PROGRESSIVE METASOMATISM OF SERPENTINE IN THE SIERRA NEVADA OF CALIFORNIA

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ABSTRACT

Nodules of serpentine enclosed in mica schist close to a body of intrusive quartz diorite have been altered by igneous emanations. Cores of residual serpentine are surrounded by successive envelopes of talc, talc and actinolite, actinolite, chlorite, and biotite. In some, veinlets of biotite transect the entire nodule. Chemical and micrographic analyses indicate that the changes involved the loss of magnesia from the nodules, the addition of silica in the inner zones, and the addition of small amounts of other oxides in the outer zones. The process of alteration resembled that often designated as granitization, but because of the extremely mafic composition of the original rock, the products have no similarity to a granitic rock.

INTRODUCTION

In the northwestern part of the Dinuba quadrangle, in the western foothills of the Sierra Nevada between the Kings and the San Joaquin rivers, California, serpentine nodules enclosed in mica schist have been altered by emanations from an adjacent body of quartz diorite with resultant formation of a group of new minerals arranged concentrically about residuals of the original rock. Typically, a core of serpentine is surrounded by talc, which passes outward into a zone of admixed talc and actinolite, and finally into a zone of nearly pure actinolite. The actinolite in turn is surrounded by a rim of biotite, and the whole is embedded in a matrix of biotite schist. The occurrence is closely similar to others on the island of Unst in the Shetland Islands, described by H. H. Read.[1]

The nodules are exposed for only a few tens of feet in a road-cut just west of the store at Humphreys, in section 22, T 11 S, R 23 E, Mount Diablo Base and Meridian. They were discovered by Professor Howel Williams and a class in field geology from the University of California, and have been studied by the writer in connection with an investigation of the geology of the surrounding region. At the time the locality was first visited by the writer, the surface of the cut was heavily masked by soil and debris from the bank above, but violent rains during the spring of 1938 washed away much of the concealing soil and exposed the bedrock. Succeeding collecting expeditions by classes from the University of California have nearly exhausted the locality.[2]

The writer wishes to thank Dr. Howel Williams of the University of California, and Dr. Cordell Durrell of the University of California at Los Angeles, both of whom read and criticized the manuscript of this paper, and Mr. James Y. Nitta, who prepared the illustrations.

[1] Read, H. H., On zoned associations of antigorite, talc, actinolite, chlorite, and biotite in Unst, Shetland Islands: *Min. Mag.*, **23**, 519–540 (1934).

[2] Williams, H., personal communication, May 1940.

Geologic Setting

The Bedrock Complex of the western Sierra Nevada in the vicinity of the Kings and San Joaquin rivers consists of a series of metamorphosed sedimentary and volcanic rocks intruded by the granitic rocks of the

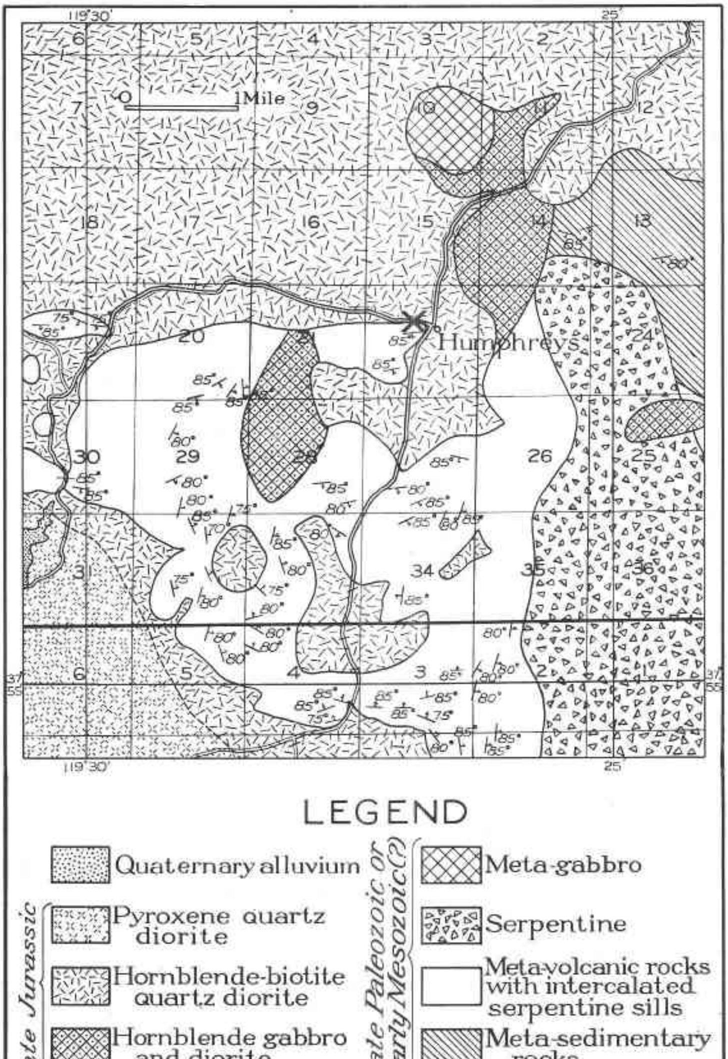

Fig. 1. Geologic map of the northwestern part of the Dinuba quadrangle, Calif.

Sierra Nevada composite batholith. The sediments and volcanic rocks were accumulated probably during late Paleozoic and early Mesozoic time in the sinking Sierra Nevada geosyncline, and during the geosynclinal period they were intruded by numerous sills of serpentine. These serpentine bodies have undergone the same degree and type of metamorphism as the enclosing rocks.[3] Accompanying the intrusion of the Sierra Nevada batholith there was widespread granitization along contacts, resulting in the production of extensive areas of injection gneisses, as well as other more local effects. The alteration of serpentine described herein is merely one local result of this widespread granitization.

The accompanying map (Fig. 1) shows the position of the zoned nodule locality in relation to the general geology of the surrounding region. The serpentine body from which the nodules were derived is a narrow sill lying between biotite schist and plagioclase amphibolite. The granitic intrusion which followed the folding removed part of the enclosing rocks, so that the sill now lies near the northern edge of a roof pendant which continues westward for about twelve miles through the Academy and Friant quadrangles. This roof pendant is made up very largely of plagioclase amphibolites, with lesser amounts of interbedded metasedimentary rocks. Several narrow sills of serpentine are present, and these have been extensively altered by igneous emanations to talc or talc-tremolite schists.

The quartz diorite of the batholith is in contact with the mica schist, along the other margin of which was intruded the serpentine sill from which the zoned nodules were derived. The actual contact of the quartz diorite with the mica schist is not exposed, but the thickness of the schist cannot be more than 50 feet, and is probably less. The attitudes in the metamorphic rocks are nearly vertical, and the quartz diorite contact dips under the mica schist at a high angle.

Description of the Nodules

The zoned nodules are embedded in the mica schist between the serpentine sill and the margin of the batholith. They range in diameter from about 10 cm. to over a meter. In shape they vary from nearly spherical to much flattened ellipsoids. When it was well exposed, the roadcut had somewhat the appearance of pillow lava, the nodules standing out in relief from the less resistant biotite schist matrix. The entire mass is cut by narrow dikes of aplite and pegmatite, and by a few quartz veins.

All of the larger nodules, and many of the smaller ones, contain a core

[3] Durrell, C., Metamorphism in the southwestern Sierra Nevada northeast of Visalia, Calif.: *Univ. Calif. Publ., Bull. Dept. Geol. Sci.*, **25,** 15 (1940). Macdonald, G. A., Geology of the western part of the Sierra Nevada between the Kings and San Joaquin rivers, Calif.: *Univ. Calif. Publ., Bull. Dept. Geol. Sci.*, in press.

of massive, dark grayish-green serpentine, and in general the size of the core increases with the size of the nodule. The core is sharply separated from an enclosing zone with radial fibrous structure composed of varying amounts of talc and actinolite. The thickness of this radial zone ranges from about 1 to 20 cm., and has little relation to the size of the nodule. In many of the smaller nodules the serpentine core is absent and the talc-actinolite zone extends to the center. Conversely, in the largest nodules the serpentine core may be $\frac{1}{2}$ to 1 meter in diameter but the radial zone still only a few centimeters thick. The radial zone is in turn surrounded by a massive zone, of very variable thickness, composed almost entirely of actinolite. In places this zone attains a thickness of a little over $2\frac{1}{2}$ cm., but elsewhere it is entirely absent. The boundary between this zone and the radial zone appears quite sharp in the hand specimen. Also sharply separated from the actinolite zone is the outer envelope of biotite. This too is of variable thickness, ranging from a mere film to over 2 cm. in cross-section. It is made up almost entirely of flakes of brown biotite oriented parallel to the margin of the nodule. The biotite rim passes gradationally outward into a matrix of biotite schist. In some nodules veinlets of brown biotite lead inward from the biotite rim across the actinolite zone and the radial talc-actinolite zone, and in a few instances they transect the entire nodule (Fig. 2-B). These veins pinch and swell from a mere film to as much as a centimeter in thickness. A chlorite zone situated between the actinolite and biotite zones, such as is found in some of the Unst occurrences,[4] is present only in rare instances. Chlorite is found in small amounts throughout the nodules, even in the serpentine cores, but generally does not form any definite zone.

One specimen, typical of the completely developed nodules of intermediate size, approaches in shape a triaxial ellipsoid, with diameters of 19 cm., 16 cm., and 12 cm. The serpentine core is very small, its cross-section along the plane of the major and minor axes of the ellipsoid measuring only 1.2 cm. by 2.5 cm. It is surrounded by a zone with pronounced radial structure measuring in the same plane 3.7 cm., by 7.5 cm. This radial zone consists of an inner band about 7 mm. thick composed almost entirely of talc, and an outer band composed of a mixture of talc and actinolite in varying proportions. This latter band is light green in color, and within it lie dark green radial streaks consisting almost entirely of actinolite. Surrounding the radial zone is a zone of dark green actinolite in which the prismatic crystals show haphazard orientation. In places this actinolite zone is absent, but in other places it reaches a thickness of 1.5 cm. Completely surrounding the entire nodule is an envelope of biotite ranging from a thin film to about 7 mm. thick.

[4] Read, H. H., *op. cit.*, pp. 526, 529.

Another specimen is slightly smaller, and the serpentine core is absent. The dimensions of the nodule are 17 cm., by 15 cm., by 8 cm. It consists very largely of the radial talc-actinolite zone, which is surrounded by a zone of actinolite ranging in thickness from 0 to 1.2 cm., and this in turn is surrounded by an outer layer of biotite 1 to 10 mm. thick. Veinlets of biotite transect the entire nodule.

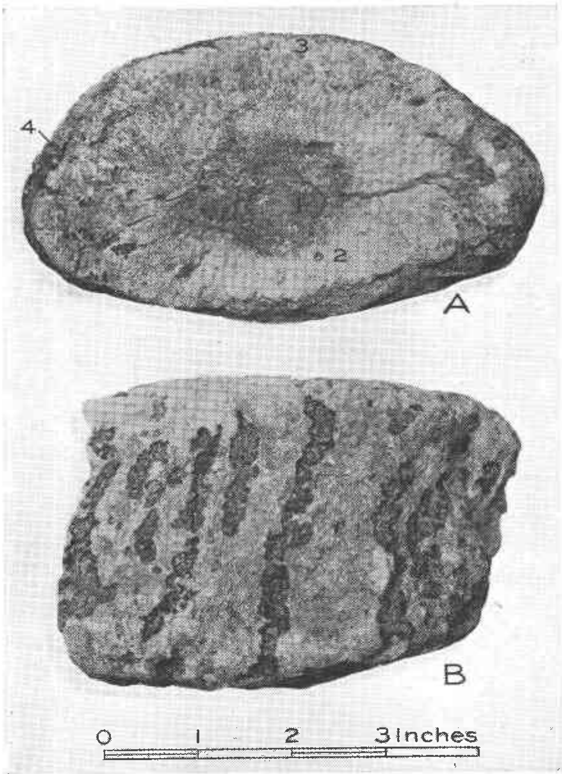

FIG. 2. *A*. Cross-section of a zoned nodule showing the serpentine core (1) surrounded by the radial talc-actinolite zone (2), the actinolite zone (3), and the biotite rim (4). Dark spots in the radial zone are nests of biotite.

B. Nodule with edges broken away to expose the talc-actinolite zone, crossed by dark veinlets of biotite.

The serpentine core. In thin section the serpentine of the cores is composed predominantly of web-structure antigorite, polarizing in light gray colors, the small length-slow fibers showing a criss-cross orientation like the warp and woof in woven cloth. Scattered throughout this matrix are grains of a rhombic pyroxene, forming irregular frayed-appearing patches as much as 3 mm. across, which evidently represent relict grains of the original peridotite, spared by the serpentinization and by the dynamothermal metamorphism which produced the web-structure antigorite. These grains are pale brown, non-pleochroic, and are cut by many small veinlets of the antigorite and also by rows of small grains of regenerated olivine. The pyroxene has an optic angle near 90°. Tiny subhedral to anhedral grains of iron ore are scattered abundantly through the pyroxene. Small subhedral to anhedral grains of colorless olivine are distributed throughout the rock, embedded in the antigorite and also in the pyroxenes. Some grains of pyroxene are almost completely replaced by small grains of olivine, the outline and structure of the original pyroxene grain being still visible. The olivine has an optic angle close to 90°. It is evident from its relationships that it represents regenerated metamorphic olivine, like that described elsewhere.[5]

Scattered throughout the antigorite groundweb are small, subhedral to anhedral flakes and tablets of an ultra-brown polarizing chlorite, which shows a (+) $2V$ of about 10°, and negative elongation, the acute bisectrix Z emerging approximately normal to the basal cleavage. Its dispersion is $r<v$ weak. The mineral may be a positive penninite, but except for its lower birefringence, its properties correspond with those of the clinochlore which is a common constituent of the contact metamorphosed serpentines of the Sierra Nevada.[6] Associated with this in a few places are small flakes of an ultra-blue polarizing chlorite with positive elongation, which is probably penninite. Talc is present locally as tiny flakes and shreds between the fibers of antigorite. Anhedral grains of iron ore, opaque in transmitted light and metallic gray in reflected light, are scattered abundantly throughout the rock.

The talc zone. A thin section cut from the talc zone is intermediate in composition between the talc-actinolite zone and the serpentine core, being composed largely of talc and serpentine, with talc about twice as abundant as serpentine. Chlorite, polarizing in both ultra-brown and ultra-blue colors, is also fairly abundant. Ore minerals are found as scattered small grains throughout most of the rock but certain small irregular areas are composed almost wholly of ores and chlorite. In some of these areas the two minerals are present in nearly equal amounts, but chlorite is usually considerably the more abundant. In one place a few flakes of brown biotite ($-2V=0°$) are associated with talc and serpentine.

The talc-actinolite zone. A section cut across the inner part of the talc-actinolite zone consists largely of a felty aggregate of talc, in which lie needles of actinolite. The actinolite, which forms about 5 per cent of the rock, shows the following properties: colorless, with a very large negative

[5] Durrell, C., *op. cit.*, p. 82. Macdonald, G. A., *op. cit.*

[6] Durrell, C., *op. cit.*, p. 84.

optic angle, an extinction angle $Z \wedge c$ of 18°, and birefringence moderate, about .025. The talc appears uniaxial, with a negative sign. The individual grains composing the aggregate of talc are xenoblastic and often highly irregular. The actinolite is hypidioblastic in the prism zone, but terminal faces are lacking. A few small flakes of chlorite are present, and grains of iron ore are scattered throughout the slide. The iron ore grains are for the most part hypidioblastic, and more or less square in outline, and often contain small inclusions of talc. The presence of a small amount of brown picotite associated with some grains indicates that they are probably chromite, but others may be magnetite.

Another section, from the middle of the talc-actinolite zone, is very similar to that just described, except that actinolite forms about 40 per cent of the rock.

A thin section from the outer part of the radial zone of the specimen analyzed (see accompanying table) is composed largely of long blades of actinolite, idioblastic in the prism zone but lacking terminal faces, with a large negative optic angle and $\gamma = 1.646$ ($\pm .003$). Between them lie xenoblastic grains of talc. A small amount of chlorite is present as anhedral grains, pleochroic from X = pale yellow to Y and Z = pale yellowish-green. It appears uniaxial, with X nearly normal to the basal cleavage. Irregular granules of iron ore are scattered throughout the rock, and associated with some grains are small amounts of a brown isotropic mineral with a high index of refraction, probably picotite.

A Rosiwal microscopic analysis of a strip across the section at right angles to the radial structure yields the following results in per cent by area:

Actinolite =	89.1%
Talc =	7.9
Chlorite =	2.6
Ore =	0.4

Sections through the actinolite zone are made up very largely of hypidioblastic to xenoblastic grains of actinolite, nearly colorless in slides of normal thickness but in thick slides pleochroic with X = very pale yellow, Y = pale yellowish-green, Z = pale bluish-green. Biotite generally makes up about 10 per cent of the rock. It is scattered throughout the slides as irregular anhedral grains. A small amount of talc and chlorite is present in several slides, the chlorite being in many places intergrown with biotite. In some specimens small irregular patches are made up entirely or almost entirely of biotite.

Biotite zone. The outermost zone is composed largely of biotite, generally with about 10 per cent of actinolite and a little chlorite. The biotite shows a small negative optic angle, $\beta=1.565$ ($\pm.003$), and X = nearly colorless to very pale yellow, Y and Z = yellowish-brown. The analysis of the biotite zone in the accompanying table is of a sample containing about 95 per cent biotite. It shows the mineral to be a phlogopitic variety, low in iron and in alkalies, especially K_2O, and fairly high in magnesia.

Biotite schist. The mica schist in which the zoned nodules are enclosed is composed largely of brown biotite, with a smaller amount of quartz and a little orthoclase and oligoclase. The biotite occurs in hypidioblastic plates, with their basal planes oriented in parallel position, giving rise to the schistosity. Only a few flakes lie at an angle to the foliation. Between the foliae of biotite lie xenoblastic grains of quartz and feldspar. The schist is distinctly richer in biotite than most of the mica schist of the surrounding region. It is also unusually coarse grained, but in this regard it conforms to the condition generally prevailing in the metamorphic rocks of the district, both the mica schists and the plagioclase amphibolites showing a coarsening of grain near the contacts of the plutonic bodies.

Quartz diorite. The adjacent biotite quartz diorite appears normal in every respect, although it has much less hornblende than is typical of the quartz diorites of this region. The texture is granitic. The rock is composed largely of subhedral to anhedral andesine, with abundant albite twinning and rare pericline twinning. Many grains show normal zoning. Anhedral grains of quartz make up about 20 per cent of the rock. Subhedral flakes of biotite, showing slight alteration to chlorite, make up about 10 per cent; it appears to be uniaxial, with a negative sign, X = brownish-yellow, and Y and Z = dark brown. A few grains of pale green hornblende and a few flakes of muscovite are also present. A small amount of orthoclase is interstitial, and zircon and apatite are minor accessories.

Chemical Composition

Representative specimens of the serpentine core, the outer part of the radial talc-actinolite zone, and the biotite rim have been analyzed. Their chemical compositions are shown in the accompanying table. Column 2 represents the specimen of the talc-actinolite zone of which a Rosiwal analysis has already been given. Assuming the talc to have the composition of the pure mineral, and the chlorite to have the composition of optically similar material found elsewhere in the serpentines of the surrounding district,[7] the approximate composition of the actinolite in this specimen has been calculated. It is shown in column 4 of the table. Using these values the approximate compositions of typical specimens from the

[7] Durrell, C., and Macdonald, G. A., Chlorite veins in serpentine near Kings river, California: *Am. Mineral.*, **24**, 454 (1939).

inner and middle parts of the talc-actinolite zone have then been calculated. The approximate values for the principal oxides thus obtained, together with the same oxides from the analyzed specimens recalculated to 100 per cent, are shown in Fig. 3.

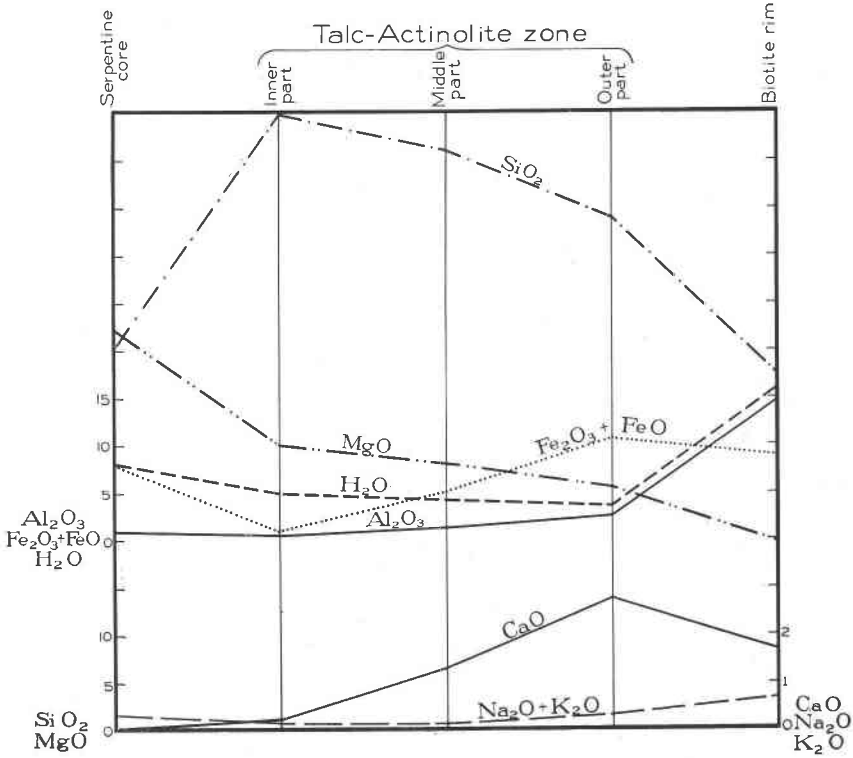

FIG. 3. Graph showing compositions of successive zones in the zoned nodules. The compositions of the inner and middle parts of the talc-actinolite zone were calculated from micrometric analyses; those of the other zones were determined by chemical analyses.

The changes in composition are very similar to those described by Read.[8] The talc zone shows the addition of considerable silica. Magnesia and iron appear to have been removed. The decrease in iron is not definitely proved, since the talc has not been analyzed, but it appears highly probable that at least some decrease in iron, as well as in magnesia, has taken place. The same decrease in percentage of iron is shown in Read's curves.[9] It is possible that some of this apparent loss of iron and magnesia is merely the result of the addition of large volumes of silica, since there is

[8] *Op. cit.*, pp. 533–535.
[9] *Idem*, p. 535.

no evidence that some increase in total volume of the mass has not taken place, but the change in ratio of iron to magnesia clearly indicates migration of one or both of these constituents.

If the decrease in the percentage of iron in the talc zone is considered to be only passive, as a result of the addition of other elements, then there is little or no addition of iron in the outer part of the nodules until the outermost part of the talc-actinolite zone is reached, and there it is only slight. In the outer part of the talc-actinolite zone iron oxide exceeds by only 1 per cent that in the serpentine core.

Other oxides have also been added to the nodules, but in small amounts and to any appreciable degree only in the outer zones. Alumina and lime increase markedly in the outer part of the talc-actinolite zone. Alumina rises still further in the biotite rim, and alkalies show a decided increase. Silica decreases from the talc zone outward, until in the biotite rim its percentage is less than that in the serpentine core. The percentage of magnesia in the biotite rim is less than half that in the serpentine, while the amount of iron is nearly the same.

TABLE 1

	1	2	3	4
SiO_2	40.22	54.14	37.46	55.1
TiO_2	none	0.19	0.87	—
Al_2O_3	1.49	2.52	14.64	1.8
Fe_2O_3	4.94	3.42	7.57	3.9
FeO	2.86	7.17	1.22	8.0
MnO	0.07	0.22	0.09	—
MgO	42.09	25.35	19.66	25.2
CaO	0.02	2.82	1.66	3.2
Na_2O	0.21	0.19	0.53	0.2
K_2O	0.07	0.08	0.19	0.1
H_2O-	0.07	0.07	6.89	0.04
H_2O+	7.98	3.34	8.89	3.1
CO_2	none	none	none	—
P_2O_5	none	none	0.06	—
S	none	0.03	0.04	—
Cr_2O_3	0.14	0.28	0.07	—
	100.16	99.82	99.93	100.64

1. Serpentine core. Analyst F. A. Gonyer.
2. Outer part of radial talc-actinolite zone. Analyst F. A. Gonyer.
3. Biotite rim. Analyst F. A. Gonyer.
4. Calculated composition of actinolite in outer part of radial zone.

It has been suggested that the migration of the various constituents into the serpentine nodules was in part controlled by the radii of the various ions involved.[10] The greater penetration of silicon in relation to the

[10] Merriam, Richard, unpublished manuscript, 1938.

other elements may be the result of greater ease of diffusion owing to its considerably smaller ionic radius ($Si^{++++}=0.39$Å, in contrast to $Al^{+++}=0.57$Å, $Fe^{+++}=0.67$Å, $Fe^{++}=0.83$Å, $Na^{+}=0.98$Å, $Ca^{++}=1.06$Å, and $K^{+}=1.33$Å[11]). With this exception, however, there appears to be no relationship between the ionic radii and the extent to which the different elements penetrated the serpentine.

Origin of the Nodules

Small nodular masses of serpentine were in some way separated from the parent serpentine sill and embedded in biotite schist. They may have been small apophyses from the sill which were later sheared off and isolated from the main mass during the Sierra Nevada orogeny. It is also possible that they represent "cold intrusions" of serpentine squeezed into the schist long after consolidation of the sill, in much the same way that masses of serpentine have been squeezed up along fault planes long after solidification in the vicinity of Polonio Pass and elsewhere in the California Coast Range. Masses of serpentine detached from the sill by one means or another would probably migrate readily by plastic flow through the mica schist.

Whatever the method by which they were separated from the parent sill, it is evident that small masses of serpentine enclosed in biotite schist were exposed to the action of permeating emanations from the adjacent quartz diorite. These mineralizers introduced new compounds into the rock, and furthered the recrystallization of the entire system. The process was akin to that of granitization, but because of the extreme composition of the original rock, the product was different from those usually identified as resulting from granitization. The production of amphibolites from limestones by igneous emanations in the Haliburton-Bancroft area in Ontario,[12] and in the Pyrenees[13] is a directly comparable process. Likewise, comparable are the alterations of xenoliths of olivine norite in the Trégastel-Ploumanac'h granite, producing a rock in which the femic minerals are hornblende and biotite,[14] and the similar alteration of holomafic xenoliths in a pegmatite cutting the Dalbeattie granite in Kirkcudbrightshire, England.[15]

[11] Bragg, W. L., *Atomic Structure of Minerals;* Cornell Univ. Press, Ithaca, p. 31 (**1937**).

[12] Adams, F. D., and Barlow, A. E., Geology of the Haliburton and Bancroft areas, Province of Ontario: *Canada Geol. Survey,* Mem. **6** (1910).

[13] Lacroix, A., Le granite des Pyrénées et ses phénomènes de contact: *Services carte géol. France Bull.,* **11,** No. 71 (1900).

[14] Thomas, H. H., and Smith, W. C., Xenoliths of igneous origin in the Trégastel-Ploumanac'h granite, Côtes du Nord, France: *Geol. Soc. London Quart. Jour.,* **88,** 274–296 (1932).

[15] MacGregor, M., A xenolithic pegmatite in the Dalbeattie "granite": *Geol. Mag.,* **73,** 171–184 (1936).

In all of these examples, and particularly in the alteration of the serpentine and limestone, the tendency has been to produce mineral phases in equilibrium with the crystallizing magma, rather than a rock identical with the plutonic rock in composition. This principle was recognized by Lacroix[16] and was clearly stated by Nockolds in his discussion of reciprocal reaction between basic xenoliths and acid magmas.[17]

As a result of his study of the Unst occurrences, Read concluded that the outer edge of the replaced serpentine was at the inner margin of the biotite zone, and that the biotite zone was derived from the enclosing granite gneiss as a result of the migration of magnesia out of the serpentine.[18] This may have been true at the Sierra Nevada locality as well. Indeed, the trend or slope of all of the curves in Fig. 3 except that for the alkalies show a sharp change between the talc-actinolite zone and the biotite rim, supporting the hypothesis that the biotite rim was derived from the enclosing schist rather than from the serpentine. However, the presence of irregular veinlets of biotite penetrating the entire nodules, identical in composition to, and in many places continuous with, the biotite rim, is a conflicting factor. The irregularity of the veinlets, and the fact that frequently nests of biotite are connected with the biotite rim only by minute almost indetectable films of biotite, appear to eliminate the possibility of their having been formed by plastic flow of schist or biotite rim into fractures in the nodule. The biotite veinlets have apparently been formed by metasomatic replacement of the serpentine. Whether the biotite rim was also formed in this way cannot now be definitely decided.

Migration of magnesia out of the altered serpentine nodules probably enriched the surrounding mica schist in that constituent, thus accounting for the greater amount of biotite in the schist at this locality than in most of the mica schists of the district. The greater than usual coarseness of the schist is probably the result of recrystallization in the presence of mineralizers from the adjacent magma.

[16] Lacroix, A., *op. cit.*

[17] Nockolds, S. R., Some theoretical aspects of contamination in acid magmas: *Jour. Geology*, **41,** 571 (1933).

[18] *Op. cit.*, pp. 534–536.