lobe of the intrusive, illustrates unusually well the features of the tactite zone and its relationships to the contact. In the course of both underground and open-pit mining, the deposit has been opened to a depth that exceeds its length and affords a chance to observe the downward projection of the tactite. As at the Richmond and Riley mines, the feature of special interest at the Granite Creek mine is the control of the metamorphism by special structural conditions at the contact, in this case, the occurrence of limestone beds in reentrants in the granodiorite.

Plate 7 shows a part of the south contact of the granodiorite stock. Plate 8 is a detailed map and section of the Granite Creek mine area and illustrates the major features of the most important ore deposit. The sedimentary sequence contains an abundance of limestones and impure limestones which strike into the granodiorite at an angle of approximately 40° to the general trend of the contact. Additive contact-metamorphic effects are present to some extent along nearly 2,000 feet of the contact except at places where occasional argillaceous layers occur, but it is evident from the distribution of the tactite as illustrated on plate 7 that special conditions obtain at certain places along this contact and localize the larger volumes of the tactite. The light-silicate zone forms an irregular halo extending beyond the tactite for different distances in different places, and the intensity of the metamorphism seems to be controlled by the bedding. At the outer limits of the zone, the metamorphosed limestone tends to fade out gradually into unaltered rock. The most notable feature of the contact in this locality is its irregularity. Numerous projections of leucogranodiorite and dacite extend southward from the main stock into the sedimentary beds, some as narrow dikes for as much as 600 to 1,000 feet, but most as blunt prongs for only a few tens or hundreds of feet. The larger tactite bodies occur against the granodiorite within the limestone reentrants enclosed by the granodiorite projections. The Granite Creek mine tactite body is the best example of one of these and will be described in more detail. It is notable that very little tactite occurs along the margins or at the ends of the dikes.

The tactite at the Granite Creek mine occurs in a rectangular reentrant, 230 feet long, in the granodiorite contact. Limestone in the reentrant strikes parallel to its length and dips 55°-60° southeast, parallel to the dip of the contact. Granodiorite thus borders the deposit on the foot wall and at each end. Much of the tactite zone of the contact metamorphic aureole at this locality has been mined out from the surface to a depth of 300 feet on the dip. The tactite in this tabular mass ranged in thickness between 5 and 35 feet with an over-all average thickness of nearly 20 feet. Several smaller bodies of tactite lie in the hanging wall of the main mass and probably result from emanations working out along more favorable layers from the cross-cutting granodiorite contacts at the end of the deposit.

The tactite zone in the Granite Creek mine is composed predominantly of a dark red-brown birefringent garnet. The second most abundant mineral is black hornblende with a pleochroism formula X = olive drab, Y = green, Z = dark-blue green. This mineral is abundant only at the Granite Creek mine and may form as much as 40 percent of the tactite, though usually it is in smaller amounts. Some diopside, secondary carbonate, and a little quartz comprise the bulk of the remaining material. Vesuvianite in narrow stringers was found in this deposit, which, so far as is known, is the sole occurrence in the Osgood area. Scheelite, for which the tactite was mined, occurs in scattered grains throughout the garnet and usually enclosed in the crystals. Mining operations proved the WO_3 concentration to be about 0.5 percent by weight of the tactite which would make the concentration of the scheelite about 0.62 percent by weight or 0.3 percent by volume. The tactite is banded parallel to the bedding of the limestone. The different bands are distinguished from each other on the basis of grain size and differences in color which depend on the amount of black amphibole in the rock. Much of the tactite is medium to coarse grained; irregular bands, streaks, and discontinuous layers of fine, dense garnet ramify through part of the zone, and coarse- to very coarse-grained segregations of garnet and white carbonate are dispersed erratically through the mass. Occasional grains of pyrite and chalcopyrite are interspersed through the tactite, and a small amount of molybdenite occurs locally. Plate 16, B, shows a typical specimen of Granite Creek tactite.

The contact of the granodiorite with the tactite is marked by a zone of intense silicification which ranges from a foot or less to as much as 10 feet wide. The silicified zone comprises a dark-gray, coarse-grained, vitreous quartz rock with the textural appearance of the granodiorite. It is composed essentially of an interlocking mass of clear quartz crystals with scattered, partly replaced crystals of pyroxene and amphibole. There are also scattered euhedral crystals of apatite, sphene, and a little carbonate. Contact of the quartz-rich facies of the contact rock with the tactite is gradational over a few inches; with the granodiorite it is exceptionally sharp, being observable in total in one thin section. In spite of the over-all sharpness of the contact with the granodiorite, the relationships in detail indicate that the contact is a replacement one. The origin of the quartz rock from granodiorite by replacement processes is indicated by: the character of the contact between the quartz rock and the granodiorite, the presence of residual mafic minerals in the quartz which are identical with the mafic mineral in the granodiorite, the presence of the accessory minerals sphene and apatite in the quartz, and the granodiorite texture of the quartz rock. The feldspars are completely replaced, the mafic minerals partly so, and the accessory minerals are unaffected. A minor amount of replacement of the tactite has very likely occurred but in no large amounts. The influx of the silica to produce the quartz rock replacement is analogous to the development of the quartz along the contact at the Richmond mine and elsewhere in the district. Plate 16, D, shows granodiorite and the quartz rock derived from it.

The light-silicate zone at the Granite Creek mine is developed on a large scale. The most notable feature is a strong development of contrasting light and dark layers, essentially parallel to the bedding, as the result of the production of light-colored silicates along certain beds and the absence of silicate minerals along others which retain the medium- to dark-gray and blue-gray color of the original limestone. (See pl. 16, A.) The light layers are predominantly wollastonite with a minor amount of associated diopside and pyrite, and, in some instances, scattered streaks, splotches, and individual grains of a very light honey-colored garnet. Some of the darker layers are recrystallized dark-gray limestone, others are dark-gray cordierite hornfels which represent more impure argillaceous layers in the series.

The parallelism of the metamorphic layers with the bedding indicates that the variations in the mineral content result from recrystallization of sediments of different compositions. Such is true, in part, but the relations between layers shows that there has been much introduction of material along with the recrystallization. In numerous instances the wollastonite layers converge and replace the intermediate dark layers. Elsewhere veins of wollastonite and garnet cut across the bedding, and irregularly shaped masses of essentially pure wollastonite as much as 5 or 10 feet in diameter replace the layered rock. Most of the wollastonite could be developed by the introduction of silica alone.

Summation of the igneous metamorphism

The igneous metamorphism of the sedimentary rocks surrounding the Osgood Mountains stock displays two very distinctive, even though closely related, facies, whose distinctive features are directly related to the composition of the original sediments—specifically to the differences between clastic sediments and limestones. Furthermore, the two facies are believed to represent, in a broad way, the results of two different types of igneous metamorphism—thermal metamorphism and additive metamorphism.

Thermal metamorphism was likely most effective during the early stages of intrusion of the igneous rock when the temperatures were highest and before any great volume of emanations were available for discharge from the magma. The country rock was, in all probability, partly heated in advance of the intrusion, either by virtue of deep burial or by an advance wave of heat from a subjacent magma. The coarse grain of the granodiorite against the contact is incompatible with the concept of the sudden intrusion of the magma into cold rock. Furthermore, if the temperature of the country rock had been elevated in advance of the final intrusion, far less burden would have to be placed on the granodiorite to effect the metamorphism we now see, and the extensive production of hornfels, quartzite, and recrystallized carbonate rock could be more easily accounted for. In view of the experimentally determined low conductivity of heat through rock, it seems necessary to call upon some such process as gaseous or liquid transfer of heat to bring about the extensive metamorphism noted in the Osgood Mountains. It is believed that gaseous or liquid emanations, predominantly water, given off during the early stages of the cooling of the granodiorite, would be rather low in reactive elements and would be capable of transferring heat and promoting recrystallization without leaving obvious traces of its presence. In fact, the presence of water introduced from the magma may have been the catalyst necessary to induce recrystallization and reconstitution in the partly heated rock. Some heat may have been transferred by the circulation of connate waters in the sedimentary rocks. Evidence for other than thermal metamorphism of the argillaceous rocks is slight, even at the contact with the stock, although a small amount of sodium and potassium appears to have been added to a zone a few feet wide against the granodiorite. From these facts, the inference is drawn that thermal metamorphism produced recrystallization and reconstitution of the argillaceous rocks and thereby rendered them unreactive to later metasomatizing solutions, either because of their composition or because of their increased imperviousness resulting from recrystallization. Quartzite and chert are affected by the same general processes and show little evidence of metasomatism. Limestones are recrystallized to medium-grained, sugary marbles for long distances from the contact. Most of the carbonate layers are blue gray in color and retain this color in some of the thin layers to within a few feet of the contact. Experimental evidence has shown that pigment in limestone may be retained to temperatures as high as 600° C. but not much higher.

In general, the thermal contact effects in the Osgood Mountains are of low to moderate intensity, and the relative changes on approach to the contact are gradual and not profound. Chiastolite, at a distance from the contact, contains the usual oriented inclusions which become less prominent closer to the intrusion. Some of the argillaceous layers contain abundant carbonaceous matter which remains in the rock nearly to the contact, although much of it may be converted to graphite. Biotite in the argillaceous hornfels is enlarged but not replaced by amphibole or pyroxene.

In comparison with thermal metamorphism, additive metamorphism is volumetrically quite insignificant, and is localized by very special conditions. The most important of these conditions is the restriction of the process to the contacts of granodiorite with calcareous rocks and for the most part to contacts with relatively pure limestones. This control appears to be fundamentally a chemical one. The carbonate is easily reactive with the metasomatizing emanations from the magma and fixes any introduced elements in new minerals of a density considerably greater than that of the carbonate rock. There is no evidence that the total volume of the limestone decreases when it is altered to tactite, and consequently the difference in specific gravity between the limestone (average near 2.65) and the tactite (3+) must be due to the introduction of material from the magma. The transformation of relatively pure limestone into tactite necessarily calls for a large introduction of silica, alumina, and iron with smaller amounts of soda, magnesium, and the elements that make the ore minerals. Carbon dioxide and some calcium must be expelled. This pronounced metasomatic effect is so restricted in its distribution, and the changes are locally so complete that there must be some reason beyond the mere chemical affinity of limestone for other elements to explain it. Bearing directly on this problem is the general paucity of pegmatites, quartz veins, or other ore deposits outside the replacement contact areas. It is a notable fact that the only pronounced escapement channels for late magmatic residues and post-magmatic emanations are these same zones of contact-replacement rocks--the very rocks that are now the densest, hardest, and perhaps the most impervious in the whole area. In addition to the common minerals of the tactite, these zones contain the scheelite which makes them economically interesting, sulfides of iron, copper, and bismuth, and concentrations of silica. It seems inevitable that these tactite zones, during the time of their formation, were channels for a succession of solutions whose effects are recorded in the replaced rocks. Numerous workers have postulated a channeling of solution through such zones. Barrell (13), in the Marysville District, Montana, discusses the dependence of contact metamorphism upon a temporary permeability of the affected rocks due to a minute fracturing or parting—especially in the harder rocks. In carbonate rocks the more extensive alteration seems due both to a greater depth of permeation and to a closer fracturing. He states that "........such fracturing may be dependent in some way on the reactions which take place with volume changes.......". Some such control of the paths of solution must be postulated in the Osgood Mountains.

Another notable feature of the Osgood Mountains contact-replacement zones is the localization of the major shoots of tactite along reentrants of limestone in the granodiorite or in sharp angles of the contact. This relationship in which granodiorite partly surrounds the areas of most intense and best-developed replacement at first suggests the hypothesis that material is added to the contact zone directly from the adjacent igneous rock, and, the greater the contact with the source of supply, the larger is the replaced zone. There is no evidence to indicate any such direct contribution from the adjacent magma. The tactite is not zoned out from the contact in any regular fashion; there are no consistent cross fractures leading solutions through the zone to the outer rim of reaction; there is no evidence of feeding channels or compositional variations in the granodiorite next to the contact; and the late phase silicification of the granodiorite is working into the igneous rock from the contact instead of showing derivation from the granodiorite itself. The lack of specific criteria for additions directly from the magma, should not imply that no material was transferred in this manner to the limestone contact zones. It is entirely conceivable that early in the consolidation of the granodiorite there was direct transfer of material, which combined to form some of the early silicates such as wollastonite and possibly some garnet. In fact, such an addition would be a practical necessity in the case of pure limestone to initiate any reconstitution and the consequent production of porosity which is necessary for the establishment of a channel. For the most part, however, the limestones are sufficiently impure for partial reconstitution to occur without major addition. In either case, the limestone in re-entrants is heated from two or three sides with the consequent more rapid thermal metamorphism and more profound reconstitution which thus form a larger, more continuous and preferred channel of porosity into which residual solutions will be drawn. These channels are envisioned as open systems with exits at the upper end and through-going emanations.

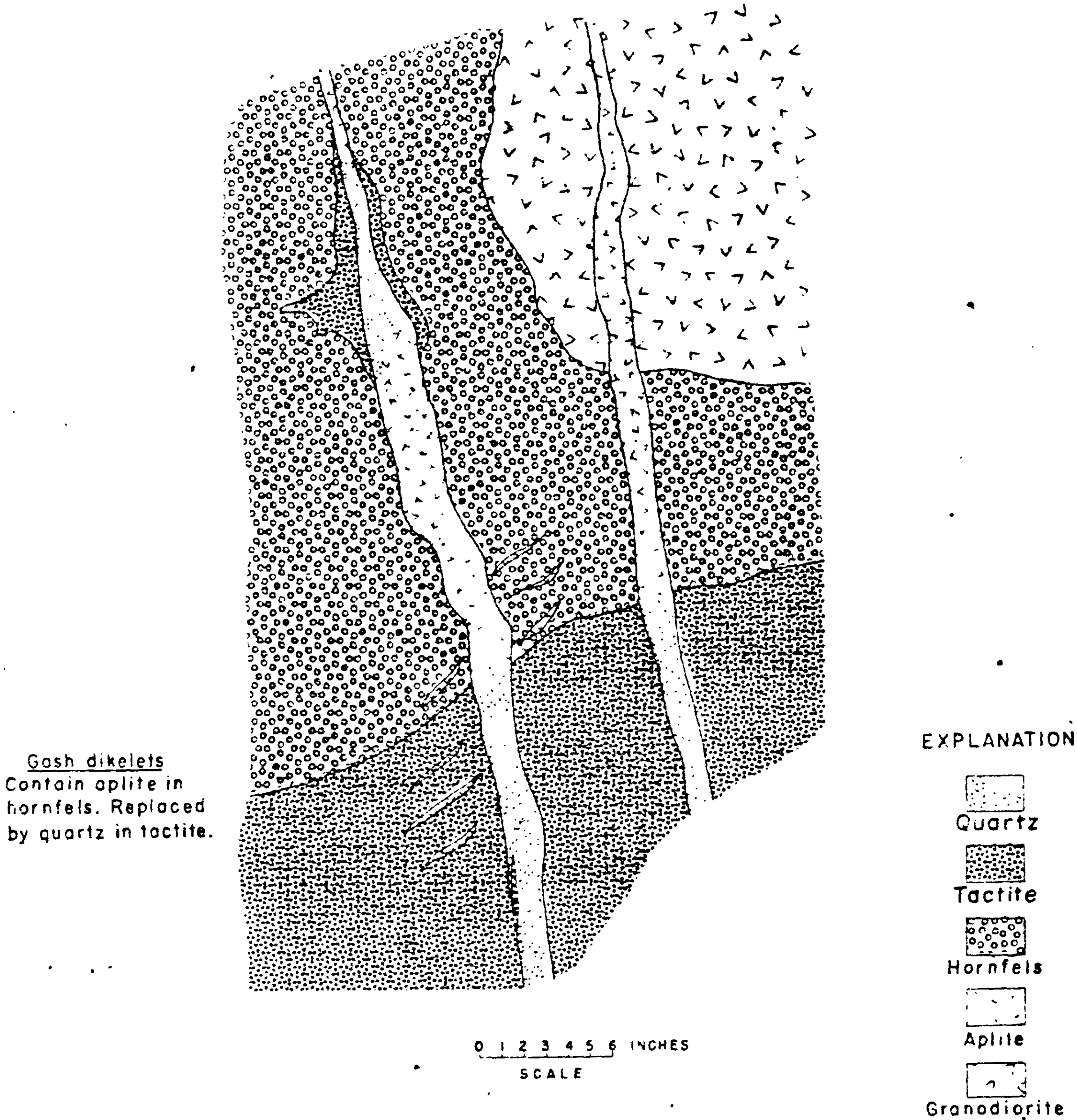
The assumption that these tactite channels are continuous in depth is based, in part at least, on fact. Ore at the Granite Creek mine was removed from one such channel for a maximum distance of 300 feet down the dip, and diamond drilling has determined that it extends for at least several hundred feet more with undiminished size. At the Riley mine, drilling proved that the relatively narrow shoots of tactite localized in the troughs produced by angular jogs in the granodiorite contact are continuous down the pitch of such troughs for over 600 feet. So long as the contact of granodiorite and limestone continues, there is every reason to expect the zone of replacement metamorphism to continue, and the structural conditions at most of the Osgood Mountain localities give every reason for projecting such contacts for many hundreds and possibly thousands of feet.

Mineralogic evidence for the hypothesis that the major tactite facies of the additive metamorphism results from the relatively long-continued passage of solutions through definite channels is suggestive, if not conclusive. The production of wollastonite is apparently early, probably related to the early stages of intrusion and relatively high temperatures. In fact, it is probably one of the earliest minerals formed. Part of it is formed through direct reconstitution of impure layers in the limestone, but much of it is undoubtedly related to the introduction of silica. Laboratory studies by Bowen (18) and others have established some of the facts about the conditions of formation of wollastonite. In a detailed study of the system dolomite-quartz, Bowen found that reactions at ordinary pressures started when the temperature reached only a few hundred degrees and that tremolite was the first new mineral produced. In order of rising temperatures, the following series of minerals follow tremolite: forsterite, diopside, periclase, wollastonite, monticellite, okermanite, spurrite, merwinite, and larnite. Increased pressure raises the temperatures of formation rather abruptly until 600 atmospheres are attained beyond which further increase in pressure has but little effect. In this system, wollastonite forms under 1 atmosphere of pressure at a temperature of about 650° C. At a pressure of 600 atmospheres the reaction takes place at 900° C. It is notable that all the minerals which precede wollastonite in the series are magnesium bearing. The question is raised as to whether wollastonite would be formed at the same temperature under the conditions attained at the contacts in the Osgood Mountains where non-magnesium limestones are affected. The other unknown factor, of course, is the pressure conditions at the time of formation. Considering the known factors, it seems reasonable to place the temperature of formation of the wollastonite somewhere between 700 and 800 degrees C. Possibly it should be placed lower, since it is intimately associated with crystalline limestone that retains its pigment.

The formation of garnet, which makes up the greatest bulk of the dark-silicate zone, requires the addition of iron, aluminum, and silica to the limestone. Paragenetic relations indicate that part of the garnet results from the replacement of the light-silicate minerals as well as the calcite. At the Valley View mine small areas of garnet are found to be replacing the diopside hornfels of the light-silicate zone in such relationships as to indicate that the introduction of silica-rich solutions was the essential feature in the development of tactite. All of the garnet is strongly birefringent and highly zoned, and, as such, probably formed below 800° C. The zoning is noticeable microscopically, not only under crossed nicols, but in plane light by pronounced color variation in zonal arrangement. (See pl. 22, A, B.) Such color zoning suggests variation in composition which can best be explained by variation in the composition of the metasomatizing solutions. Whether such variations in composition of solutions can occur suddenly or slowly during a relatively long passage of the additive medium is a moot point. Also of interest with regard to the relative time of garnetization is the association of the scheelite with it. The scheelite occurs predominantly as small grains enclosed within crystals of garnet, which suggests that the two minerals were formed contemporaneously. Sulfides are, in part, enclosed in the same way, but more often occur between the grains of garnet and are associated with later-interstitial carbonate. The introduction of ore minerals contemporaneously with, and also subsequently to, the garnet supports the idea that solutions flowed for some time through the channels established at limestone-granodiorite contacts.

The last phase of the metasomatizing activity indicates continued falling temperatures, and the final events in the solidification of an intrusion. Secondary carbonate fills the remaining pore space in the tactite; late fractures in the tactite are filled with sulfides, silica, and scheelite along with quartz and carbonate. Some or all of these late minerals may represent redistribution of material deposited earlier in the sequence of events.

The silicification phenomena along the contact between tactite and granodiorite presents a special problem as to localization and timing. The facts about the silicification to be explained are as follows: its localization only along the portions of the contact where tactite is abundant, its major development through replacement of the granodiorite, and the general absence of narrow silicified seams cross cutting the metamorphic zones. It seems probable that a part of the silica was introduced into the granodiorite by the same solutions that produced the tactite, and, as such, represents the effect of these solutions on a rock of granodioritic composition. The quartz first completely replaces the feldspar and then attacks the mafic constituents. Many skeletal remains of pargasite and biotite attest to the nearly complete replacement power of the silica-bearing solutions. Euhedral crystals of titanite, apatite, and zircon are scattered through the quartz and represent residual minerals from the granodiorite. However, unusual concentrations of small crystals of sphene in the areas of nearly destroyed mafic minerals suggest that this sphene has formed from titanium originally contained in the composition of the amphibole or pyroxene. At the Valley View mine a special relationship adds weight to the genetic relationship believed to exist between the production of tactite and the replacement of granodiorite by quartz. The sketch shown in figure 2 illustrates the situation in which a narrow leucocratic dikelet from the granodiorite cuts through three types of rock: granodiorite, tactite, and diopside hornfels. In the granodiorite and in the hornfels the dikelet is a normal, leucocratic, fine-grained granodiorite. However, in the main tactite and also wherever bordered by small discontinuous patches of tactite in the hornfels, the dike becomes a quartz vein. The most logical explanation of these relationships is that the dike was replaced by later quartz introduced along openings adjacent to it and concomitantly that the same solutions developed tactite in the adjacent hornfels. The relations described above are strictly analogous to those developed on a much larger scale at the Richmond, Riley, and Granite Creek mines where the main granodiorite is replaced by quartz adjacent to the contact with tactite. Such phenomena as the extensive production of vuggy vein-quartz along the contact at the Richmond mine represents a carry-over of silicification beyond the stage of tactite formation, and its localization by fractures developed between the brittle tactite and the granodiorite. Should the silicification be later than the final production of tactite, it is difficult to explain its localization along the tactite-granodiorite contacts, which, in their final condition, are the densest, most impervious portions of the periphery of the stock.



Sketch of area on quarry face at Valley View mine showing relation of the silicification of aplite dikes to the development of tactite

Figure 2

The general sequence of events in the development of the contact metamorphism is believed to be as follows: intrusion of the stock into country rock which, in all probability, was already warmed; the consequent thermal metamorphism of the argillites, quartzites, volcanics, cherts, and limestones; the start of metasomatic replacement in the limestones with the production of light silicates and the establishment of channels for emanations from the magma; replacement of light silicates and some carbonates by the tactite and the penecontemporaneous replacement of the solidified granodiorite by quartz; late introduction of quartz along fractures, especially at the junction of tactite and granodiorite. Whereas the progress of thermal metamorphism is affected by the advancing as well as declining temperature conditions attendant on intrusion, the metasomatic phase is, for the most part, related to declining temperatures, starting from a maximum at the time of final emplacement of the magma.

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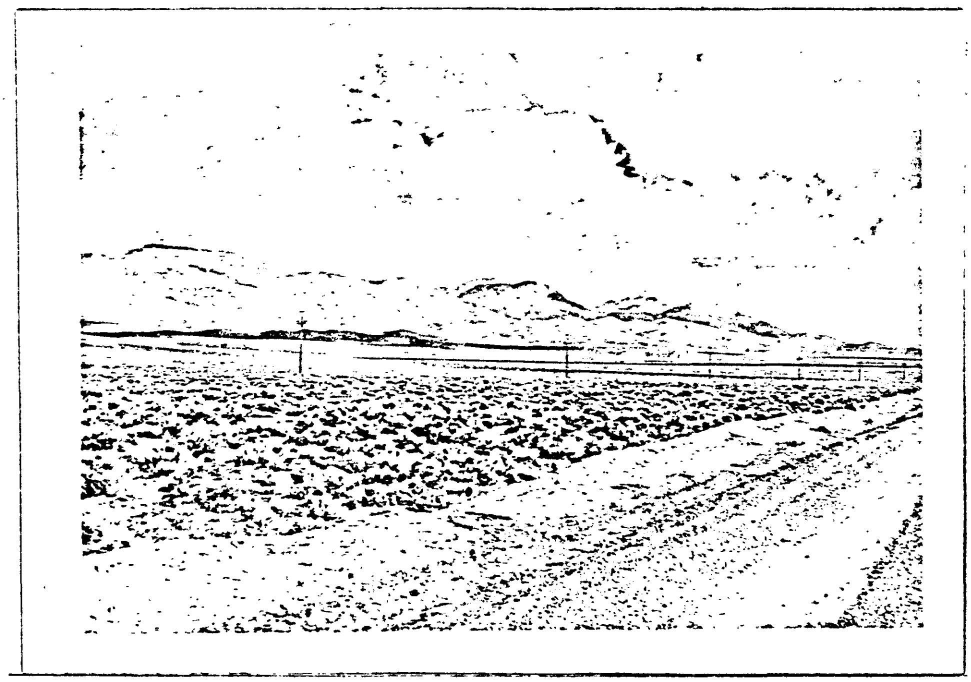
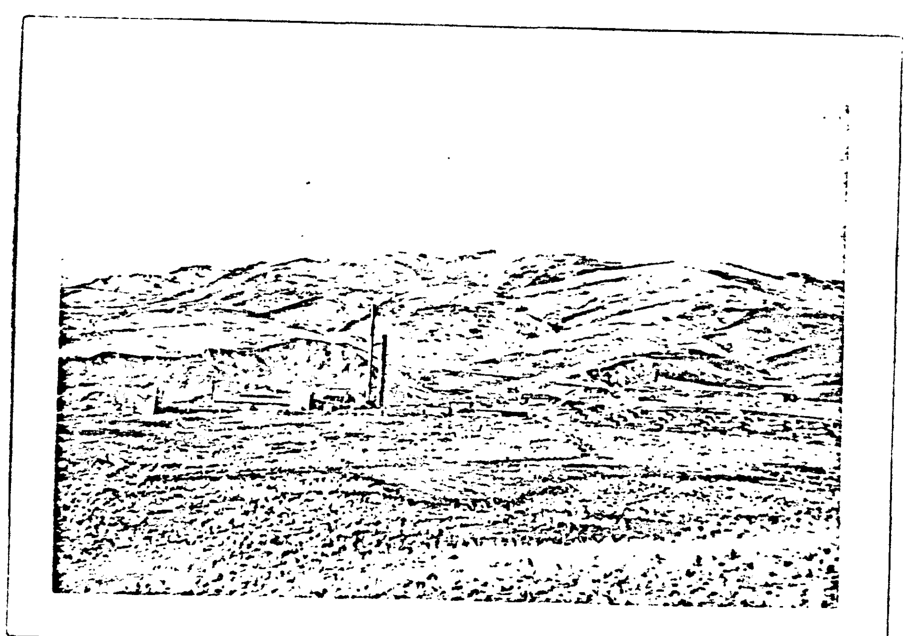
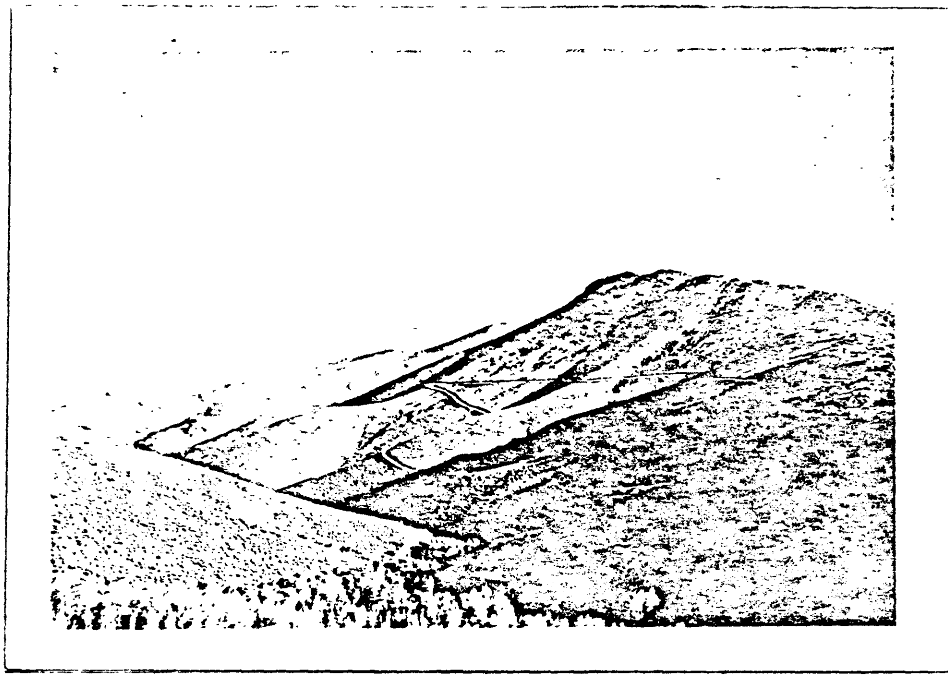


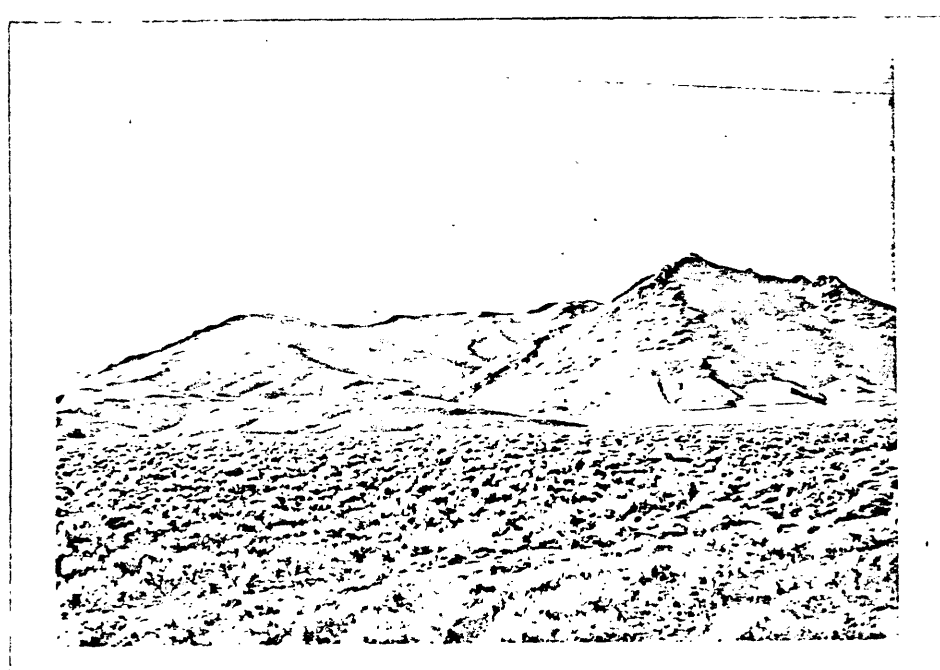
A. VIEW OF THE OSGOOD MOUNTAINS FROM THE SOUTHEAST.



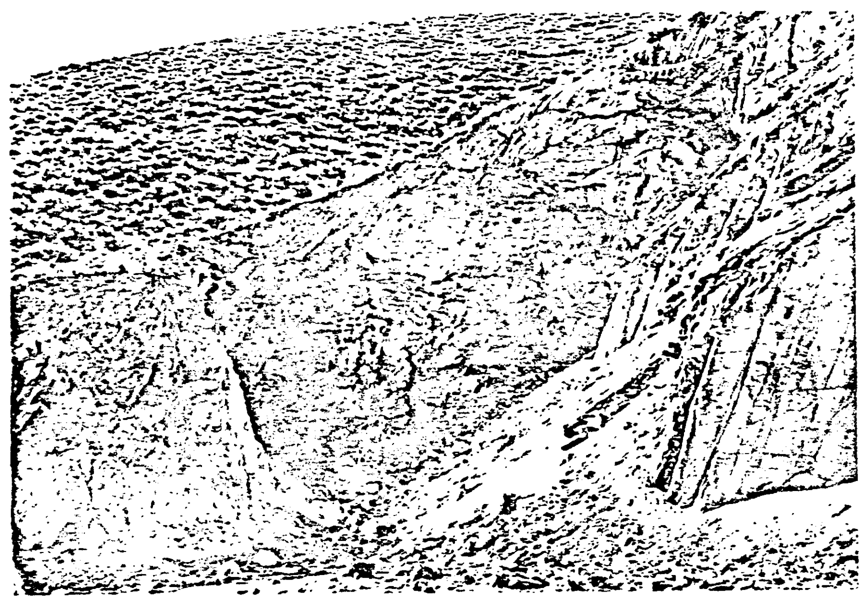
B. GETCHELL MINE AND THE OSGOOD MOUNTAINS FROM THE EAST.



A. VIEW NORTH ALONG WEST SIDE OF OSGOOD MOUNTAINS.
Burma Road in distance.

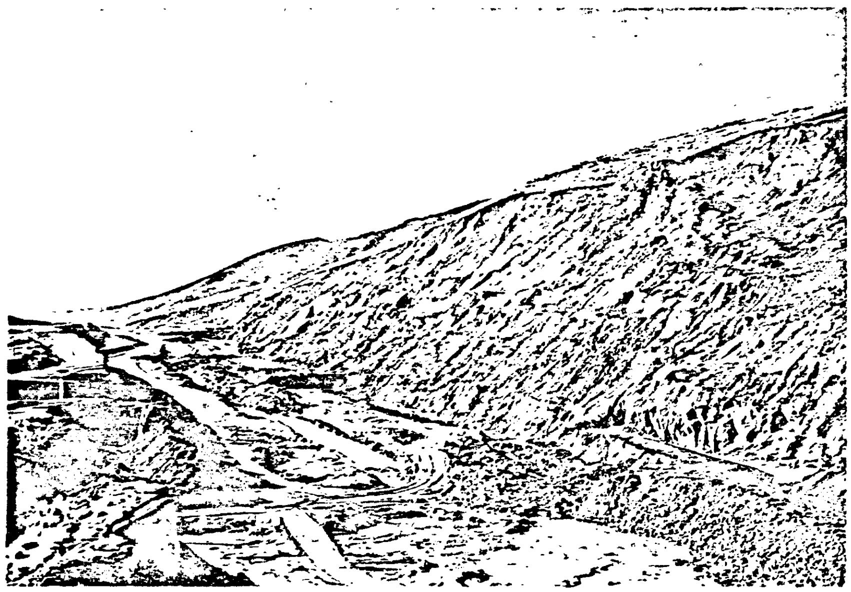


B. VIEW UP GRANITE CREEK.



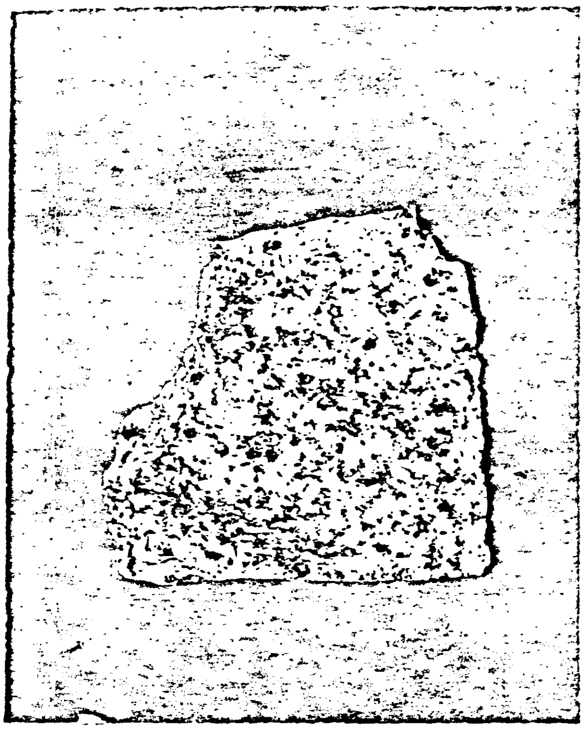
A. CONTORTED LIMESTONE AT KIRBY MINE.
Contorted limestone above, blocky granodiorite below.

B. FANGLOMERATE NORTH OF ANDERSON CANYON.

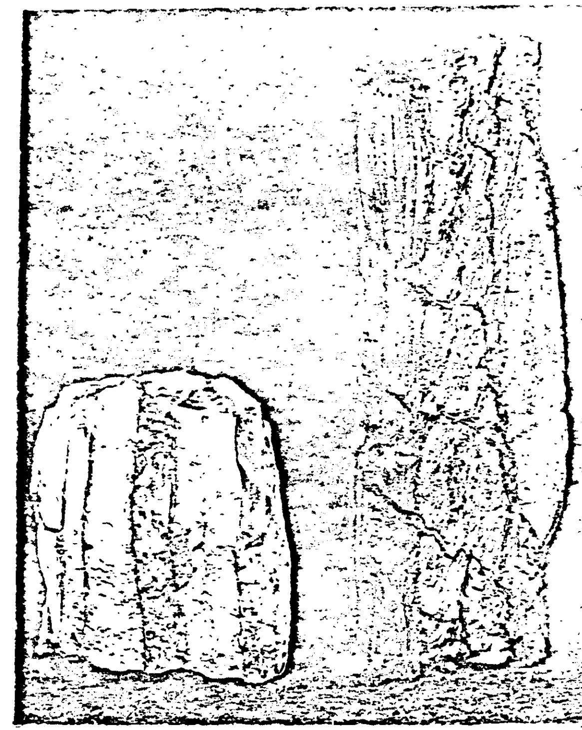


A. VIEW SOUTH ALONG THE WORKINGS OF THE GETCHELL MINE.
Cut bank is exposed footwall of Getchell fault.

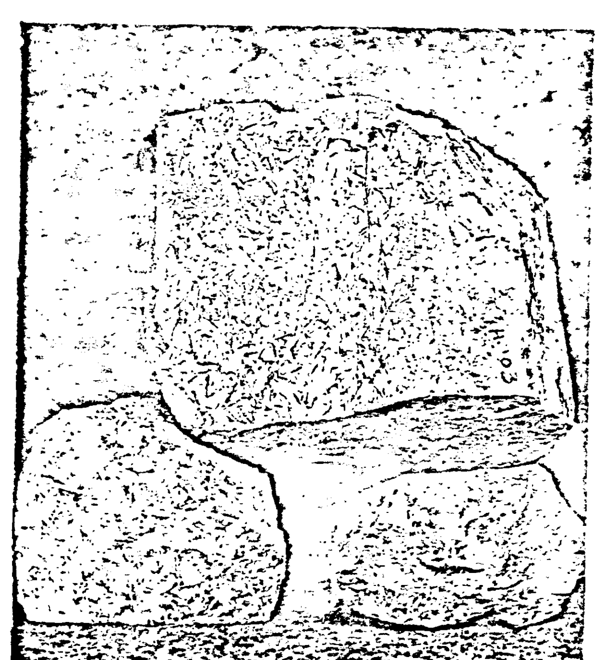
B. SLICKENSIDES ON FOOTWALL OF GETCHELL FAULT



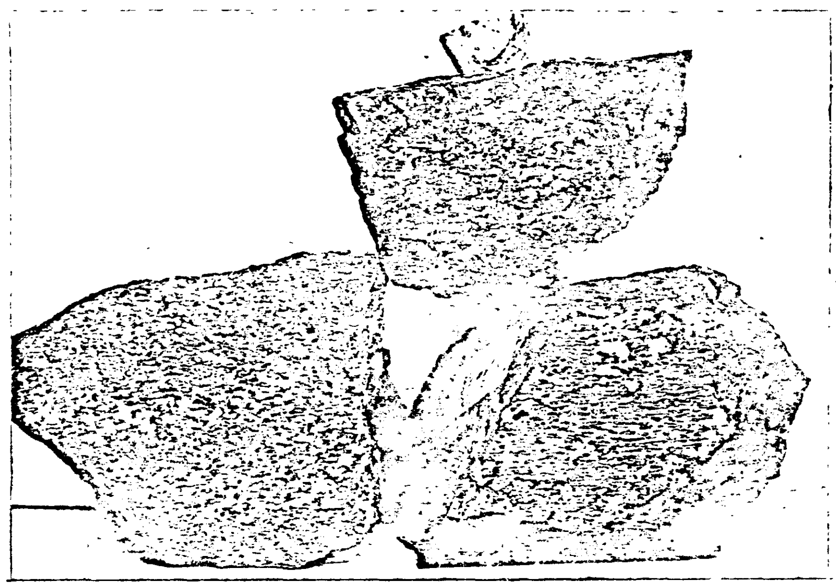
A. TYPICAL GRANODIORITE FROM THE OSGOOD MOUNTAINS.



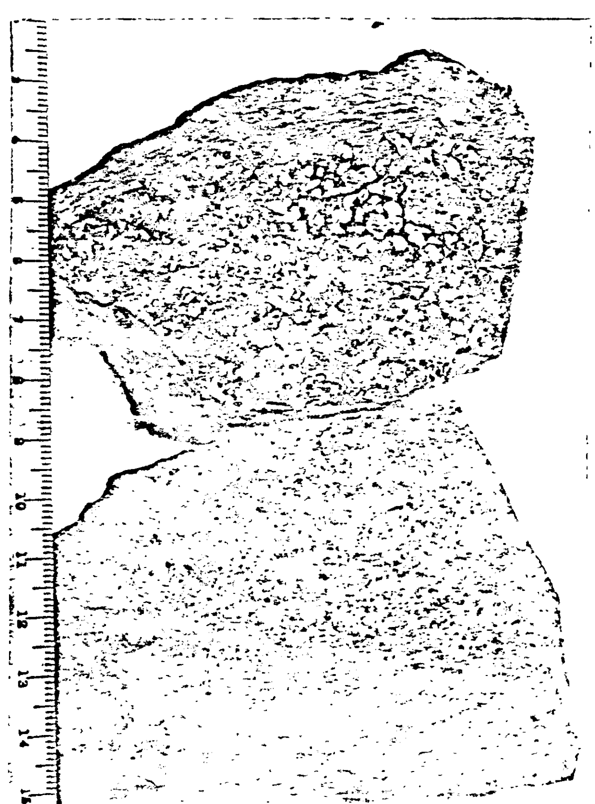
B. LAYERED ROCKS.
Partly silicated limestone on left, interbedded limestone and hornfels on right.



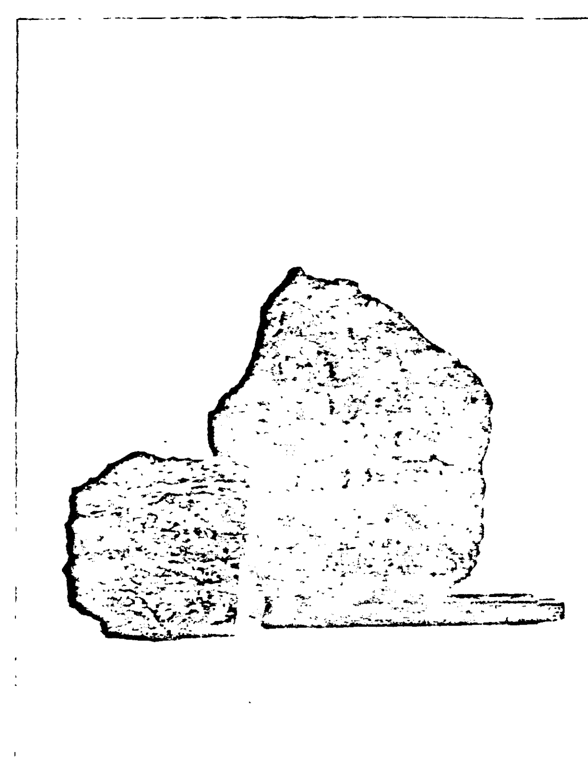
C. SPOTTED ANDALUSITE HORNFELS.



A.

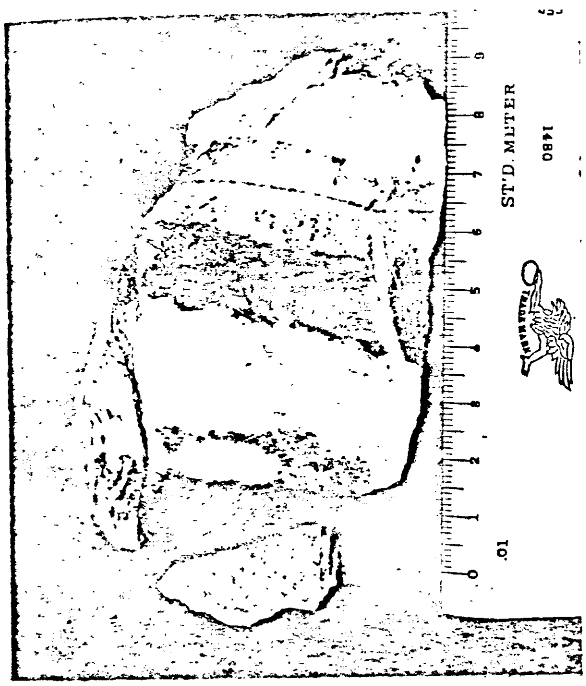


B.

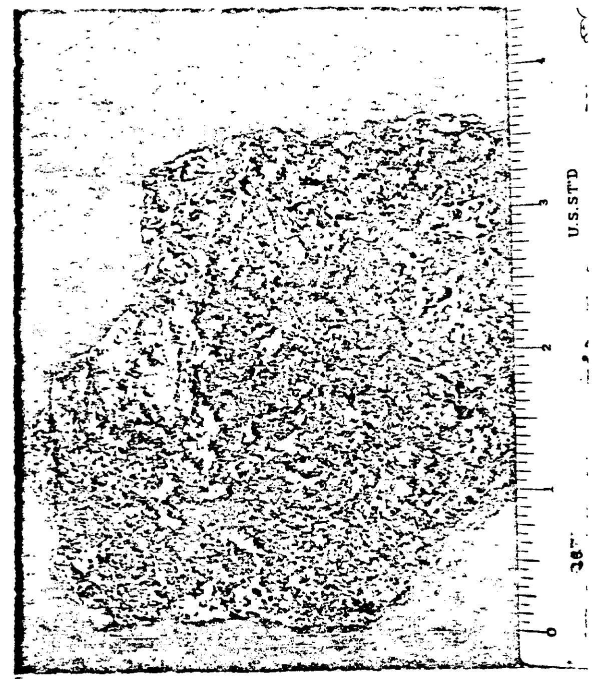


C.

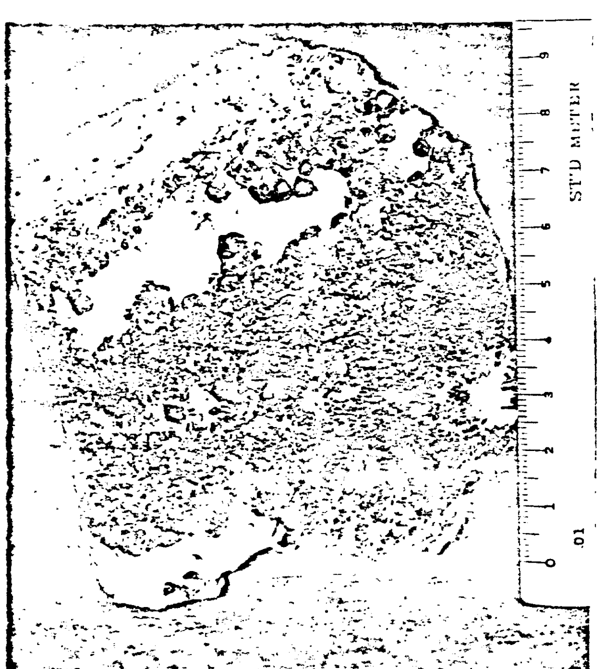
SPOTTED HORNFELS



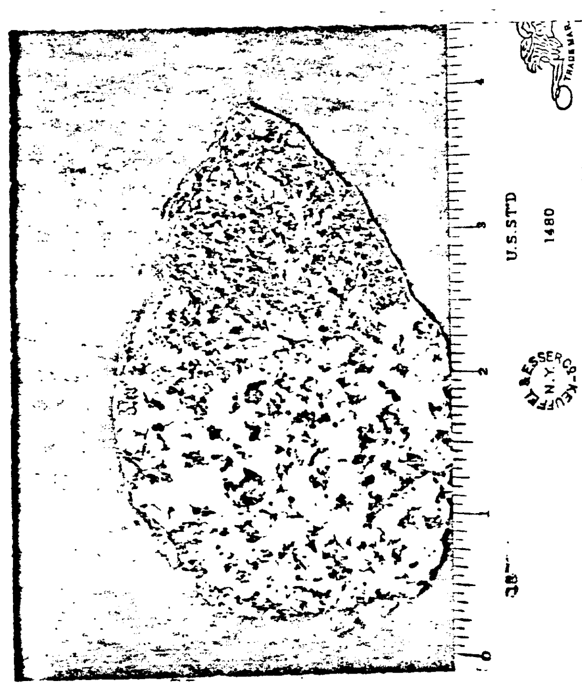
A. BANDED LIGHT-SILICATE ROCK FROM GRANITE CREEK MINE. Dark layers are marble; white layers wollastonite. Zone of diopside between wollastonite and marble.



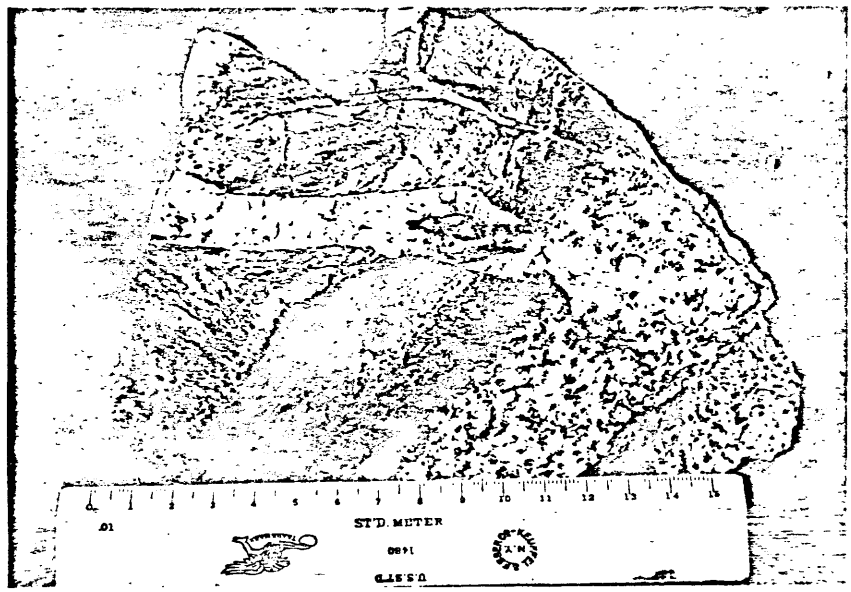
B. MASSIVE TACTITE FROM GRANITE CREEK MINE.



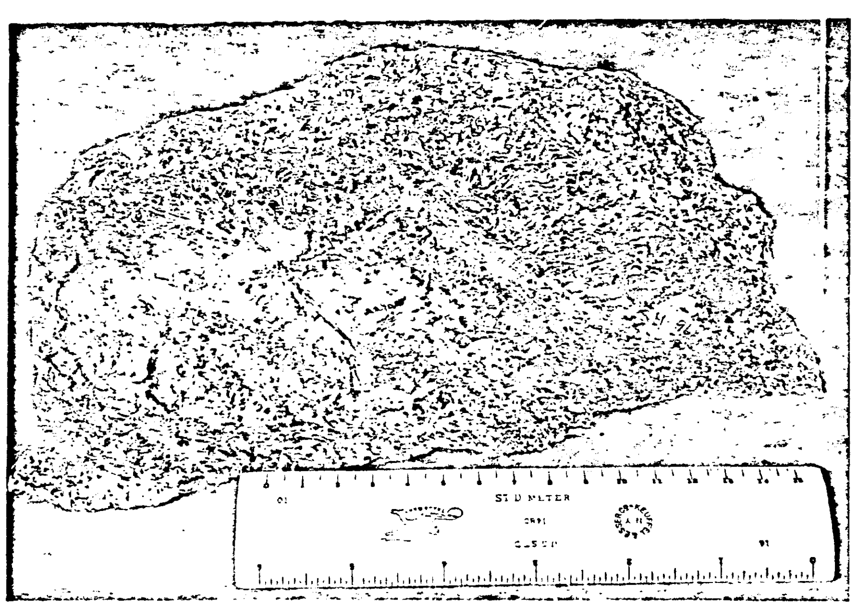
C. COARSE TACTITE FROM RICHMOND MINE. Shows development of large garnets in calcite.



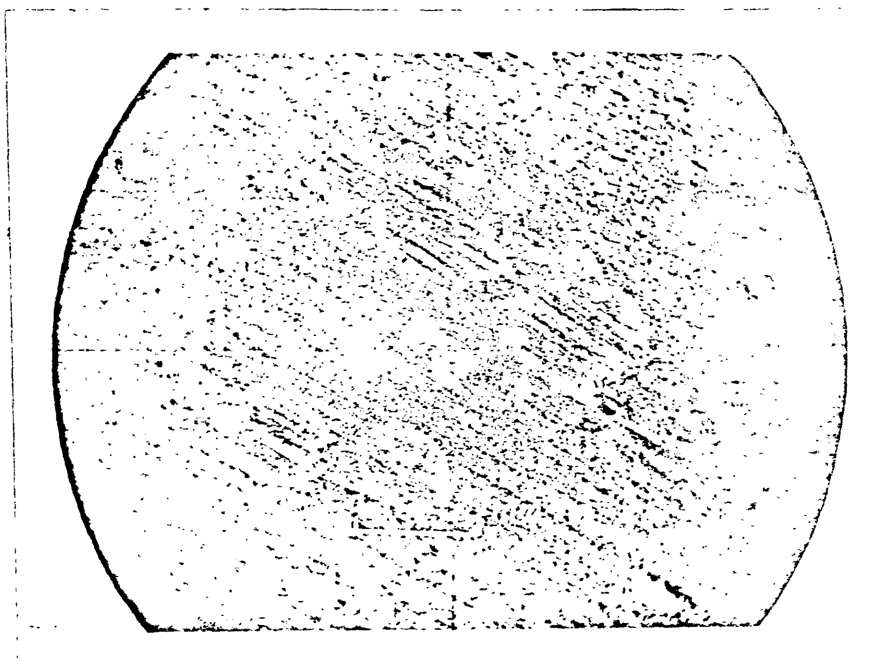
D. GRANODIORITE SHOWING REPLACEMENT BY QUARTZ.



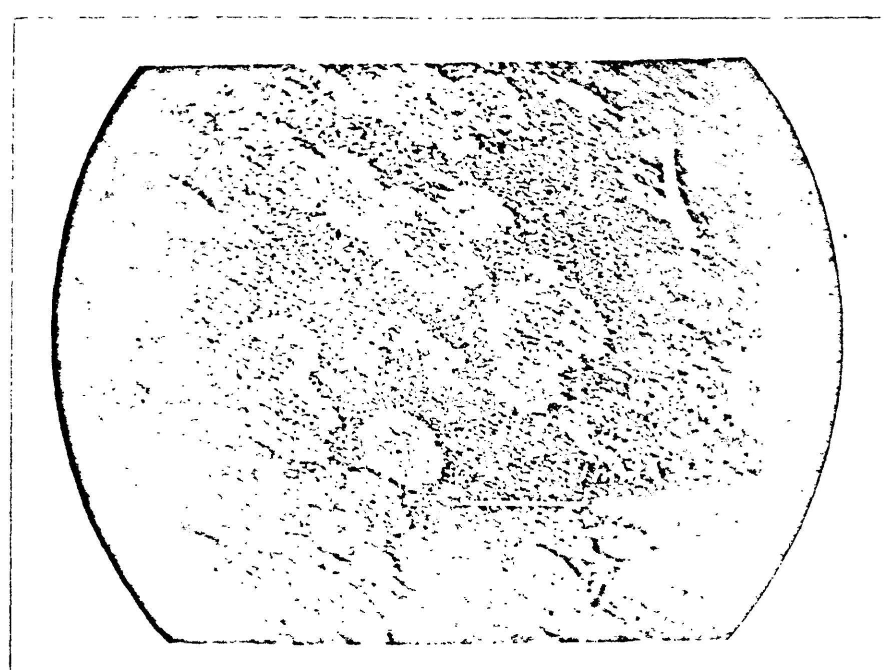
A. CONTACT OF GRANODIORITE AND DIOPSIDE HORNFELS AT THE VALLEY VIEW MINE.
Shows development of hornblende (black) between granodiorite and diopside hornfels (gray). Aplite dike fades out into granodiorite, and shows narrow selvage of amphibole on borders.



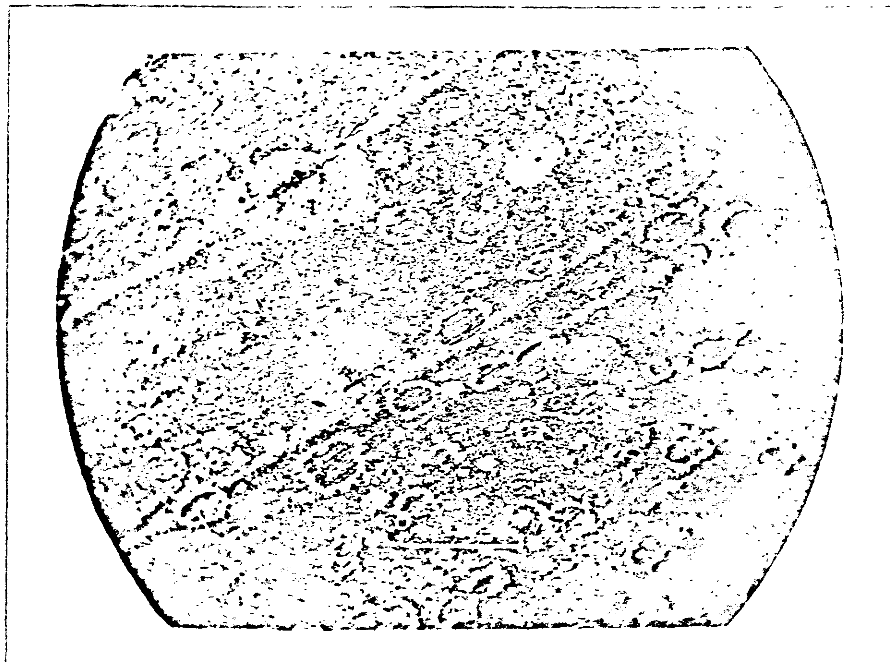
B. INCLUSION OF DIOPSIDE HORNFELS IN GRANODIORITE.
Shows nearly complete conversion of hornfels to amphibole with only a small area of unreplaced hornfels in center (gray).



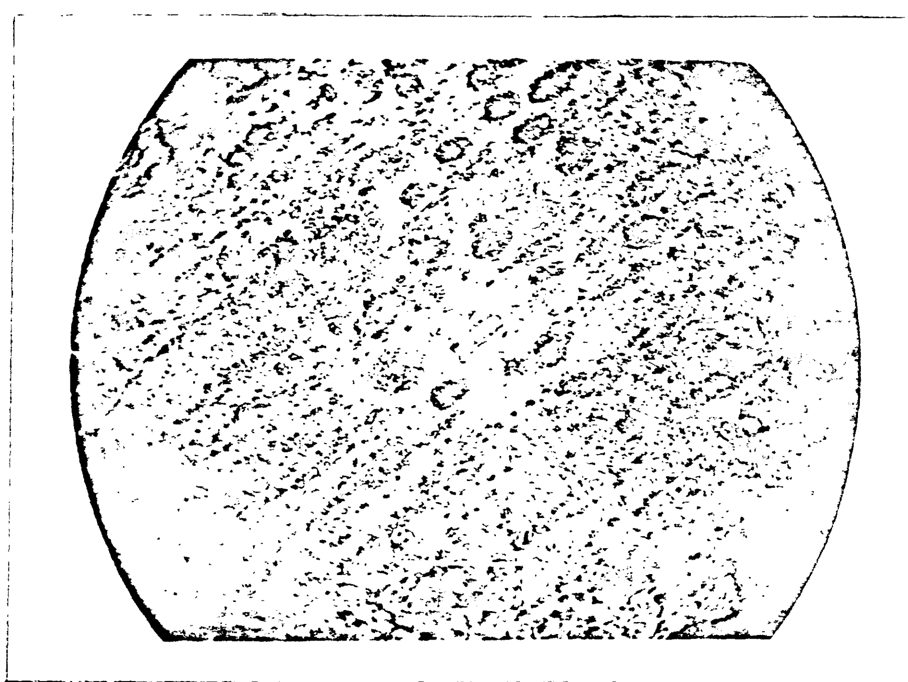
A. PHOTOMICROGRAPH OF HORNFELS SHOWING INCIPIENT SPOTS. Spots result from slight increase in grain size and clearing of dark minerals from area of spot. Plane light.



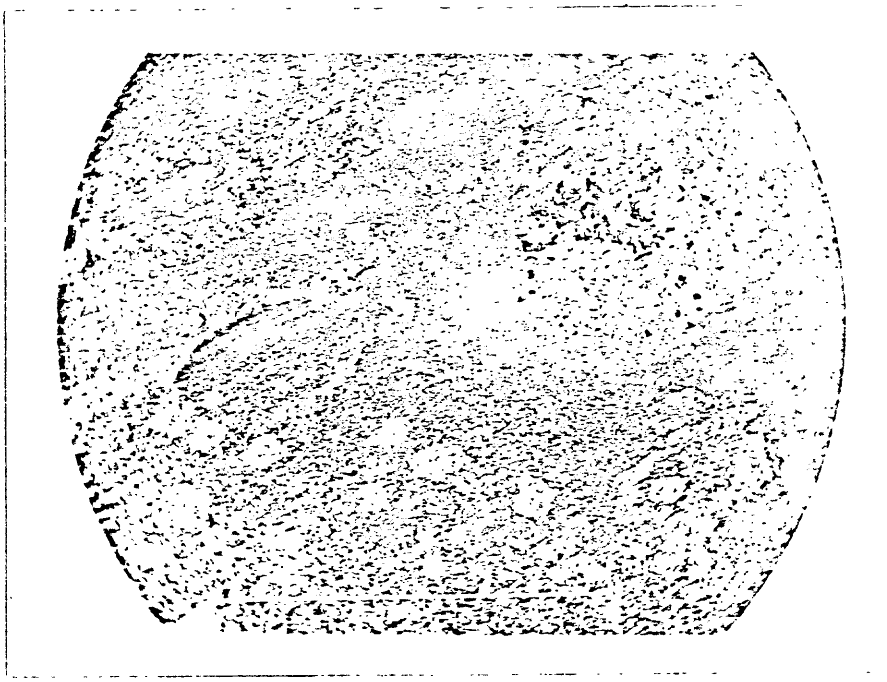
B. SAME AS A.
Crossed nicols.



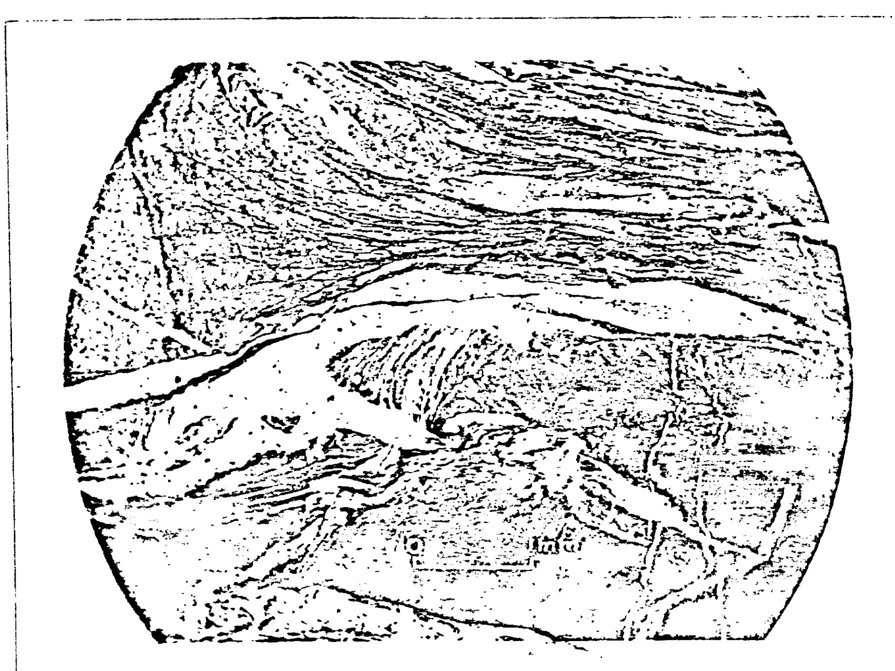
A. PHOTOMICROGRAPH OF BIOTITE-CORDIERITE HORNFELS.
Shows spots of three kinds:
1. Clusters of biotite (small dark areas);
2. Large spots with cleared edges and lines of inclusions that parallel the schistosity (cordierite porphyroblasts);
3. Large clear spots with opaque minerals in core (are essentially areas cleared of the groundmass biotite). Plane light.



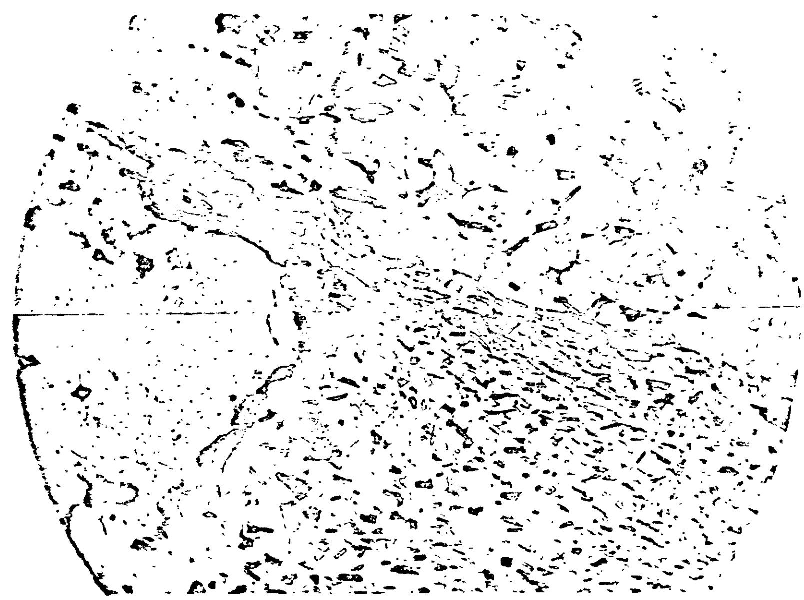
B. SAME AS A.
Crossed nicols.



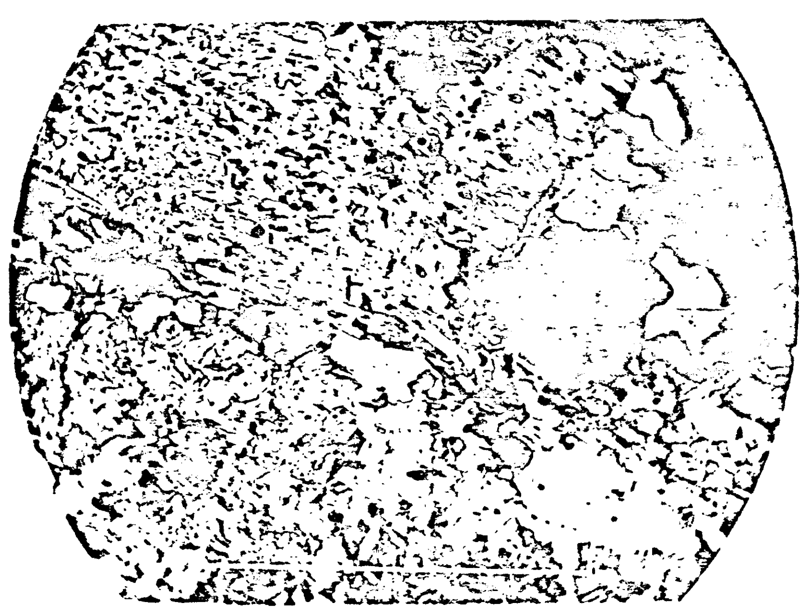
A. SAME AS PLATE 19.
Higher magnification; plane light.



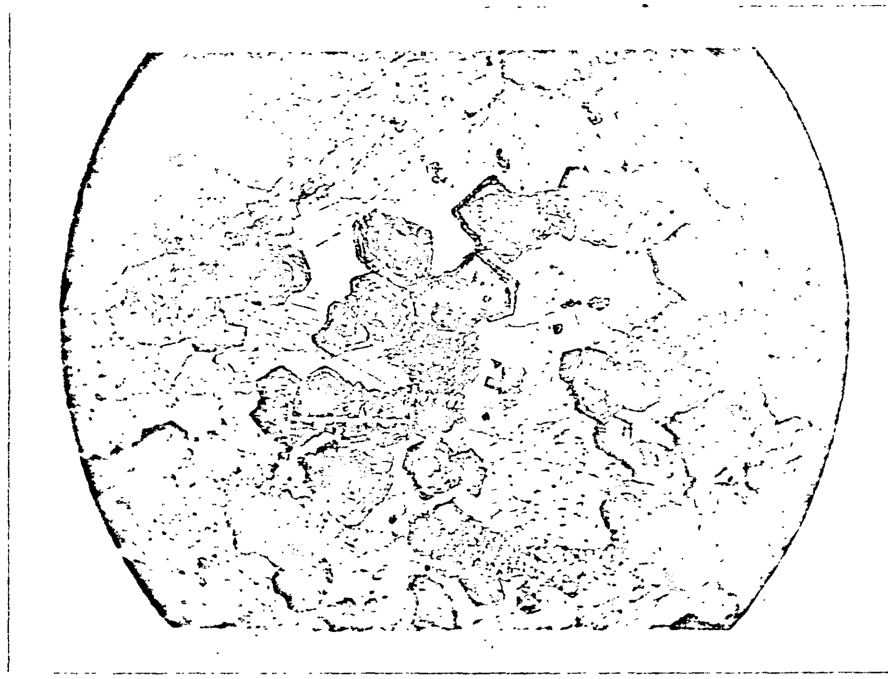
B. PHOTOMICROGRAPH OF SILICEOUS CORDIERITE HORNFELS SHOWING CONTORTION AND INTRODUCTION OF SILICA.



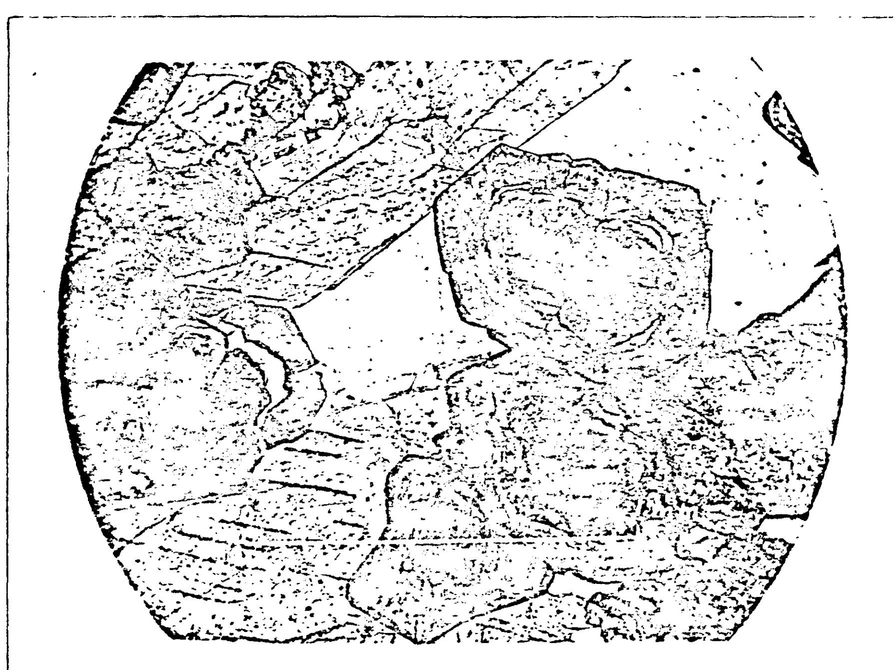
A. PHOTOMICROGRAPH OF BIOTITE-CORDIERITE HORNFELS NEAR CONTACT WITH GRANODIORITE.
Note inclusions of biotite in cordierite. Plane light.



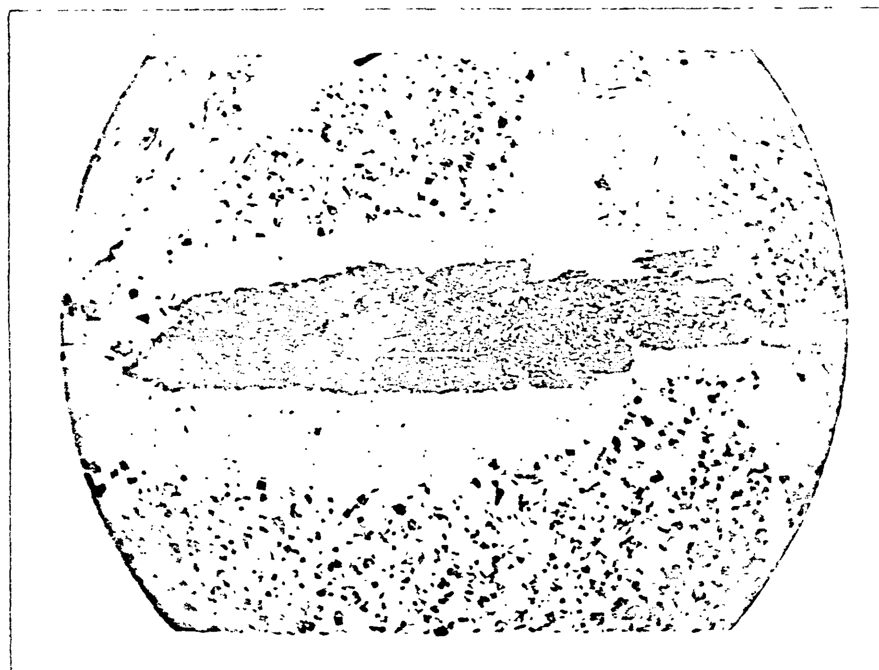
B. SAME AS A.
Crossed nicols.



A. PHOTOMICROGRAPH OF TACTITE SHOWING DEVELOPMENT OF ZONED GARNET.
Plane light.

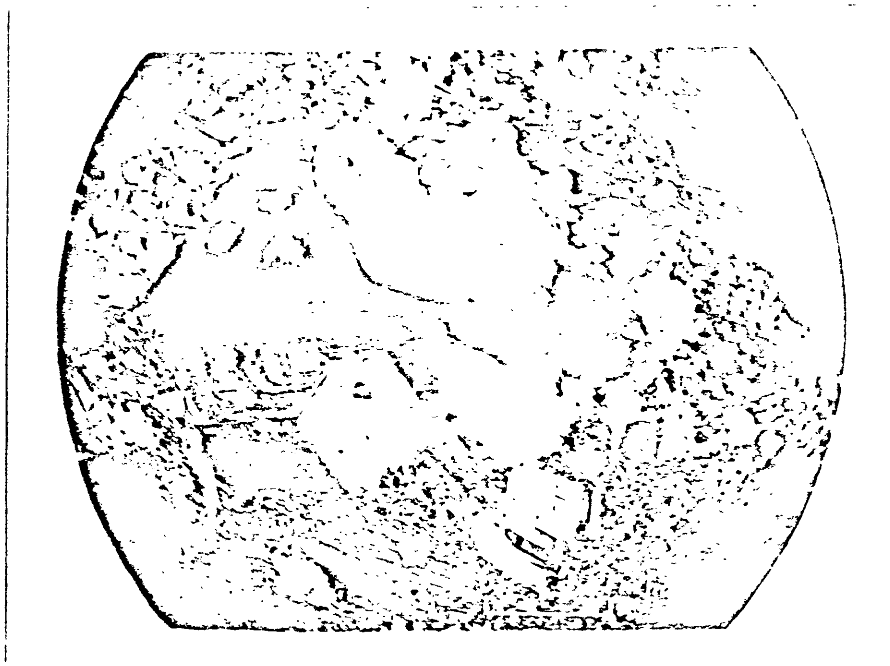


B. SAME AS A.
Higher magnification. Plane light.

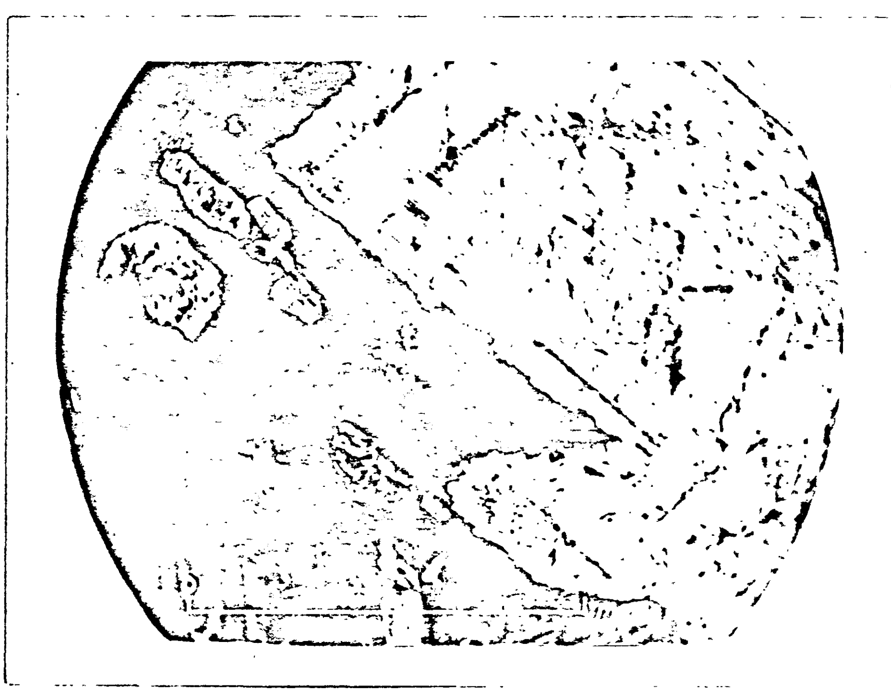


A. PHOTOMICROGRAPH OF PORPHYROBLAST OF PARGASITE AT THE VALLEY VIEW MINE.
Developed in diopside hornfels at contact with granodiorite. Shows clearing of biotite from surrounding area. Plane light.

B. PHOTOMICROGRAPH OF BANDED METAVOLCANIC ROCK FROM ROCK GROUP E.
Plane light.



A. PHOTOMICROGRAPH OF ZONED PLAGIOCLASE PORPHYROBLAST IN HORNFELS AT CONTACT ZONE OF VALLEY VIEW MINE. Crossed nicols.



B. PHOTOMICROGRAPH SHOWING PLAGIOCLASE WITH CORROSION BORDER AGAINST ORTHOCLASE. Plagioclase white, orthoclase black. Crossed nicols.