6. CONTACT METAMORPHISM IN SOUTHERN CALIFORNIA*

By Ian Campbell †

General Features. A highly condensed introduction to "Contact metamorphism in southern California" is obviously not the place in which to indulge in semantic niceties nor to engage in terminological tussles, and thus the title is not intended to reflect a carefully delimited concept. Instead it is freely admitted that in some of the examples to be cited, such terms as "contact metasomatic," "pyrometasomatic," "optalic" or "thermal metamorphic," "hydrothermal," "pneumatolytic," and even "injection metamorphism" might be more precisely appropriate. Suffice it to say that "contact metamorphism" will be herein employed in its broader connotations.

There is an old adage which states that "it takes two to make a quarrel." Likewise, it takes two (rocks) to make a contact, and unless one of these rocks was at one time pretty hot, preferably indeed in the magmatic state, there is likely to be no contact metamorphism as such. With the concept of contact metamorphism thus reduced to these two essentials, an invaded rock and an invading magma, let us survey the southern California field.

In terms of rocks available for invasion, southern California presents a wide range: in age, from pre-Cambrian to Recent; and, in type, encompassing sandstones, shales, cherts, limestones, dolomites, graywackes, pyroclastics, conglomerates, the regionally metamorphosed equivalents of these rocks, and a considerable variety of igneous rocks. Details concerning "country rock" types will be found elsewhere in this volume.

The invading magmas likewise involve wide spans of time and of type. In the early pre-Cambrian ("Archean" of some writers) terranes, plutonic intrusives, largely granitic, have been recorded principally from the southeastern parts of the State. In the later pre-Cambrian ("Algonkian" of some writers), intrusive activity seems to have been largely confined to injection of diabasic sills, also in the southeastern parts of the State. The Paleozoic record is very fragmentary, but gives the impression that this era, if not wholly devoid of igneous activity, at least did not involve any very significant effects of such. The Triassic was a period of considerable volcanism, manifested more in the pyroclastic record than in other ways, and involving chiefly andesitic types. Then, probably in Upper Cretaceous time,‡ came the invasion of the southern California batholith (Larsen, 1948) and its correlatives, e.g. the Cactus granite (Vaughan, 1922), some of which are found far to the east. In this, as in other major plutonic sequences throughout the State, rocks ranging from norite and gabbro through diorite, tonalite, granodiorite, and quartz monzonite (adamellite) to granite and alaskite are represented, with the sequence in most instances proceeding from the more mafic toward the more felsic types. Hewett (1948) has recognized late Laramide granitic intrusives in the southeastern portion of the State, and as dating methods improve, other occurrences may be assigned to this period, and to periods not now included in the record of igneous activity.

In Cenozoic time there was abundant igneous activity in southern California, but probably not until erosion has provided us with much deeper exposures will evidence of plutonic phases be found. Cenozoic activity is manifested chiefly in widespread volcanic phenomena, with basaltic, intermediate, and rhyolitic magmas involved. Even within the Quaternary there is a widespread record of both basaltic and rhyolitic effusions, as, for example, in Mono County (Putnam, 1938). Throughout the time scale, the great bulk of igneous activity has been confined to what are sometimes classed as the "calc-alkaline rocks." Ultramafic types are few and far between (these are much more abundant in northern California), and alkaline types are almost non-existent save for some relatively minor intrusions of nepheline syenite and associated types in the northern Panamint Range (McAllister, 1952), and the shonkinite recently recognized (Sharp and Pray, 1952) in connection with the bastnaesite deposits of the Mountain Pass area in San Bernardino County (see also Olson and Pray, Contribution 3, Chapter VIII).

In view of the diversity of both invaded and invading types, it might be anticipated that southern California would exhibit contact metamorphic types whose number would approximate the number of invaded types multiplied by the number of invading types. That no such tremendous number of metamorphic types actually exists might be explained in two ways. First, if we assume that metamorphism is purely thermal, then it matters little what the composition of the intrusive is; results will be a function only of its temperature, and of the physics and chemistry of the intruded rock. Second—and this

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‡ The dating of the "batholith of southern California" presents a problem not as yet fully solved. The intrusives of the Sierra Nevada to the north, with which the southern California batholith has been correlated by some investigators, have been rather closely dated by Hinds (1934) as probably late Jurassic. On the other hand, the intrusives of the Sierra San Pedro Martir in Baja California, with which the southern California batholith might better be correlated, have been shown by Woodford and Harriss (1938) to be Upper Cretaceous in age (see also Larsen, Contribution 3, this chapter).

is doubtless the commoner case—if we assume that thermal effects are in part transmitted and augmented by emanations associated with the intrusive, the major components of these emanations are likely to be such end-stage concentrates as H_2O and SiO_2, regardless of whether these stem from a gabbroic or a granitic magma. Thus with respect to the best known sequence in this region, that of the southern California batholith, Larsen (1948, p. 36) comments, "Both the thermal and hydrothermal contact metamorphism around the tonalite, gabbro, and peridotite are much alike, and they are similar to the metamorphism commonly found around granite and granodiorite."

In general it can be said that contact metamorphism is most extensively developed around granitic (granodiorite, quartz monzonite, and granite) intrusives of Mesozoic age. Earlier intrusives commonly invaded rocks that already had been regionally metamorphosed, and therefore were less likely to display effects of contact metamorphism. And contact metamorphism is most extensively developed in pelitic and impure calcareous country rocks, whereas arenites, meta-arenites, pure marbles, igneous rocks, and metamorphic rocks commonly show little or no contact effects other than local recrystallization.

Despite these simplifying considerations that are involved in this picture of contact metamorphism, southern California does not lack for a notable range of contact metamorphic types. Varieties are found that range from spotted (cordierite) slates (Hoots, 1931) that may be classed in the green schist facies, to diopside-plagioclase rocks (Durrell, 1940) that manifestly represent the intense conditions of metamorphism of the pyroxene-hornfels facies. Sillimanite schists (for example, Merriam, 1946) are widespread high-rank types in the region, although by no means all of the sillimanite can be ascribed to contact metamorphism.

The greater part of the contact metamorphism to be found in southern California appears mainly to confirm principles and examples already well documented from many other parts of the world, although some of the examples are particularly well exposed, either because of king-size road cuts or because of scanty desert vegetation. But California prides itself on providing superlatives and uniqueness! Granting that the majority of the contact metamorphic rocks display nothing out of the ordinary, there are nevertheless instances to which special attention might be called. The remaining discussion will cite briefly a number of such instances, several of which receive more extended discussion elsewhere in this volume.

Examples of Contact Metamorphism. Evidence of a superlative thermal punch packed by some California magmas is provided by a granodiorite locally vitrified by intrusion of a Pleistocene (?) basalt, near Bishop (Knopf, 1938). Here tridymite is found in a low-index glass formed by the melting down of quartz and alkali feldspar. And from near Carlsbad, in San Diego County, Larsen and Switzer (1939) record a large (40 by 50 feet) inclusion of tonalite that has been nearly half melted down to glass of rhyolitic composition by an intrusive plug of andesitic lava (figs. 1, 2). But the highest thermal effects undoubtedly are those represented by sand fulgurites near Indio, for which Rogers (1946) estimated temperatures of around 1800°C. Within the writer's broadly stated conception, the conversion, in these fulgurites, of quartz to lechatelierite and cristobalite, accompanied by fusion of biotite and of feldspar, is certainly contact (thermal) metamorphism, although admittedly of a very special (non-magmatic) type!

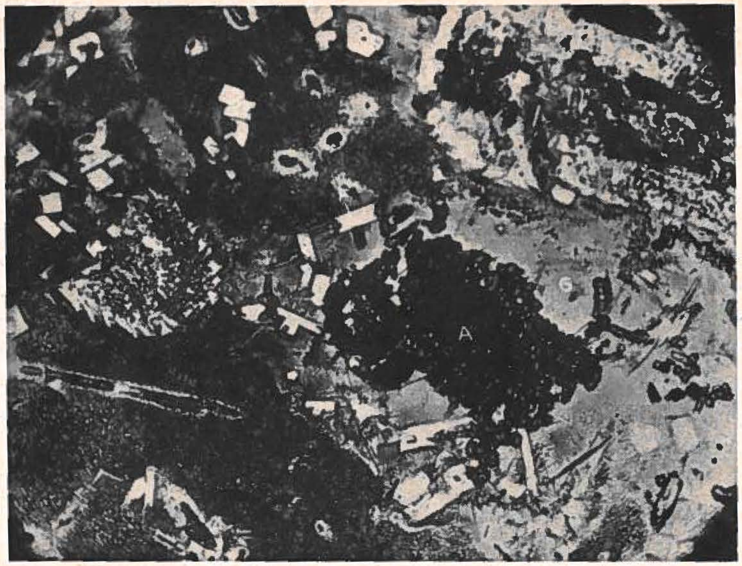

FIGURE 1. Fused inclusion, Calaveras quarry, San Diego County. Hornblende phenocryst altered to augite (A), glass (G) with swallow tail feldspar (F) phenocrysts. *Reproduced from Larsen and Switzer (1939), courtesy American Journal of Science.*

Other indications of thermal punch are less dramatic, but deserve mention. Sillimanite, considered by many as an index mineral of maximum metamorphic intensities, has been recorded from a number of widely separated localities (Murdoch and Webb, 1948, p. 273). Much of it may well be the result of regional metamorphism, but some is to be attributed to contact metamorphism. A much more unique indicator of the attainment of an advanced stage of meta-

FIGURE 2. Fused inclusion, Calaveras quarry, San Diego County. Partially melted feldspar (F), showing manner in which solution progressed along cleavage directions. Glass (G) and quartz (Q). *Reproduced from Larsen and Switzer (1939), courtesy American Journal of Science.*

morphism is the mineral merwinite, which is present at Crestmore.* In the well-known Bowen (1940) series of 10 mineral indicators of progressive metamorphism of siliceous dolomites, merwinite stands ninth, with only larnite above it. If, as is now generally done, rankinite is added as an eleventh member of this list, merwinite is still only two from the top, and thus places the rock in which it occurs with the pyroxene-hornfels facies. Monticellite, lower (sixth) in the Bowen table, still represents an intensity stage of contact metamorphism not commonly reached. It is present at Crestmore, and also is found in the Ivanpah area (Schaller, 1935) far to the east. Predazzite, a rock representing the periclase stage of contact metamorphism, is somewhat of a rarity in the United States, but it has been reported (Rogers, 1918 and 1929; Woodford, et al., 1941) from three quarries in the vicinity of Riverside (City quarry, Crestmore quarry, and Jensen quarry), and from Lucerne Valley (Campbell, 1950).

Not only have southern California magmas carried, at times, exceptionally high thermal energy, but they have invaded rock types not commonly found in contact zones. For example, Miocene cherts and other high-silica beds of the Monterey formation in the Palos Verdes Hills develop, according to Bramlette (1946), narrow contact zones adjacent to dikes and sills of basalt. These zones are characterized by an increase in chalcedonic silica and by formation of ankerite. Durrell (1940) cites progressive recrystallization and sutured boundaries of quartz as the major effects where meta-cherts are present within contact zones of the southern Sierra Nevada intrusives. It is of interest to note, by way of providing a measure of the intensity factor, that sillimanite is locally formed in these meta-cherts.

Gypsum provides further evidence that monomineralic rocks seldom are greatly affected by contact metamorphism. In the Palen Mountains, Hoppin (quoted in Ver Planck, 1951) has mapped thick gypsum beds and associated sediments of uncertain but possibly Paleozoic age. These have been intruded by Jura-Cretaceous (?) quartz diorite, with resultant development of garnet skarns in the lime-silicate formation, but apparently with no recognizable effects on the gypsum. Hoppin does postulate that dehydration to anhydrite might have resulted, but that subsequent approach to the surface and to the zone of ground-water circulation may have rehydrated the formation to its earlier composition. Progressive effects of emanations from a quartz-diorite upon serpentine in the southern Sierra Nevada have been recognized by Macdonald (1941) as characterized by successive development of talc, talc and actinolite, actinolite, chlorite, and biotite.

One of the most unusual of southern California's contact metamorphic deposits is the andalusite mass in the northern Inyo Mountains, which for many years furnished ore for the Champion Spark Plug Company. Whether this notable concentration of highly aluminous minerals developed because of unusual composition of the country rock, or because of other factors, it is impossible now to say. Extensive alteration has so obscured the relationships as to leave certain important elements of the geology in doubt. Knopf (1917), who first called attention to the occurrence, postulated pneumatolytic metamorphism of a volcanic porphyry subsequent upon granitic intrusions. Kerr (1932) suggested that the host rock may have been an aluminous volcanic type, or possibly an aluminous sediment intercalated in a succession of trachytic flows, now largely schists, and that the metamorphism responsible for development of the andalusite was associated with intrusion of a porphyry of trachytic composition.

* To what extent Crestmore, the most remarkable of all of California's mineral deposits in terms of number and rarity of mineral species, owes its exceptional features to contact metamorphism and to what extent these are to be attributed to more strictly hydrothermal effects, is discussed elsewhere in this chapter (Burnham, Contribution 7). Let it suffice to point out here that the bulk of the marmorization and of the lime-silicate zones at Crestmore are certainly contact metamorphic in origin; the rare, minor, and in part hydrous constituents (e.g., custerite, hillebrandite) are very probably of later, but related, hydrothermal development.

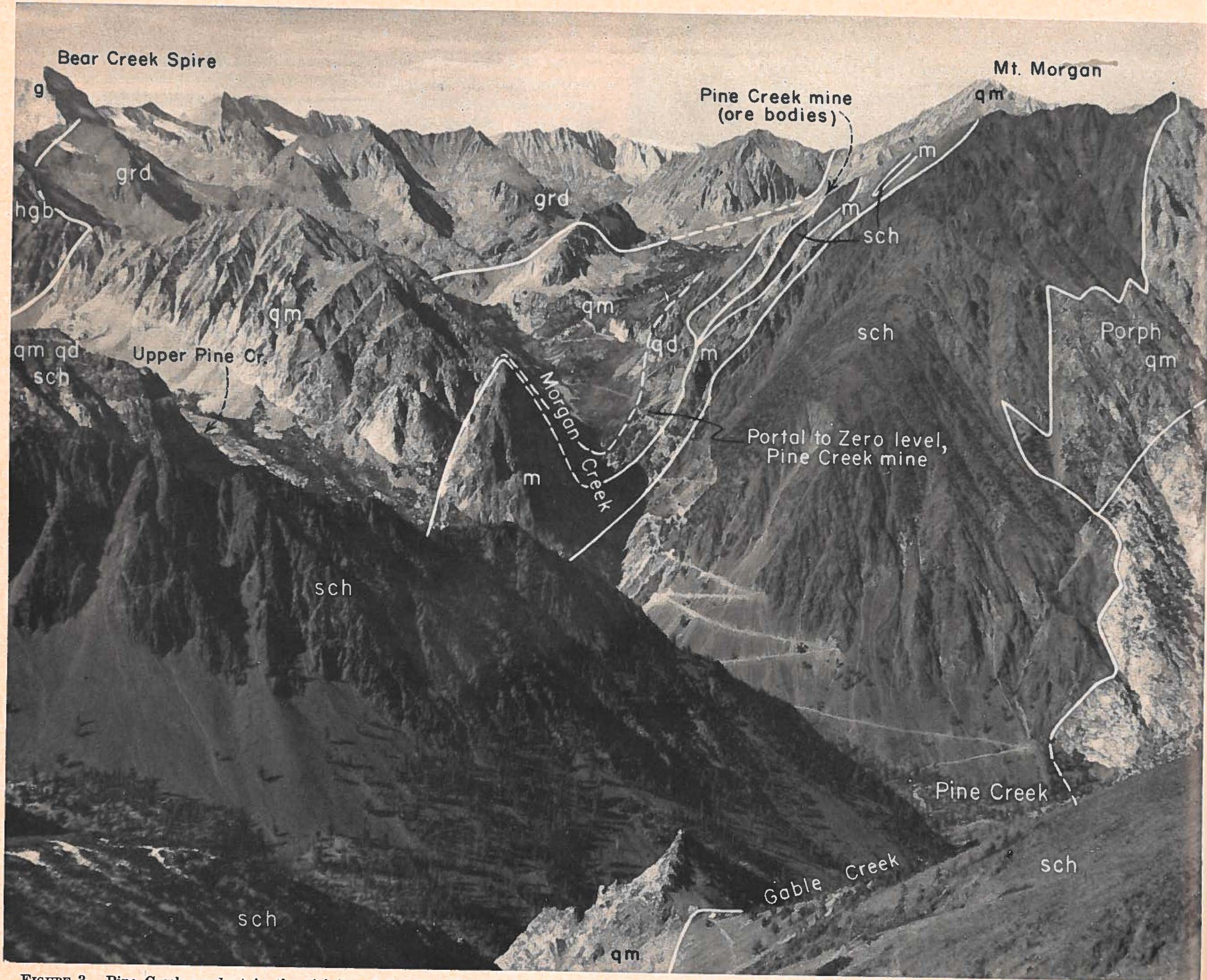

FIGURE 3. Pine Creek pendant in the vicinity of the Pine Creek mine of U. S. Vanadium Company, Inyo County. g, Orthoclase-albite granite; grd, granodiorite; hgb, hornblende gabbro; porph qm, quartz monzonite with large phenocrysts of orthoclase (probably correlative with Cathedral Peak granite of Yosemite Park); qd, mafic quartz diorite; qm, quartz monzonite; sch, schistose quartz rock; m, marble. *Photo and geology by Dwight Lemmon and Paul Bateman, U. S. Geological Survey.*

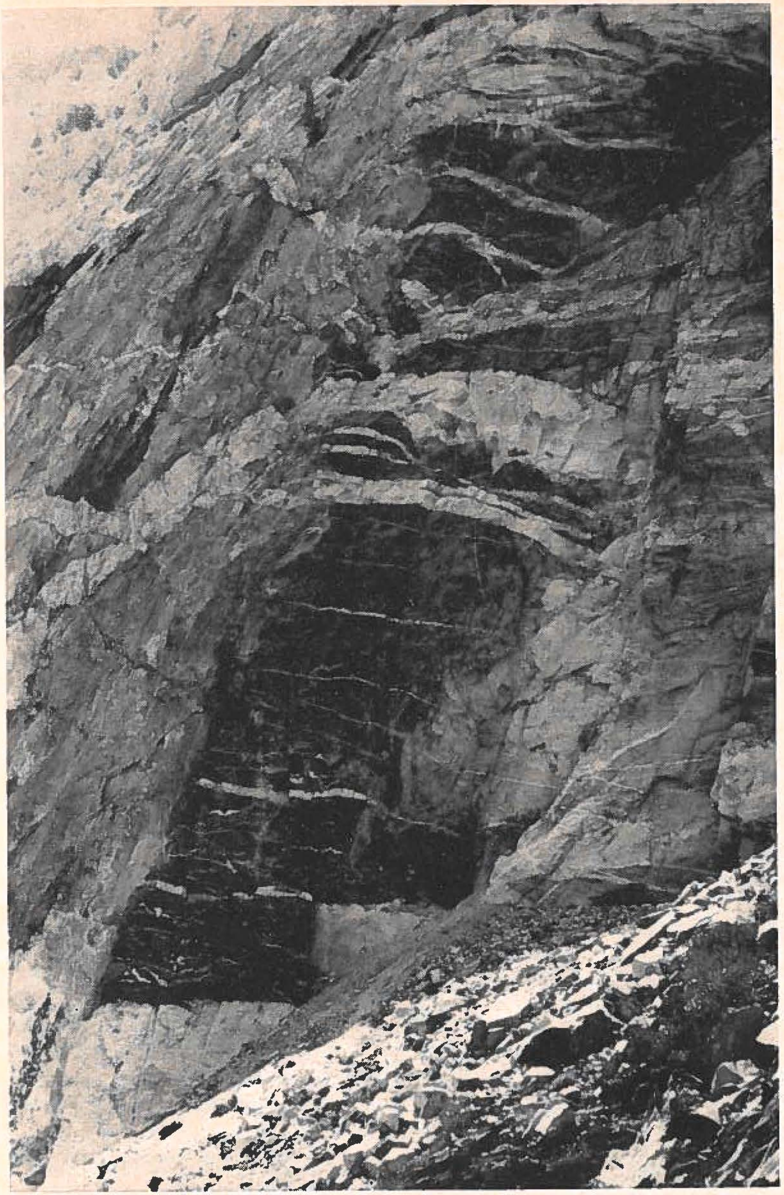

FIGURE 4. Tactite zone in cliff face (face showing is about 150 feet high) at Brownstone tungsten mine, Pine Creek Canyon, Inyo County. The dark material is garnet-pyroxene tactite. It is bounded on the right by quartz monzonite, and on the left by marble. All these are cut by gently dipping felsite dikes (lightest gray). *Photo courtesy Paul C. Bateman, U. S. Geological Survey.*

Later, Lemmon (1937) indicated that the andalusite occurs in a pre-Cambrian metaquartzite, and is a result of intrusion of late Jurassic granitic rocks associated with the Inyo batholith. At any rate, there is general agreement that the andalusite deposit resulted from igneous invasion, but whether large or small amounts of aluminum were supplied by the intrusive cannot be determined in advance of final decision as to the original composition of the host rock. The first stages of metamorphism are characterized principally by the development of corundum and andalusite. Later, and more particularly, hydrothermal stages resulted in formation of diaspore, pyrophyllite, muscovite, alunite, lazulite, and such rare minerals as augellite and woodhouseite.

Emanations are almost invariably involved in contact metamorphism, and it is from these that some of the State's most important economic mineral deposits have resulted. Certainly no summary of contact metamorphism in southern California would be complete without reference to the scheelite-bearing tactites (fig. 3) that through two world wars have yielded a very large share of our domestic output of tungsten. Economic and scientific interest first focussed upon these deposits during World War I, and in 1922 Hess and Larsen pointed out that the vast majority of them are present in the Great Basin region of California and Nevada, and that they are most commonly found in limestone country rocks associated with quartzose intrusives. Many early studies of these deposits have shown that their broad relationships are remarkably consistent, and this generalization has been confirmed by extensive and detailed mapping of tungsten deposits during the period of World War II.

In a typical contact-metamorphic deposit of scheelite, the zone immediately adjacent to and extending outward from the intrusive contact—in some places for tens, in others for hundreds, of feet—is the "tactite zone". It is commonly distinguished by colors darker than those of the adjoining rocks, and is characterized by development of such minerals as garnet, diopside, epidote, and idocrase. Scheelite ordinarily is most abundant in this zone, but is by no means confined to it. Molybdenite not uncommonly accompanies the scheelite, and pyrite, chalcopyrite, and magnetite are common and locally abundant accessories. The borders of the tactite zone are characteristically though not invariably sharp (fig. 4). The shapes of tactite bodies are notoriously irregular, and this irregularity has led to many difficulties in the economic and engineering development of these deposits.

Beyond the tactite zone, as traced away from the intrusive rock, is the "zone of light-colored silicates," which is characterized by such minerals as wollastonite and tremolite, and in rare instances by scheelite in commercial concentrations. This zone in turn passes

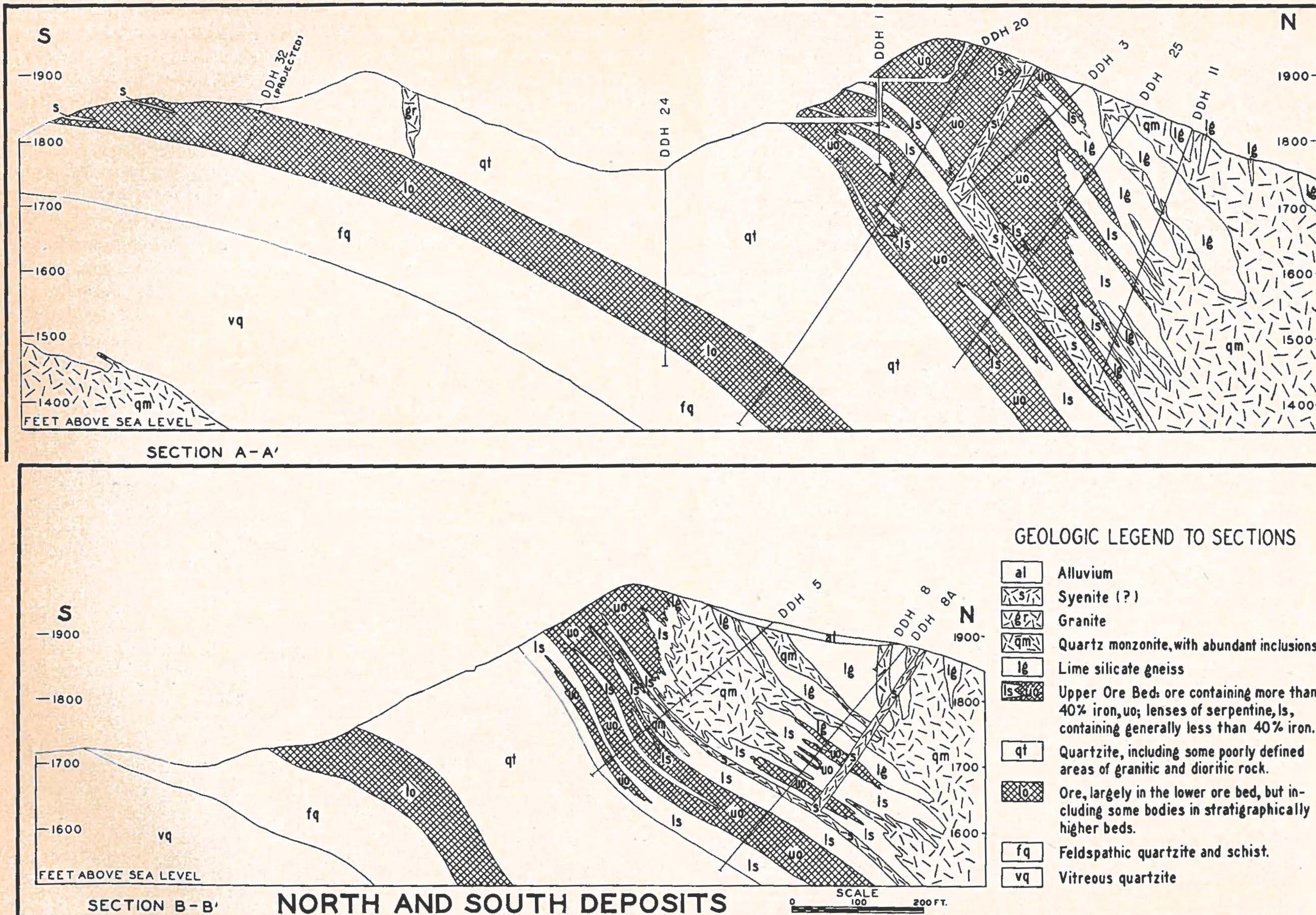

FIGURE 5. Structure sections, showing the relationships of iron-ore bodies in the Eagle Mountains, Riverside County. Both the upper and lower bodies are shown in a single pattern, and all intrusive rocks are likewise shown in a single pattern. *Modified from Hadley, 1945.*

gradually outward into a marmorized zone, characterized by an absence of additive minerals, and in which the only contact effect is recrystallization of the calcite. This zonal pattern, with variations, is found in many parts of southern California, although the major deposits * occur within the area underlain by the Sierra Nevada batholith. As more or less typical of the many occurrences that have been described, may be cited the Round Valley deposit (Chapman, 1937) and the Pine Creek deposit (Lemmon, 1941). The extensive literature on this subject has been summarized by Kerr (1946). (See also Bateman and Irwin, Contribution 4, Chapter VIII).

The iron deposits of southern California are more abundant and are even more impressive as examples of bulk metasomatism on a large scale. Although some of them had been studied and described more than 40 years ago (Harder, 1912), it was not until World War II that any of the iron deposits were brought into commercial production. Extensive mapping and drilling in several areas have disclosed reserves totalling more than 50 million tons of iron ore, the bulk of which is attributable to contact metamorphism and to hydrothermal activity closely associated therewith. Descriptions of the most significant deposits have been brought together in Bulletin 129 of the California State Division of Mines (1948).

In general the chief minerals of these iron deposits are magnetite and hematite, with some maghemite, and they occur at or close to contacts between granitic (tonalite, quartz monzonite, etc.) intrusives and calcareous country rock. At the Eagle Mountains deposit (Hadley, 1948), much the largest of this group, an early thermal phase of metamorphism produced such minerals as diopside, actinolite, grossularite, wollastonite, scapolite, and labradorite. These are found chiefly in the more impure calcareous beds, and metamorphism of the purer dolomite appears to have resulted mainly in recrystallization. A later, and more distinctly hydrothermal phase of metamorphism led first to formation of tremolite in the dolomite, and then to serpentinization, and to deposition of the iron ores. Although most extensively developed in the calcareous country rock, iron ores are present in silicated zones and even in quartzite (fig. 5).

Minuscule as compared to the iron deposits in terms of tonnage, and yet of sufficient scientific interest to deserve mention here, are the cassiterite-bearing contact-metamorphic deposits in the vicinity of Gorman (Wiese and Page, 1946). Here Paleozoic sediments have been invaded by intrusive rocks of late Mesozoic age, with attendant development of lime-silicate hornfelses, especially in inclusions that lie within the igneous rocks. Cassiterite, regarded as a rather uncommon constituent of contact zones (Lindgren, 1933, p. 727), was obtained commercially from these deposits to the extent of a few tons during World War II. It occurs at or very close to the margins of granitic contacts against the limestone.

Contact action involving magnesium metasomatism is by no means common, and yet some striking illustrations of this are to be found in southern California, particularly in the southern Death Valley-Kingston Range area. Here Wright (1952) has pointed out the remarkably close control of talc formation by (1) the host rock—carbonate strata in the basal portion of the Crystal Spring formation of the late pre-Cambrian Pahrump series—to which all of these deposits are confined, and by (2) the juxtaposition of a thick diabase sill to which the metamorphism and metasomatism are ascribed. Throughout an area of more than 1,000 square miles, talc can be found in nearly all places where a contact between these two rocks is exposed; at several such localities, important commercial concentrations occur (fig. 6). It is interesting to note that there is a direct correlation between the thickness of the diabase intrusive, which ranges from 200 feet to as much as 600 feet, and the size of the silicated zone in which talc and tremolite are the principal

FIGURE 6. Body of talc-tremolite rock at contact between diabase and dolomite, all in the pre-Cambrian Crystal Spring formation. Acme talc mine, San Bernardino County. *Photo courtesy Lauren A. Wright, California Division of Mines.*

* To avoid possible confusion of types, it perhaps should be pointed out that the important scheelite deposits at Atolia and at Darwin are more properly to be classed as hydrothermal vein types, rather than as contact-metamorphic deposits.

minerals. The history of the alteration starts with a veining of the original carbonate rock by tremolite, alkali feldspar, serpentine, and talc. This is followed by a corrosion and veining of tremolite by serpentine and talc, and next comes a rimming and veining of serpentine grains by talc. Finally, the tremolite is corroded by carbonate, and all of the other minerals are transected by carbonate veinlets. The replacements seem to have taken place on a volume-for-volume basis.

Should the Kramer borate deposits be included among examples of contact metamorphism? If so, they should be referred to as being economically, if not also mineralogically, the most famous of California's contact-metamorphic deposits, and they may thus provide a fitting conclusion to this brief paper. Even the most recent discussions (Connell, 1949) of the origin of the million-odd tons of the unique mineral kernite indicate that there is not yet any generally accepted hypothesis. All who compare the composition of the much commoner and better understood mineral borax ($Na_2B_4O_7 \cdot 10H_2O$) with that of kernite ($Na_2B_4O_7 \cdot 4H_2O$) are struck by the probability that at some stage in the paragenesis, borax has been partially dehydrated to yield kernite (see Mumford, Contribution 2, Chapter VIII).

Schaller (1930), assuming that the basalt known to underlie the deposits might be intrusive, suggested that the thermal action of such an igneous rock upon already accumulated borax would account for the kernite. In this case, we have a relatively simple (albeit unique in terms of its product) example of thermal metamorphism. But the work of Gale (1946), based upon a study of much more extensive underground exposures than were available to Schaller, seems to indicate that the underlying basalt was extrusive, and that the borax beds that overlie it are therefore younger. Nevertheless, Gale suggests that the basalt was still giving off heat at the time when borax-laden lake waters accumulated above it, and that this thermal effect aided in the precipitation of borax and possibly also in its partial dehydration to kernite. That some volcanic phenomena still were active in the vicinity after accumulation of the borax is attested by small amounts of realgar and orpiment found in the deposits.

If, as has been suggested, the basalt did contribute to the thermal metamorphism of the borax, the situation is truly unique. In all other known examples of contact metamorphism, the metamorphosed rock was in place at the time of the igneous invasion. Thus spatially, as well as thermally, the igneous rock plays the dynamic role; the country rock, the passive role. But at Kramer, it might be conjectured that the igneous rock was *in situ* and that subsequently the country rock moved, by means of sedimentary accumulation, into position for its metamorphism. However fantastic such speculation may be adjudged, it is fair to conclude that such an extensive deposit of such a unique mineral as kernite may well deserve a unique explanation!

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FIGURE 7. View southward of talc-bearing zone in Warm Spring Canyon, southeastern Panamint Range, Inyo County, California. The talc is an alteration of siliceous carbonate strata and has formed along the upper margin of a diabase sill. Another diabase sill forms the skyline, but shows very little contact metamorphism. All of these rocks are part of the Crystal Spring formation of later pre-Cambrian age. *Photo by Lauren A. Wright.*

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