2. PROBLEMS OF THE METAMORPHIC AND IGNEOUS ROCKS OF THE MOJAVE DESERT *

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INTRODUCTION

The Mojave Desert region, as defined by Baker (1911, pp. 335-336), is the region of desert plains, mountains, and valleys comprising the extreme southwestern portion of the Great Basin (fig. 1). It lies entirely within California, including parts of San Bernardino, Los Angeles and Kern Counties, and embraces an area of approximately 160,000 square miles. Its climate is arid, and the drainage is interior.

Because much of the geology of this region is imperfectly known, any discussion of the regional aspects of the metamorphic and igneous rocks must take the form of a progress report. The relatively few published geological reports describe more or less widely separated areas, involve investigations of widely differing scales and qualities, and in general have not been coordinated parts of any broad, systematic program of research. Knowledge of the geology thus is peculiarly spotty, and some apparently critical areas and subjects have been completely neglected. Present knowledge provides a basis for some conclusions, but at the same time it points to numerous problems awaiting solution. This paper is written in an attempt to focus attention upon some of these interesting unsolved problems, as well as to collate the conclusions already reached by various workers.

PRE-TERTIARY METAMORPHIC AND IGNEOUS ROCKS

General Statement

Pre-Tertiary metamorphic and igneous rocks crop out over approximately 25 percent of the region. With the exception of Quaternary alluvium, which covers about 60 percent of the region, no other group of rocks is as important areally. They form virtually the only record of a long and involved pre-Tertiary history. They also form the foundation and framework for the Tertiary and Quaternary stratigraphy and structure, the complexities of which have been recognized only in recent years, and they can be expected to yield information that should clarify some of those complexities.

The topics to be considered here are: 1) the problems of the ages and correlations of the metamorphic rocks, and the related problems of pre-Tertiary stratigraphy and paleogeography; 2) petrology of the metamorphic rocks, and the causes of the metamorphism; 3) structures of the metamorphic rocks, and their relation to metamorphic and igneous activity; 4) the pre-Tertiary volcanic rocks; 5) the pre-Tertiary intrusive rocks; 6) ages and correlation of the plutonic rocks.

Ages and Correlations of the Metamorphic Rocks

Pre-Cambrian Rocks. North and northeast of the Mojave Desert, and in its eastern portion, well known Paleozoic sedimentary sections rest in different localities upon pre-Cambrian sedimentary, metamorphic, and igneous rocks. The pre-Cambrian rocks have not been studied extensively, but the following facts are known.

Thick sections (up to 11,000 feet) of practically unmetamorphosed "younger pre-Cambrian" Pahrump sedimentary rocks have been described from the Kingston Range[29] ‡ (Hewett, 1940), and from southern Death Valley (Noble, 1934; Kupfer, 1951; Wright, 1952). Noble writes that in the latter area[27] these "Algonkian" strata rest unconformably upon "Archean" schist, gneiss, and granitic rocks. Kupfer, on the other hand, reports that in the Silurian Hills[30] the unmetamorphosed sedimentary rocks grade into feldspathized, intruded, and metamorphosed rocks which previous workers called "Archean." More work is needed to reconcile such statements as these.

Murphy (1932) and Hopper (1947) describe thick sections of dynamothermally metamorphosed pre-Cambrian sediments from the Panamint Range. "Archean" gneisses, schists, marble, gneissoid granitic rocks, and migmatites underlie Cambrian or Pahrump strata in much of the eastern Mojave Desert, east and south of Death Valley. Such rocks have been described by Hazzard and Crickmay (1933) from the Marble,[32] Ship,[33] and Providence Mountains,[34] by Noble (1934) from the Black Mountains and Amargosa Range,[28] by Hazzard and Dosch (1936) from the Piute[36] and Old Woman Mountains,[37] and by Hewett (1940) from the Kingston Range.[29] The great variety of metamorphosed sedimentary and associated pre-Cambrian intrusive rocks occurring in these areas, and the local great thicknesses of metasediments (for example the Essex series of Hazzard and Dosch, 1936), strongly suggest a complicated history for the "Archean" rocks. Furthermore, the simple classification of the "pre-Cambrian" rocks as "Archean" if they are intensely metamorphosed and "Algonkian" if they are mildly metamorphosed may well be open to some question.

The relation of the "Archean" gneisses to the pre-Cambrian metasediments of the Panamint Range is unknown. The latter were divided by Hopper (1947), in part following Murphy (1932), into three units, the Telescope group, Surprise formation, and Panamint

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‡ Numbers following geographic names are shown in figure 1 at the locations of the geographic features mentioned.

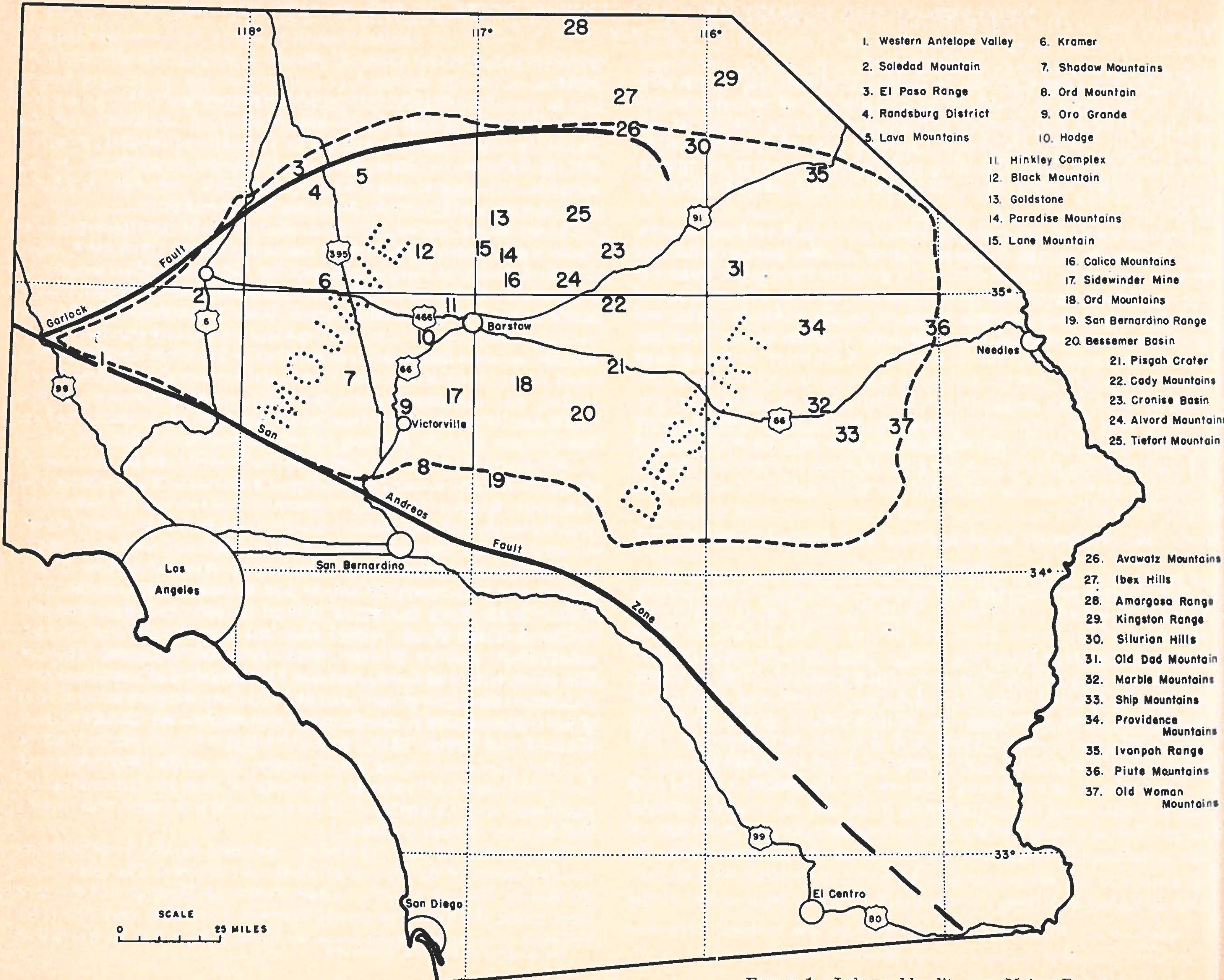

FIGURE 1. Index and locality map, Mojave Desert.

metamorphic complex, from youngest to oldest. Noble (1934, p. 174) has suggested that the Telescope group may correlate with the "Algonkian" Pahrump strata.

The author feels that the available evidence suggests that the pre-Cambrian rocks of the eastern Mojave Desert and the region to the north record a complex history of events separated by space and time. Thus far only hints of that history have been deciphered, but enough is known to suggest that the most promising areas for further study lie in the Panamint Range and in the southern Death Valley region.

In contrast to the situation in the eastern Mojave Desert, no early Paleozoic strata have been recognized in the central and western Mojave Desert. There the base of known Paleozoic rocks apparently has not been seen, and no rocks are proven to be unquestionably pre-Cambrian. Figure 2 shows the portions of the Mojave Desert in which the base of the Paleozoic has been mapped or where such rocks have been seen resting unconformably upon pre-Cambrian rocks. Clearly a pre-Cambrian age assignment for a given rock of the central or western Mojave Desert cannot be based upon any stratigraphic evidence now available.

The known Paleozoic rocks of the central and western Mojave Desert are dynamothermally or thermally metamorphosed sedimentary and volcanic rocks which are locally, but commonly, migmatized and injected near igneous contacts. They range from highly foliated to practically unfoliated. Petrologically similar rocks that have yielded no fossils are questionably assigned to the Paleozoic or Mesozoic.

In the same region with these known and probable Paleozoic rocks, are considerable areas of strongly foliated schists and gneisses of unknown age. Examples are the Rand schist and Johannesburg gneiss of the Randsburg district [4] (Hulin, 1925, pp. 1-29), and other rocks that have been observed by Gardner (1940, p. 264) in the Bessemer basin,[20] and by the writer in the Alvord Mountains,[24] Tiefort Mountains,[25] and Cronise basin.[23] These rocks, some of them granitic gneisses, are more highly deformed and more extensively altered than most of the proven Paleozoic rocks of the central Mojave region, and they are similar in appearance and petrology to some of the "Archean" rocks of the eastern Mojave. They have been termed pre-Cambrian by various investigators because of these similarities, or because of their petrologic contrasts with known Paleozoic metamorphic rocks. Although these age assignments may prove to be correct in sóme or all instances, it should be kept in mind that, at present, trustworthy stratigraphic evidence of pre-Cambrian age is lacking in the central and western Mojave Desert. As outlined below, some of these rocks could be early Paleozoic instead of pre-Cambrian in age.

*Paleozoic Rocks.** In those parts of the eastern Mojave Desert where pre-Cambrian rocks are known to exist, they are, or were at one time, overlain by fossiliferous Paleozoic sedimentary rocks. The principal stratigraphic relations of these rocks, which are only locally metamorphosed in contact zones next to Mesozoic plutonic intrusions, are known from careful studies in several areas. The stratigraphic relations and lithologies are diagramatically shown in the columnar sections of figure 2. With the exception of the predominantly clastic lower part of the Cambrian, especially the thick clastic sections in the Nopah, Resting Springs, and Panamint Ranges (north and northeast of the Mojave Desert), these unmetamorphosed Paleozoic strata are predominantly carbonate sedimentary rocks. Clastic increments are relatively unimportant, and volcanic and pyroclastic materials are absent.

As in the case of the pre-Cambrian rocks, there is a striking contrast between the Paleozoic rocks of the eastern and central parts of the Mojave Desert. The known and probable Paleozoic rocks of the central Mojave are poorly understood, rarely contain identifiable fossils, and are dynamothermally or thermally metamorphosed on a regional scale. They occur as roof pendants and septa partially engulfed by Mesozoic plutons, and generally are complexly folded and faulted. Fossils thus far found and identified from these remnants of Paleozoic rocks range from Mississippian (?) (Woodford and Harriss, 1928, p. 270) to Permian (Bowen, 1954). No fossiliferous rocks older than Carboniferous have been reported to date.

Although most of the nine fossiliferous Paleozoic units known to the writer in the central Mojave Desert are limestone or marble, these rocks are generally associated with hornfelsed argillaceous dolomite and notable or predominant amounts of metamorphosed pelitic sediments (schist or hornfels), quartzite, meta-arkose, and meta-conglomerate. Metamorphosed volcanic rocks are minor but notable associates. The following are representative examples of thick sections containing metamorphosed clastic sediments: On the northeastern slope of the Calico Mountains 25,000+ feet of apparently conformable strata, of which at least half are late Paleozoic in age, consist of 60 percent metamorphosed clastic sediments, 24 percent meta-volcanics, and minor amounts of marble and lime-silicate hornfels (McCulloh, 1952, p. 1339). The type section of the Oro Grande series [9] (Hershey, 1902, p. 288; Baker, 1911, p. 336; Bowen, 1954) contains a large proportion of quartzite and schist. On the northern slope of the San Bernardino Range [19] the thick Saragossa and Arrastre quartzite formations (Vaughan, 1922, pp.

* See also Merriam, Contribution 2, Chapter III.

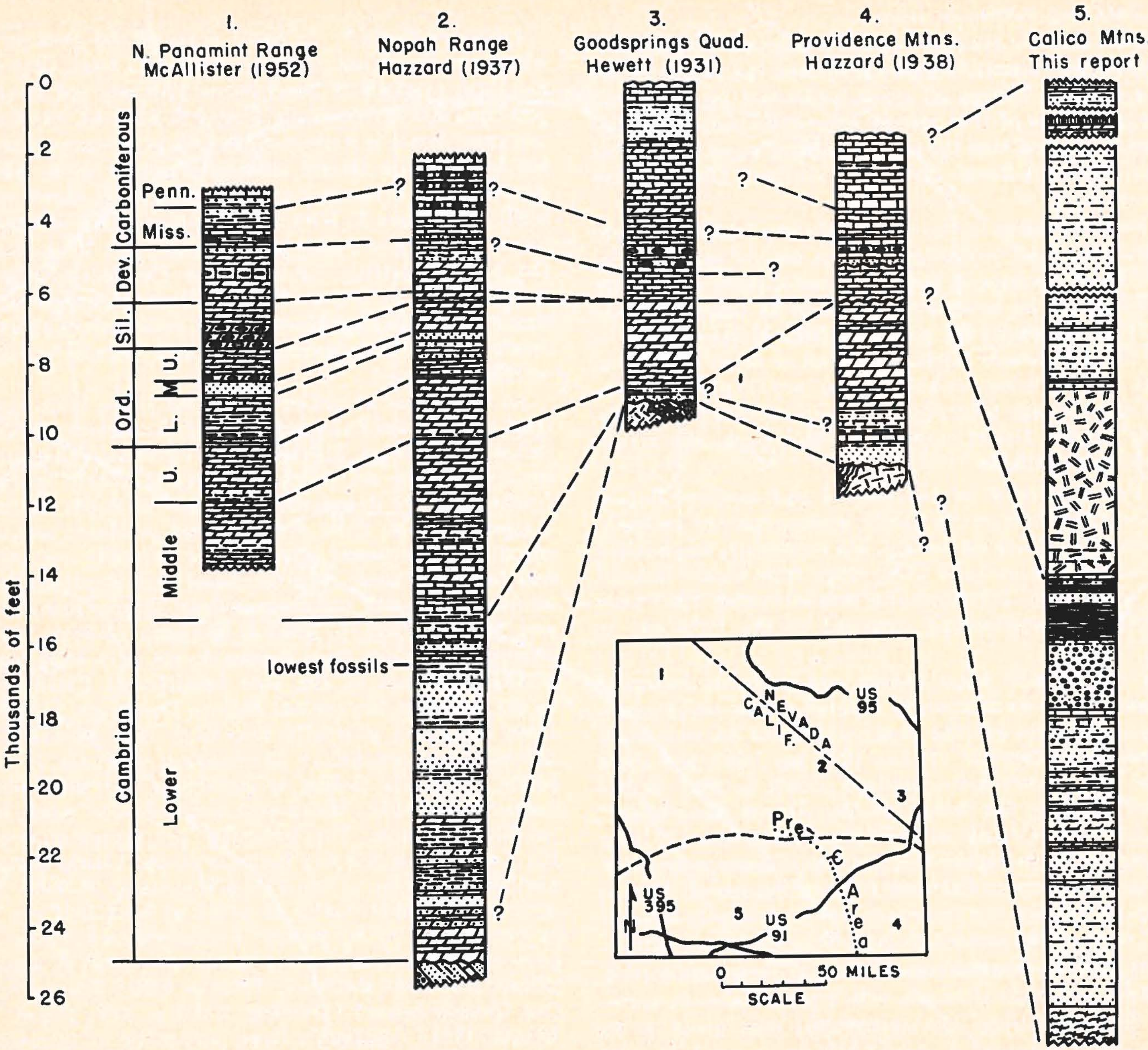

FIGURE 2. Tentative Paleozoic correlations, Mojave Desert.

352-361; Woodford and Harriss, 1928, p. 270) and associated Mississippian (?) Furnace limestone invite further attention.

The stratigraphic relations among these and the other known and suspected Paleozoic metamorphic rocks in the central Mojave Desert are so poorly understood that it would be pointless, and in fact misleading, for the writer to attempt to correlate from one imperfectly known section to the next. Inasmuch as such correlations constitute some of the more important and interesting unsolved problems of the region, however, specific facts concerning some of the better known sections will illustrate the kind of problems encountered, and might suggest possible answers to some of them.

In figure 2, the 25,000+ foot section of metamorphosed sedimentary and volcanic rocks of the northeastern Calico Mountains [16] is diagrammatically compared with the unmetamorphosed Paleozoic sections of the eastern Mojave Desert and the region to the north. Poorly preserved circular crinoid stems near the middle of this section suggest a late Paleozoic age, and heavy-shelled, ribbed mollusks in rocks which are either older or younger than the principal section indicate that 12,000+ feet of these predominantly clastic metasediments are post-Cambrian. As the entire post-Cambrian Paleozoic section of the eastern Mojave Desert is characterized by carbonate rocks which at no place total more than 8000 feet in thickness, the metamorphosed clastic sediments of the central Mojave Desert are evidence of a westward coarsening and thickening of a part of the younger Paleozoic strata. The thick meta-arkose units, characterized by detrital feldspar and accessory detrital zircon and tourmaline, and the local occurrence of granitoid pebbles in meta-conglomerate suggest that the source of these sediments was an area containing granitic or metamorphic rocks. Consideration of the distribution of known Paleozoic sedimentary rocks, coupled with their westward thickening and coarsening, strongly suggests that the source area was situated west of the site of deposition.

Bowen (1954) describes several metamorphic units, which he considers to be of Paleozoic age, from the Barstow quadrangle, southwest of the Calico Mountains. Only the two units that are fossiliferous are discussed in detail here.

The 2350+ feet of dolomite, marble, quartzite, mica schist, and lime-silicate hornfels (Bowen, 1954) just east of Oro Grande [9] were first described by Hershey (1902, pp. 287-288), who referred them to the Cambrian because of lithologic similarity to Cambrian quartzite in western Nevada. Baker (1911, p. 336) named these rocks the Oro Grande series, described them somewhat more fully, and cautiously refrained from correlating them. Miller (1944) reported finding crinoid stems in marbles of the type section, and suggested that the rocks are Carboniferous. Bowen has found more fossils near the type section, and has substantiated Miller's report. The relation of the Oro Grande series to the Calico Mountains section is unknown. The crinoid stems in both sections suggest a younger Paleozoic age for parts of each, but the sequence of lithologic units in the Oro Grande series has not been recognized in the Calico Mountains section. The thick quartzite and mica schist units of the Oro Grande series have no lithologic analogues in the Carboniferous sections of the eastern Mojave Desert, and provide further evidence of westward coarsening of the late Paleozoic strata.

The type section of the Fairview Valley formation [17] (Bowen, 1954), located in the eastern part of the Barstow quadrangle, consists of 6000+ feet of mildly metamorphosed conglomerate and hornfelsed fine-grained limy clastic sediments. The basal beds are reported by Bowen to rest unconformably upon unfossiliferous massive limestones and quartzites that are correlated with the Oro Grande series, and to contain well-rounded pebbles of porphyritic andesite and leucogranite in addition to some of quartzite and limestone. Clasts of granite, aplite, quartzite, and limestone are reported from strata higher in the section, and fossils collected by Bowen and others from limestone clasts in conglomerate that is high in the section are reported by C. W. Merriam (oral communication, 1953) to represent a typical Lower Permian fauna. A few fossils reportedly collected from the matrix of this conglomerate are also Permian, but may have been reworked from older sediments. Triassic (?) volcanic rocks are younger than this formation.

Bowen has concluded that the age of the Fairview Valley formation is Permian, but the writer considers that the available evidence permits an assignment to either the Mesozoic or the Permian. The unconformity reported by Bowen at the base of the formation is of considerable regional interest, especially in view of the granitic clasts in the overlying conglomerate. If the age of the formation can be unequivocally determined, a Permian or Mesozoic structural event of first-order importance will be dated. Whether or not the rocks can be dated more precisely than post-lower Permian does not alter the conclusion that major diastrophism, sufficient to allow erosion of considerable areas of Permian sedimentary rocks and important areas of pre-Permian granitic rocks, occurred in late Permian or early Mesozoic time. Without precise dating and more complete knowledge of the original areal extent of the formation, conclusions regarding the location of the source area can be only careful guesses. The factors that led to the conclusion that the clastic meta-sediments of the Calico Mountains Paleozoic section were derived from sources to the west can be extended, with somewhat less assurance, to the Fairview Valley formation.

Evidence now available thus indicates that the metamorphosed late Paleozoic strata of the central Mojave Desert are the thicker and more clastic equivalents of predominantly carbonate sections of the eastern Mojave Desert and the regions to the north. The more westerly sediments were deposited in a mobile area adjacent to a land mass from which large quantities of limestone, chert, quartzite, and granitic debris were being eroded for considerable intervals of late Paleozoic time. This land mass was situated somewhere to the west of the site of deposition. Determination of its position, boundaries, and area, and of the boundaries of the region of marine deposition comprises two of the most fundamental problems to be solved through a study of the metamorphic rocks of the Mojave Desert.

Several other areas of known or probable late Paleozoic rocks, when they have been adequately mapped, may well provide essential information to add to the rather nebulous picture described above. Such areas are the northern part of the San Bernardino Range,[19] Ord Mountain [8] south of Victorville (Noble, 1932, p. 356), the Shadow Mountains [7] northwest of Victorville, and the Goldstone area [13] 30 miles north of Barstow.

Pre-Carboniferous Paleozoic rocks have not been found in the Mojave Desert far west of the longitude of Baker. In the light of present knowledge, their apparent absence from the central and western Mojave Desert might be explained in several ways. First, pre-Carboniferous Paleozoic sediments may have been deposited, and subsequently so thoroughly and extensively metamorphosed that they have not yielded recognizable fossils. Second, such rocks may have been deposited, and then elevated and eroded prior to or during deposition of the younger Paleozoic strata. Third, such rocks may never have been deposited in this region.

The character, thickness, and distribution of the pre-Carboniferous Paleozoic strata of the eastern Mojave Desert (fig. 2) suggests that the area of deposition of these strata originally extended a considerable distance west of their present westernmost outcrops. That they may have covered some of the central Mojave Desert seems a plausible assumption. The abundance of sedimentary and granitic clastic debris in the younger Paleozoic rocks of the central Mojave Desert implies that much of any preexisting pre-Carboniferous Paleozoic cover was stripped from the source area, which lay an unknown distance farther west. If the older Paleozoic strata were similarly stripped from the central Mojave Desert, that event is not reflected in the predominantly non-clastic character of the Paleozoic sections in the eastern Mojave Desert and in the region to the north. These considerations lead to the tentative opinion that pre-Carboniferous sedimentary rocks were deposited in the area of the central Mojave Desert, and that they were probably not eroded prior to deposition of the known younger Paleozoic metamorphic rocks.

If this opinion is correct, perhaps some of the undated metamorphic rocks of the central Mojave Desert are actually early Paleozoic rocks in which fossils have not been recognized. For example, the folded, extremely foliated, and thoroughly recrystallized marbles, quartzites, and gneisses of the Hinkley Complex [11] (Miller, 1944, p. 79) could be of older Paleozoic age. Miller, in his original description, assigned these rocks, on unsatisfactory grounds, to the pre-Cambrian. Later (Miller, 1946, pp. 503-504) he correlated them, for almost equally unsatisfactory reasons, with the questionably Carboniferous metasediments of the Paradise Mountains.[14] If their markedly greater degree of deformation through shearing can be trusted to reflect a greater age, the rocks of the Hinkley Complex should be considered older than the fossiliferous late Paleozoic rocks of adjoining areas. As such, they could be either pre-Cambrian or early Paleozoic in age. Careful structural and stratigraphic studies will be needed to test this hypothesis. After much more careful work, similar arguments might be applied to some of the other undated metamorphic rocks of the central and western Mojave region, such as the Rand Schist [4] (Hulin, 1925, pp. 23-31) and the Hodge metavolcanic series [10] (Bowen, 1954).

Mesozoic Strata. Dated Mesozoic strata are rare in the eastern part of the region, and have not been proven, on paleontologic grounds, to exist in the central and western Mojave Desert. The only fossiliferous Triassic rocks thus far recognized are the 1000 feet of limestone, shale, and sandstone of the Providence Mountains [34] (Hazzard, 1936, p. 329). Hewett reports (oral communication, 1953) that Triassic and Jurassic formations have been mapped southwestward from the Goodsprings quadrangle, Nevada, as far as the Ivanpah Range,[35] where the Aztec sandstone is overlain by presumably Jurassic volcanic rocks.

Mesozoic metavolcanics (Ord Mountain group and Sidewinder metavolcanics) intrude and overlap the post-Lower Permian Fairview Valley formation in the eastern Barstow quadrangle [17] (Bowen, 1954), and are intruded by Mesozoic quartz monzonite in the Barstow quadrangle and in the Ord Mountains area [18] southeast of Barstow (Gardner, 1940, p. 270). The metavolcanics consist of a thick sequence of altered andesite, dacite, and rhyolite flows, and some volcanic breccias.

Petrology of the Metamorphic Rocks

Little information has been published about the mineralogy and petrology of the wide variety of metamorphic rocks discussed above, and a few general statements will suffice to summarize current knowledge and opinion.

The "Archean" rocks of the eastern Mojave Desert have been studied in detail at only one locality, in the Ivanpah Mountains [35] (Sharp and Pray, 1952), where they consist of a metamorphic complex of foliated feldspathic gneiss, quartz-mica schist, amphibole schist, and foliated pegmatitic bodies.

Silication of "Algonkian" siliceous and silica-poor dolomite to talc-tremolite-serpentine rock and tremolite-feldspar rock along the borders of "Algonkian" diabase sills in southern Death Valley [27] has been ascribed primarily to introduction of MgO, SiO_2, Al_2O_3, K_2O, and probably Na_2O from the diabase magma (Wright, 1952, p. 1347). Details of the mineral assemblages and textural relations are needed to reach conclusions concerning metamorphic grade or facies.

Aside from such pre-Cambrian contact metamorphism, the younger pre-Cambrian Pahrump strata of southern Death Valley are usually unmetamorphosed. However, the writer has observed that feldspathic sandstone has been recrystallized to biotite-quartz-plagioclase hornfels near contacts with quartz diorite on the northern slopes of the Avawatz Mountains.[26] Considerable work should be done to determine the areal distribution and grades of these metamorphic rocks, as well as the age of metamorphism. No data relating to the petrology of the reported gradation between Pahrump strata and the "Archean" gneisses in the Silurian Hills [30] (Kupfer, 1951, p. 1496) are published.

The Paleozoic and Mesozoic strata of the eastern Mojave Desert are only locally metamorphosed in thin contact zones adjacent to Mesozoic plutonic rocks, whereas the equivalent strata in the central Mojave Desert usually show evidence of one or more periods of regional thermal or dynamothermal metamorphism. So far as the writer knows, the only extensive petrographic study of metamorphosed Paleozoic rocks of any part of the central Mojave Desert has been his own work on the metamorphic rocks of the Lane Mountain quadrangle,[15] where two different periods of progressive metamorphism are discernible. An older, dynamothermal, metamorphism was particularly intense along pre-intrusive imbricate fault zones, where different rock types were recrystallized to various kinds of schists and amphibolites, characterized by shear folds and lineation (and elongation) parallel to the fold axes. The effects of a younger thermal metamorphism, unaccompanied by significant shearing, are manifested in the nearly uniform recrystallization of all rocks to hornfels, quartzite, marble, or amphibolite, depending upon original composition. The abundant minerals are plagioclase, orthoclase or microcline, quartz, calcite, wollastonite, diopside, hedenbergite, tremolite, hornblende, biotite, muscovite, scapolite, and grossularite. In rare rocks of appropriate composition forsterite, spinel, and cordierite have been found. All the mineral assemblages are appropriate to the cordierite-anthophyllite subfacies of the amphibolite facies. Preservation of relic stratification, clastic textures, and rarely of fossils indicates that the second phase of metamorphism was not accompanied by great shearing stress. The apparently stable association of quartz and calcite far from intrusive contacts, and their universal reaction to form wollastonite nearer those contacts, support the supposition that the thermal energy necessary for the metamorphism had its source in intrusive igneous masses.

Conclusions regarding regional distribution of metamorphic rocks of different grades must await further field and petrographic work. Reconnaissance of parts of the central Mojave region suggest that the metamorphic rocks of the El Paso Range,[3] Rand Mountains,[4] and Shadow Mountains [7] appear particularly worthy of such study at this time.

Structures of the Metamorphic Rocks

The metamorphosed Paleozoic sedimentary rocks of the central Mojave region were folded and faulted prior to emplacement of Mesozoic plutonic rocks. The Oro Grande series in the type area [9] and the roof pendants of the Lane Mountain quadrangle [15] contain accessible illustrative examples of such pre-intrusive structures. Bowen (1954) believes that two periods of pre-intrusive folds are discernible in the Barstow quadrangle. He concludes that rather gentle northeast-trending folds resulted from late Paleozoic orogeny, and that Mesozoic folding occurred along northwest trends. In the region north of the Barstow quadrangle, northwest- to northeast-trending folds appear to have been formed during a single period of deformation.

The significances of the foliation, tight recumbent folds, and lineation of such rocks as the Hinkley complex meta-sediments [11] and the Rand schist [4] are not known. The contrast between these and the usually mildly foliated late Paleozoic metamorphic rocks could be interpreted as the expression of a pre-Carboniferous period of dynamothermal metamorphism. On the other hand, the greater degree of deformation may be simply the result of differences in competence or structural position. In the absence of careful detailed mapping and regional study, the writer feels that no generalizations are justified. A fertile field awaits those interested in structural petrology.

The structures of the metamorphic rocks studied by the writer usually show no indication of origin through stresses imposed on their walls by forceful intrusion of igneous magma, even immediately adjacent to contacts with plutonic rocks.

Pre-Tertiary Volcanic Rocks

Although pre-Cambrian rocks are fairly widespread in the eastern Mojave Desert, volcanic rocks have not been reported among them. The unmetamorphosed Paleozoic sedimentary rocks of the eastern

Mojave Desert and the region to the north also contain no volcanic or pyroclastic material, but the metamorphosed section of the Calico Mountains [16] does contain important thicknesses of meta-andesite and meta-basalt in three widely separated zones (McCulloh, 1952). Further, the thick section in the El Paso Range [3] includes units of mildly metamorphosed volcanic rocks above and below a central fossiliferous zone that has yielded a Permian fauna (Dibblee, 1952).

Much work remains to be done to determine the time range of the Paleozoic volcanic rocks, and to determine the geographic limits of the area of volcanism. Moreover, it is desirable to establish the relationship between the area of volcanism and that of late Paleozoic clastic sedimentation. It appears significant that the Paleozoic strata of the eastern Mojave region are mostly unmetamorphosed carbonate rocks without volcanic material, whereas those of the central Mojave Desert occur in much thicker, regionally metamorphosed sections containing major proportions of clastic material, and associated with volcanic rocks. It also may not be accidental that large-scale intrusion of Mesozoic plutonic rocks was fairly well restricted to the central Mojave Desert and to the regions farther west.

The Lower Triassic sedimentary rocks of the Providence Mountains [34] (Hazzard, 1936, p. 329) are unaccompanied by Mesozoic volcanic rocks. However, coarse agglomerate overlies the Jurassic Aztec sandstone in the Ivanpah Mountains [35] (Hewett, oral communication, 1953), and similar rocks at Old Dad Mountain,[31] southeast of Baker, are described by Hazzard, et al. (1937, p. 279) as 1000 to 2000 feet of altered basic and acid lava flows, agglomerate, and tuffaceous (?) slates with marble, which are intruded by "Jurassic (?) granite." These investigators correlate the volcanic rocks of Old Dad Mountain with similar rocks at Ord Mountain,[18] and note that their age is "Triassic or Jurassic, rather than pre-Cambrian or Paleozoic—because a) the rocks lack the widespread high-degree metamorphism characteristic of the Archean and show no similarity with known Algonkian beds; b) no Paleozoic volcanics are known anywhere within the region; c) the rocks are intruded by Jurassic (?) plutonics having similar relations in the different areas." Gardner (1940, pp. 266-270) described the "Ord Mountain Group" of andesitic flows, tuffs, and breccia and hypabyssal intrusive rocks in somewhat greater detail, and repeated the reasons given by Hazzard, et al. for their Mesozoic age. Bowen (1954) correlates the post-Lower Permian Sidewinder metavolcanics of the southeastern Barstow quadrangle [17] with the Ord Mountain group, and concludes that they are questionably Triassic.

More precise dating and correlations of these rocks are desirable. Some of them are almost certainly Jurassic, and others may be Jurassic or Triassic. Their relations to Mesozoic metavolcanics outside the region, in the Inyo Mountains (Knopf, 1918, pp. 47-48) and in the Santa Ana Mountains (Larsen, 1948, p. 18), and to questionable or possible correlatives in the central Mojave Desert, such as the Hodge metavolcanics series [10] (Bowen, 1954), are prerequisite to an understanding of the regional geologic history.

Pre-Tertiary Intrusive Rocks

Pre-Cambrian intrusive or eruptive rocks have been specifically described from only three localities in the eastern Mojave Desert. The Fenner gneiss, a granitic augen gneiss exposed in the Piute [36] and Old Woman Mountains,[37] and at Chubbock on the Santa Fe Railway, was thought by Hazzard and Dosch (1936, p. 308) to have "—intruded Essex Series prior to metamorphism of both," and before deposition of Lower Cambrian strata. The "Algonkian" diabase sills of southern Death Valley [27] (Wright, 1952, pp. 1347-1348) have been mentioned above. Alkaline rocks, ranging from syenite to shonkinite, intrude a pre-Cambrian gneissic complex at Mountain Pass in the Ivanpah Mountains.[35] These rocks have been carefully studied (Sharp and Pray, 1952; Olson, et al., 1952) because of their association with veins and an intrusive carbonatite containing bastnaesite and other rare-earth minerals. No age assignment has been made, but recent radioactive age determinations of monazite suggest a pre-Cambrian age for the intrusive carbonatite and related alkaline rocks (D. F. Hewett, oral communication).

Paleozoic intrusive rocks apparently do not occur in the eastern Mojave Desert. In the central Mojave Desert, the presence of volcanic flows associated with Paleozoic metamorphosed sediments suggests that Paleozoic intrusive rocks are also to be expected, although none have been recognized to date.

The outstanding phase of intrusive activity evidenced in the Mojave Desert occurred in middle or late Mesozoic time, and resulted in the emplacement of enormous volumes of plutonic igneous rocks of normal calc-alkaline mineralogy. These rocks are probably more abundant in the basement complex of the central and western Mojave Desert than in the eastern part. They appear to be spatially and mineralogically related to the plutonic igneous rocks of the Sierra Nevada and Peninsular Ranges of California, and are of roughly the same age.

The most mafic Mesozoic rock examined by the writer is an almost black poikilitic perknite composed of nearly equal quantities of magnesian olivine, hypersthene, and hornblende with only about 15 percent of calcic labradorite. This rock occurs in a small patch of gabbroic rocks at the south end of the Paradise Range.[14] It grades through olivine-hypersthene-hornblende gabbro and hornblende diorite to areally more abundant biotite-hornblende quartz diorite.

These genetically related rocks are intrusive into Paleozoic metamorphic rocks, and are themselves intruded by hornblende-biotite quartz monzonite which grades into granodiorite. The latter rocks are intruded in turn by light gray biotite quartz monzonite or granite. This perknite-to-granite range of plutonic rock types, as found in the Paradise Range, encompasses all of the unaltered rock types, except dike rocks, thus far reported from the Mesozoic plutons of the Mojave Desert region.

Although it is known that the Mesozoic plutonic rocks of the Mojave Desert range in composition from nearly ultrabasic to very silicic, quantitative data on the relative abundances of the different rock types are lacking because of incomplete mapping. The author estimates, on the basis of reconnaissance observations, that leucocratic quartz monzonite or granite has an areal abundance many times greater than that of any other intrusive rock type, and that diorite and gabbro are far less abundant. The preponderance of leucocratic quartz monzonite over other rock types is reflected in the relatively large number of bodies of this rock type reported by various investigators from over the entire Mojave Desert. Examples include the Cactus granite (Vaughan, 1922, p. 363; Woodford and Harriss, 1928, p. 271; Miller, 1946, p. 472; Gardner, 1940, p. 273), Victorville quartz monzonite (Miller, 1944, p. 105), Atolia quartz monzonite (Hulin, 1925, p. 33), Teutonia quartz monzonite (Hewett, 1954), and White Tanks granite (Miller, 1946, p. 493). All of these units, and others that are unmentioned in the literature, are structurally, texturally, and mineralogically similar if not nearly identical. The significance of their similarities, and especially of their areal preponderance over the wide variety of more basic types, is worthy of careful study.

In the Lane Mountain quadrangle [15] rocks of the gabbro-quartz diorite complex are characterized by mineralogical and textural variability. Mineralogical composition varies notably, and sometimes rapidly, within individual plutons, and commonly the more silicic variants contain abundant irregular schlieren which grade into identifiable metamorphic inclusions near the pluton walls. Local gradational wall-rock contacts and evidence of replacement of wall rocks by hybrid quartz diorite, the gradations between schlieren and xenoliths, and compositional variability near contacts suggest that replacement and assimilation were important mechanisms in the development of this rock. On the other hand, alignment of platy inclusions in the plutonic rock parallel to the pluton walls, rather than to wall-rock structure, suggests viscous magmatic flow. In contrast to the diorite-quartz diorite, plutons of the leucocratic biotite quartz monzonite are characterized by textural and compositional uniformity. Inclusions are very rare except immediately adjacent to the usually knife-sharp contacts with metamorphic and igneous wall-rocks, where some of them can be seen to have been stoped by mobile homogeneous magma. Piecemeal magmatic stoping appears to have been the principal mode of emplacement of at least the peripheral parts of these plutons, some of which are of batholithic dimensions. Evidence of forceful intrusion of viscous magma is not usually seen, although local wall-rock mylonitization or crumpling at contacts with plutonic rock, and flow structures in the contiguous igneous rock, suggest that forceful intrusion occasionally played a part.

Ages of the Mesozoic Plutonic Rocks

The problem of the ages of the Mesozoic plutonic rocks of the Mojave Desert is part of the broader problem of the ages of such rocks throughout the southwestern Cordillera, including the western Great Basin, the Sierra Nevada, and the Peninsular Ranges of southern California and Baja California. Stratigraphic evidence within the Mojave Desert does not allow precise dating of the plutonic rocks. Hewett writes (1939, p. 1951) that at the eastern edge of the region "Mesozoic sedimentary rocks, culminating in Upper Jurassic sandstone, attain 8000 feet" in thickness and are involved in major thrust faulting. "An extensive sill of quartz monzonite, intruded on a major thrust fault,—" indicates that quartz monzonite was emplaced following diastrophism that involved Jurassic Aztec sandstone, and that the intrusive rock is therefore Upper Jurassic or younger. The exact age of the diastrophism that preceded intrusion is not known.

Comparable thrust faults and associated features, apparently in the same structural belt, were formed between late Jurassic and early Tertiary times in the Muddy Mountains, Nevada (Longwell, 1949, p. 965). Longwell has cited evidence which indicates that at least two phases of diastrophism were responsible for these structures, one in late Jurassic or pre-Bear River Cretaceous time, the other in Upper Cretaceous or Tertiary time. Probably we do not have sufficient stratigraphic data to decide whether the pre-intrusive thrust faults and associated structures of the eastern Mojave Desert were formed during either of the diastrophic phases dated in the Muddy Mountains. Therefore, the intrusive rocks themselves cannot be dated, on stratigraphic evidence, more closely than late Jurassic to early Tertiary, although they are most probably Mesozoic.

In the central Mojave Desert probable Triassic or Jurassic metavolcanic rocks are intruded by plutonic igneous rocks that are therefore late Mesozoic or Tertiary in age. The plutonic rocks of the western Mojave Desert, south of the Garlock fault, cannot be dated even this closely.

The discovery of radioactive minerals in plutonic rocks at several localities in the southeastern and central Mojave Desert gives hope that radioactive age determinations will provide additional and possibly more satisfactory bases for dating the intrusive rocks. Hewett reports (oral communication, 1953) that betafite from a granitic pegmatite in the Cady Mountains [22] has been determined to indicate a Jurassic age.

TERTIARY AND QUATERNARY IGNEOUS ROCKS

General Statement

Lavas, pyroclastic rocks, and hypabyssal intrusive rocks are areally important constituents among the Tertiary and Quaternary formations of the Mojave Desert. These rocks range in composition from basalt to rhyolite, and in age from middle Miocene, or perhaps older, to practically Recent. However, the petrologic and stratigraphic relations of many, perhaps even most, of these rocks are unstudied. The following problems of the Tertiary igneous rocks are discussed here: 1) distribution of volcanic rocks in space and time; 2) compositional variations; 3) hypabyssal intrusives; 4) volcanism and ore deposits.

Distribution of Volcanic Rocks

Tertiary volcanic rocks occur in discontinuous patches and strips over much of the Mojave Desert, from the southwestern corner of the region to, and beyond, its eastern edge. In the western Antelope Valley,[1] the westernmost portion of the region, Wiese and Fine (1950, p. 1644) describe about 5000 feet of andesitic lavas resting on granite 7 miles east of Quail Lake. These rocks reportedly grade upward into continental clastic sediments that may be equivalent to marine Miocene sediments that also rest on volcanic rocks farther west. Tertiary deposition in the westernmost Mojave Desert thus began with accumulation of a thick section of Miocene, or older, andesites.

In the Calico Mountains [16] of the central Mojave Desert, as much as 7000 feet of crudely stratified andesitic and dacitic tuff, tuff breccias, and agglomerate, interbedded with a few flows, is overlain by middle and upper Miocene lacustrine and fluviatile deposits with some interbedded tuffs and andesitic lavas. All these rocks are overlain unconformably by Pliocene (?) andesite, dacite, and latite flows. Farther west, in the vicinity of Black Mountain [12] north of Hinkley, Pleistocene (?) olivine basalt rests unconformably on the older Tertiary rocks (Baker, 1911, p. 366), and 30 miles southeast, near Ludlow, the practically uneroded Pisgah crater [21] is associated with a nearly Recent basalt flow. Thus, in one part of the central Mojave Desert, the rocks record a history of volcanism beginning at some time during or before the middle Miocene and continuing intermittently through late middle Miocene, upper Miocene, probably late Pliocene, and Pleistocene, into practically historic time.

In the El Paso Range,[3] at the northern edge of the western Mojave Desert, andesite breccia occurs near the base of the terrestrial lower Pliocene sedimentary section, and five lenticular flows of olivine basalt occur higher in the same lower Pliocene section, which is unconformably overlain by Pleistocene (?) basalt (Dibblee, 1952). Hulin (1925) identifies the last-named rock as augite-hornblende basalt, which is younger than the Pliocene (?) Red Mountain andesite of the Randsburg District.[4] Faunal evidence of a post-middle Pliocene age for the Red Mountain andesite has been discovered by paleontologists of the U. S. Geological Survey (D. F. Hewett, oral communication, 1953) in the Lava Mountains,[5] near the northeastern edge of the Randsburg quadrangle.

Numerous other occurrences of volcanic rocks in the Mojave Desert have been described by Hulin (1925, pp. 48-52), Hershey (1902), Simpson (1934), and Gardner (1940), but these rocks are so inadequately dated that discussion of their relations to the rocks already described is not worthwhile. However, these occurrences serve to indicate that, far from being restricted to a few parts of the region, Tertiary and Quaternary volcanic rocks are widespread over the entire Mojave Desert, and work on the task of differentiating and dating the numerous more or less separate episodes of volcanism has only begun.

Compositional Variations

Many factors, such as inadequate knowledge of the distribution of the volcanic rocks in space and time, absence of extensive petrographic descriptions of those rocks whose stratigraphic positions are known, and complete lack of chemical analyses, make it difficult to discuss compositional variations at this time. Existing data, however, suggest that there are no obvious simple trends of compositional change. Because of current advances in our knowledge of the Tertiary stratigraphy, largely the result of work by members of the U. S. Geological Survey, the problems of compositional variations of volcanic rocks extruded or intruded at different intervals during a considerable period of geologic time in this relatively large province are becoming more and more susceptible to careful systematic study.

Problems of the Hypabyssal Intrusives

Hypabyssal dikes, sills, and plugs, composed of holocrystalline to hemicrystalline basalt, andesite, dacite, latite, and rhyolite of Tertiary age, have been recognized in several parts of the Mojave Desert, particularly in the Randsburg District [4] (Hulin, 1925) and, by the author, in and near the Calico Mountains.[16] In the latter area these intrusive masses range in size from tabular dikes and sills only a few feet thick up to roughly circular plugs as much as 4000 feet across. The plugs intrude rocks of the basement complex, as well as folded stratified Tertiary volcanic, pyroclastic, and sedimentary rocks. Most are roughly circular or elliptical in plan, cut discordantly across the structures of the wall rocks, and have contacts that dip very steeply outward or steeply to gently inward. Funnel-shaped cross sections are fairly typical, and, in the larger discordant plugs, evidence of more than local wall-rock deformation is lacking. Flow layering is generally present in the intrusive rock, and near the contacts is conformable with the contacts. Wall-rock inclusions, especially of Tertiary rocks, are rare, and alteration of the wall rocks usually consists of local silicification around the periphery. The mode of emplacement of the larger hypabyssal intrusive bodies appears to have been by forceful intrusion to a limited degree, and mainly by intrusion into funnel-shaped near-surface openings that were probably formed by explosive widening of the shallower portions of the magma channels.

Tertiary Volcanism and Mineral Deposits

The principal production from the rich silver and gold mines of the Randsburg district,[4] the Calico Mountains,[16] and the area around Soledad Mountain [2] south of Mojave has been from epithermal veins and mineralized zones associated with certain of the Tertiary intrusive rocks. Hulin's (1925) account of the geology and ore deposits of the Randsburg quadrangle contains the only published detailed descriptions of the mineralogy, occurrence, and paragenesis of ore deposits of this kind (see also Gardner, Contribution 6, Chapter VIII).

Deposits of borate minerals occur in Tertiary sedimentary rocks at several localities in the Mojave Desert (see Mumford, Contribution 2, Chapter VIII). The colemanite deposits of the Calico Mountains [16] yielded a major share of California's borate production between 1884 and 1907, and the mines of the Pacific Coast Borax Company at Kramer [6] are currently providing most of California's production of this valuable resource. The possible relation between borate deposits and volcanism, either actual eruptions of lava or fumarolic activity, has been pointed out by Gale (1926, pp. 449-450).

The most recent descriptions of the several commercially important strontium deposits of the Mojave Desert are those of Durrell (1953), who concludes that the strontianite and celestite are usually genetically related to Tertiary volcanism.

Certain other mineral deposits of minor economic importance, such as bentonitic clays derived from Tertiary tuffs, and pumice for use in lightweight-concrete aggregate, obviously owe their origin also to Tertiary volcanic activity.

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