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JADEITE-ROCKS AND GLAUCOPHANE-SCHISTS FROM ANGEL ISLAND, SAN FRANCISCO BAY, CALIFORNIA

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ABSTRACT. The rocks of Angel Island comprise a series of Franciscan (Jurassic) arkosic graywackes with subordinate amounts of conglomerate and radiolarian chert. Almost all the graywackes have been metamorphosed to jadeite-bearing metagraywackes independently of proximity with basic or ultrabasic intrusions. A diabase sill, originally intrusive into the sedimentary series, has also been metamorphosed and its feldspar converted to chlorite, lawsonite, and jadeite. Glaucophane occurs in the altered diabase and is particularly abundant at its margins. Towards the diabase the jadeite-bearing metagraywackes become richer in glaucophane and pass into jadeite-free schistose glaucophane-rocks. Chemical analyses show that the change is accompanied by some desilication and an addition of Fe, Mg, Ca, Ti, and possibly Na. This metasomatism, which may have preceded, or coincided with, the metamorphism, was probably hydrothermal in nature and localized along igneous contacts and shear-planes. Similar, but more extensive developments of glaucophane-schist, also derived from graywacke, occur in association with a dike of serpentinized pyroxenite. Hydrothermal processes directly related to the serpentinization may have played a significant part in the chemical alteration of the graywacke. Movements along serpentinite contacts complicates the relationships and many large masses of glaucophane-schist and jadeite-bearing metagraywacke occur as tectonic inclusions within the serpentinite. Plagioclase is absent from, and considered unstable in, all the metamorphic assemblages. While jadeite appears to be stable in the arkosic metagraywackes deficient in Fe, Mg and Ca; its place is taken by acmitic-jadeite and eventually glaucophane in the glaucophane-schists.

INTRODUCTION

Angel Island is one of the largest of a number of islands in San Francisco Bay, and lies about half a mile from the tip of Tiburon Peninsula from which it is separated by Raccoon Strait (fig. 1). The area of the island is about one square mile and its geology was first described by Ransome in 1894 (see also Bloxam, 1955). It is of particular interest since some of the earliest conclusions about the occurrence and possible origin of the California glaucophane-schists were based on relationships observed on this island. With one or two exceptions the shore around the island is accessible at low tide, but high grass or tree-covered slopes behind the beach generally make it impossible to follow outcrops continuously inland.

The island is composed essentially of six major rock-groups (fig. 2):

(1) Franciscan (Jurassic) graywackes, conglomerates and radiolarian cherts.
(2) Jadeite-bearing metagraywackes derived from the Franciscan graywackes. This is the dominant rock-type on the island.
(3) Glaucophane-schists derived from graywackes, cherts, and basic igneous rocks.
(4) A large and apparently concordant sheet of altered diabase ("fourchite" of Ransome) intrusive into the Franciscan sediments. The diabase is extensively glaucophanized, particularly at its margins.
(5) Pillow-lavas at Point Blunt.
(6) A vertical dike-like body of serpentinite and pyroxenite near the western end of the island.

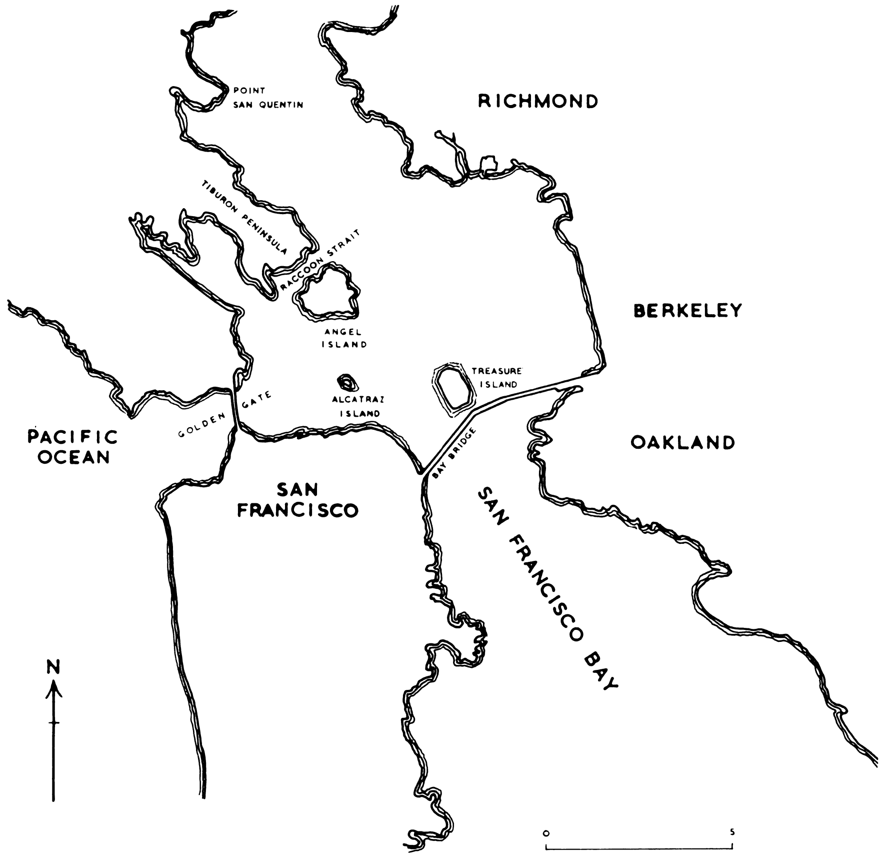


Fig. 1. Geographical position of Angel Island in relation to the San Francisco Bay area.

Ransome (1894) estimates that the total thickness of the Franciscan rocks on the island is at least 2,000 feet.

The major structure of the island is relatively simple and consists of a synclinal trough with its axis plunging to the north-east. This feature is particularly emphasized by the arcuate outcrops of the altered diabase sheet. However, as Ransome has shown (1894, p. 198), there are associated minor folds which may locally add considerable complication to the structure. In addition the present writer has mapped numerous NNW faults which do not appear on Ransome's map and complicate relationships along the shore, particularly in the region between Point Knox and Point Blunt (fig. 3).

The serpentinite dike appears to represent a boundary between structures to the east which are relatively simple and have low dips, and structures to the west which are more complex, considerably faulted, and generally have vertical dips.

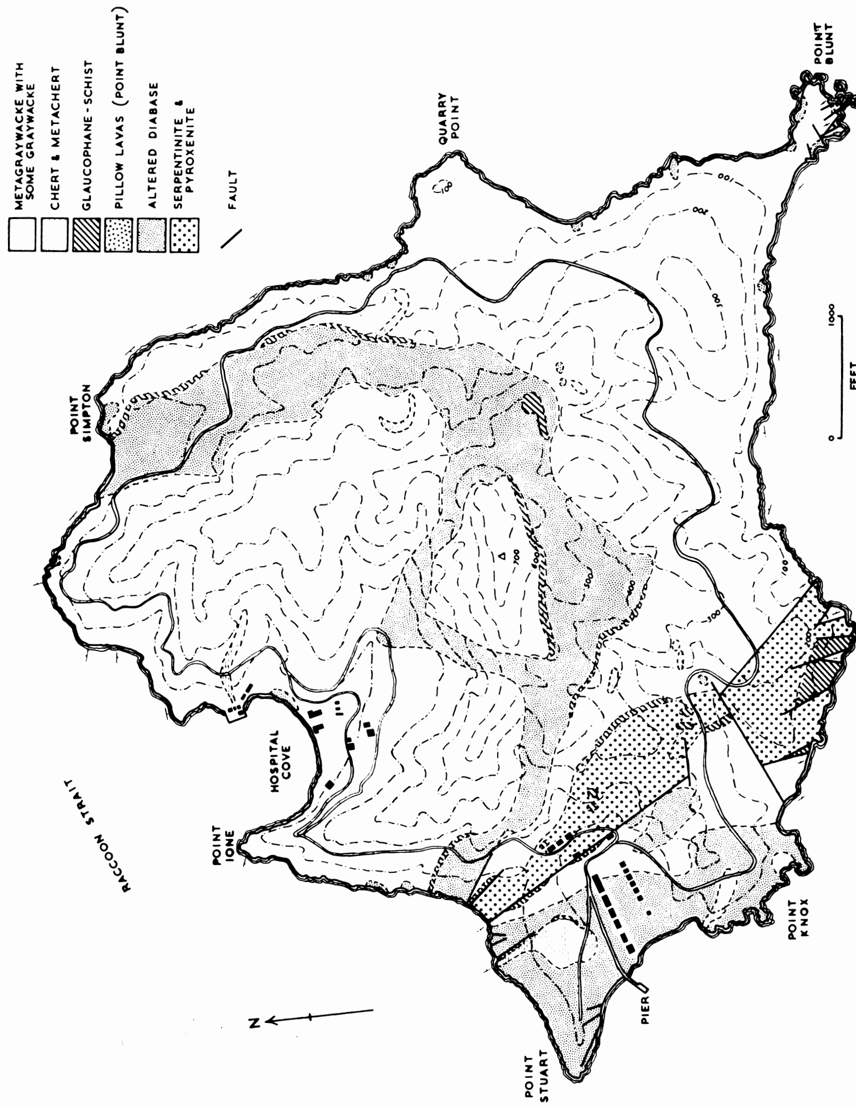


Fig. 2. Geological map of Angel Island. Modified after F. L. Ransome, 1894.

FRANCISCAN SEDIMENTS AND JADEITIC METASEDIMENTS

General statement.—The Franciscan graywackes which make up the bulk of the island have, with minor exceptions, been metamorphosed, the characteristic rock-type being glaucophane-poor jadeite-bearing metagraywacke (Bloxam, 1956; 1959). Except in extreme cases, distinguishing graywacke from metagraywacke by eye in the field is difficult or impossible; while in thin sections it is essentially dependent upon the efficiency of the optical microscope.

However, the difference in density between the two can be recognized in the field using a suitable heavy liquid (Turner, personal communication).

Of the "graywacke" specimens collected over 90 percent were found to be metamorphosed and about 80 percent of this number jadeite-bearing. Ransome (1894) failed to observe the widespread jadeitic metamorphism of the graywackes, confining his attentions to the more obvious developments of glaucophane-schist to be described subsequently (p. 566-569).

Franciscan graywackes.—Examples of least altered graywacke occur at Quarry Point and near Point Campbell. The outcrops are well bedded with occasional conglomerate bands and thin friable shales. Almost all the graywackes are sheared along planes parallel to the bedding (Ransome, 1894, p. 198). This appears to be a characteristic feature of many Franciscan graywackes in California (Bloxam, 1959) and tends to accentuate the original bedding. Seldom, however, is the shearing sufficiently intense to destroy the original clastic textures of the graywacke which in hand specimens contain obvious fragments of bright green chert, black shale and streaky carbonaceous (?plant) material.

Thin sections of the rock display abundant fragments of angular quartz and chert. Fresh clastic twinned albite is also characteristic and in some specimens makes up 35 percent of the fragments. Splinters of shale and more rounded pieces of variolitic basalt are common, the whole being cemented by sub-parallel strings of mica, chlorite and a little calcite. The mica and chlorite define the original bedding but also exhibit evidence of secondary growth in association with the later shearing. In addition a brown micaceous mineral occurs which resembles biotite but is almost isotropic suggesting some type of vermiculite. It may have been derived from stilpnomelane (p. 559).

Ransome (1894, p. 231) only gives a silica determination from the Quarry Point graywacke (table 1, column 1), but a new analysis is given in table 1, column 2. For comparison an analysis of Franciscan graywacke by Taliaferro (1943, p. 136) is also included in table 1, column 3. It has been noted elsewhere (Taliaferro, 1942, p. 83; Bloxam, 1956; 1959) that the Franciscan graywackes tend to be rather arkosic and remarkably constant in chemical composition over wide areas in California.

Metagraywackes.—It is convenient to divide the metagraywackes into two mineralogic groups: (1) *Quartz-albite-mica-lawsonite-crossite* and, (2) *Quartz-jadeite-mica-lawsonite-crossite*. Hence the division is defined by the reaction albite = jadeite + quartz, and it is assumed that, for a given chemical composition, rocks with jadeite develop under conditions of higher total pressure than those with albite (Fyfe, Turner and Verhoogen, 1958, p. 177).

(1) *Quartz-albite-mica-lawsonite-crossite.*—The first signs of metamorphism in the graywackes occurs in the groundmass and in some of the basic igneous fragments. Using a Leitz 6L objective and X8 eyepiece (x 360) fibres of a deep-blue amphibole appear within the chloritic areas. Precise optical determinations are difficult at this magnification, but larger crystals in more advanced stages have intense pleochroism from colorless to deep violet, $2V_{\alpha} = 0\text{-}10^{\circ}$, and a low birefringence characteristic of crossite.

TABLE 1

	1	2	3	4	5	6
SiO_2	70.50	70.31	71.72	69.77	70.04	69.14
TiO_2	—	0.36	0.35	0.41	0.14	0.37
Al_2O_3	—	14.03	13.23	14.82	13.88	15.08
Fe_2O_3	—	0.85	0.30	1.21	0.91	1.51
FeO	—	2.61	3.58	1.35	2.26	0.84
MnO	—	0.10	nil	0.03	0.07	0.03
MgO	—	2.07	1.81	2.38	2.11	1.08
CaO	—	1.31	1.80	1.99	1.79	2.79
Na_2O	—	4.12	2.72	3.89	4.01	5.31
K_2O	—	1.19	1.29	1.01	0.97	1.28
H_2O^+	—	2.37	2.53	2.96	3.15	1.96
H_2O^-	—	0.23	0.15	0.20	0.25	0.08
P_2O_5	—	0.05	0.09	0.08	nil	0.00
CO_2	—	0.09	0.32	0.10	0.07	0.12
		99.69	99.89	100.20	99.65	99.59
SG		2.78	—	2.89	2.91	2.91

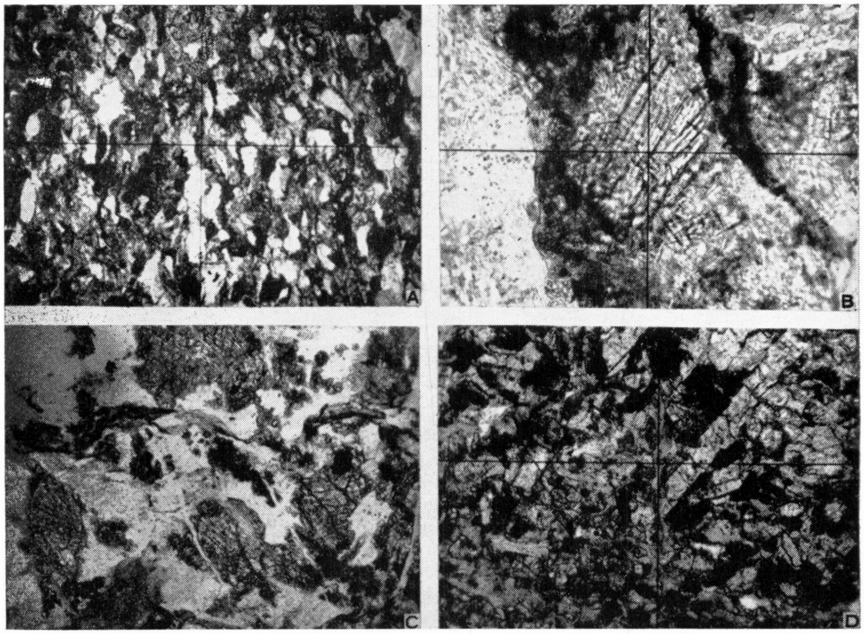
1. Franciscan "sandstone", Quarry Point, Angel Island (Ransome, 1894, p. 231. Analyst, F. L. Ransome)
2. Franciscan graywacke, Quarry Point, Angel Island. Analyst, T. W. Bloxam.
3. Franciscan graywacke, Buckeye Gulch (Taliaferro, 1943, p. 136). Also $ZrO_2 = 0.04\%$.
4. Jadeite-bearing metagraywacke, Point Simpton, Angel Island. Analyst, T. W. Bloxam.
5. Jadeite-bearing metagraywacke, Point Blunt, Angel Island. Analyst, T. W. Bloxam.
6. Jadeite-bearing metagraywacke, Valley Ford (Bloxam, 1956, p. 98. Analyst, E. H. Oslund).

Dispersed among the fibers of mica and chlorite are idiomorphic crystals of lawsonite, often bent, but generally lying parallel to the bedding/foliation. The mineral is particularly abundant in the basic igneous fragments. Recrystallization of the groundmass begins to effect the detrital quartz, chert, and albite fragments, which lose their sharp boundaries and are invaded by needles of pale green actinolite, often fringed with crossite. The brownish vermiculite noted previously (p. 558) frequently passes into fibers of stilpnomelane while the latter may also replace some of the whispy mica. Tiny garnet aggregates are common and are probably a manganese-rich variety.

(2) *Quartz-jadeite-mica-lawsonite-crossite.*—The incoming of jadeite cannot be determined visually in hand specimens, but in thin sections the mineral replaces the detrital albite. This reaction (albite = jadeite + quartz) appears to be extremely fast and sensitive to changes in metamorphic conditions. Metagraywackes of the type previously described change, within an inch or less, into jadeite-bearing metagraywackes of almost identical texture except that jadeite has developed to the complete exclusion of detrital albite.

The jadeite usually occurs as colorless radiating groups of elongated prisms which may be grouped about an area of cloudy sub-isotropic material with speckled polarization colors; probably lawsonite (Bloxam, 1956). While the average size of the jadeite crystals is from 0.1-0.3 mm (plate 1A and B), one exceptional metagraywacke contains jadeites up to 0.8 mm (plate 1C). In addition to its crystal habit, the jadeite is readily distinguished by its extremely strong dispersion which makes accurate optical determinations difficult. In some cases the usually colorless jadeite may be faintly greenish, probably representing more acmitic varieties. This change in composition is particularly common in metagraywackes containing abundant glaucophane. Optical data

PLATE 1



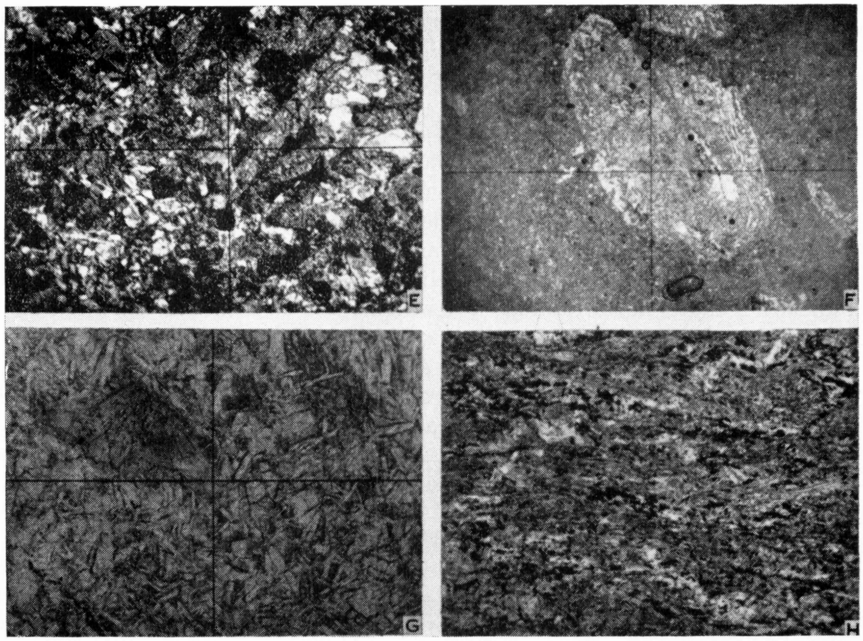
A. Jadeite-bearing metagraywacke. The specimen is slightly foliated and contains abundant clastic quartz, chert, and shale fragments. Ordinary light x 23.
B. Jadeite-bearing metagraywacke; same field as above. Sub-radiate jadeite occupies the center of the field. Ordinary light x 305.
C. Jadeite-bearing metagraywacke with large jadeite aggregates and clastic quartz. The specimen is virtually unfoliated. Ordinary light x 77.
D. Altered diabase. Sub-variolitic phase of the main sheet with outlines of original plagioclase crystals preserved (e.g. just right of center), granular pyroxene, and iron ore. The lawsonite and glaucophane are not readily distinguishable. Ordinary light x 67.

for jadeites from ten Angel Island metagraywackes cover the following range (sodium light): $\beta = 1.658 - 1.672$, $2V_\gamma = 62° - 83°$, $\gamma{:}c = 43° - 55°$ $(y = b)$. The birefringence is low and averages 0.010. These data are in fair agreement with that for an analyzed jadeite from Valley Ford (Bloxam, 1956, p. 490). It has been observed that the faintly greenish (acmitic) jadeites give the lower values for $2V\gamma$ but have a higher birefringence ($\sim$0.015): their dispersion is also weaker (Bloxam, 1959, p. 106).

Lawsonite and crossite continue to crystallise and build larger individuals, the latter mineral often forming fringes around the pale green (acmitic) jadeite but rarely about the colorless jadeite. The development of crossite is quite selective and is most abundant in association with chlorite and shale fragments which presumably have a composition more appropriate to its development. This localization of a particular mineral's development confirms the chemical evidence that there has been very little migration of material during metamorphism.

Stilpnomelane is not common in these rocks, although the same indeterminate brown micaceous mineral noted previously (p. 558) is quite abundant.

PLATE 1



E. Altered diabase; same field as D. The speckled appearance of the plagioclase is due to replacemnt by lawsonite and chlorite. Nicols crossed x 67.

F. Altered porphyritic diabase. The subhedral crystal of plagioclase in the center of the field has been altered to lawsonite, chlorite, and a little jadeite. Ordinary light x 11.

G. Altered porphyritic diabase; same field as above showing details of plagioclase replacement. Abundant idiomorphic lawsonite is present with a "brush-like" aggregate of jadeite just above and left of center. Ordinary light x 110.

H. Glaucophane-rich schist derived from graywacke marginal to the altered diabase. Ordinary light x 36.

Ransome (1894, p. 216), describing a "Franciscan sandstone" makes frequent reference to the presence of "zoisite". It is probable that the mineral is in fact jadeite since the strong dispersion and form of the jadeite are very like those of clinozoisite.

Two analyses of the jadeite-bearing metagraywackes, one from Point Simpton and the other from Point Blunt are given in table 1, columns 4 and 5. The similarity of the analyses to those of the graywackes (table 1, columns 1, 2 and 3) and to a jadeite-bearing metagraywacke from Valley Ford (table 1, column 6) is evident.

Other associated metasediments.—Conglomerates or pebbly facies of the graywackes together with radiolarian cherts are the commonest sedimentary types associated with the graywackes.

(1) *Altered conglomerates.*—In the region of Point Blunt and on the shore about 900 feet south of Point Ione, conglomerates are quite abundant. They are not sharply defined bands but merely coarser phases of the associated metagraywackes which form the matrix about the pebbles. The pebbles, like

the smaller fragments in the metagraywacke, consist of chert, variolite, quartzite, and shale. Ransome (1894, p. 197) described pebbles of a holycrystalline igneous rock of granitic affinities composed of quartz, altered feldspar, green hornblende, and blue amphibole (crossite in the present writer's specimens). Most of the crossite occurs as mantles or feathery replacements of the green hornblende. Since the crossite-bearing pebbles are contained in rocks (jadeitic-metagraywackes) which Ransome regarded as *unmetamorphosed* graywackes, he found it extremely difficult to account for their origin.

(2) *Radiolarian chert.*—Interbedded with the graywackes and metagraywackes are radiolarian cherts which are generally red in color but, when recrystallized, develop green or bluish tints. Ransome (1894, p. 199) noted the radiolarian cherts near Hospital Cove which exhibit sedimentary facies gradational with the graywackes. When associated with unaltered graywacke the radiolarian cherts generally contain abundant tests of *Radiolaria* and are deeply stained by abundant "dusty" iron oxide and some manganese. Some of those associated with the metagraywackes are recrystallized but show little further alteration. Others may contain abundant stilpnomelane and riebeckite and probably represent more impure varieties (cf. p. 560).

THE ALTERED DIABASE

The intrusive sheet of altered diabase can be conveniently divided into: (1) the main arcuate sheet east of the serpentinite dike and, (2) discontinuous outcrops west of the serpentinite dike. In addition, small isolated masses of altered diabase occur in several other places (fig. 2) and probably represent off-shoots from the main sheet (Ransome, 1894, p. 202).

Ransome (1894, p. 200) described the altered diabase as "fourchite" (Williams, 1890), but admitted that this was only for want of a better term. His difficulty in naming the rock was due to the fact that he did not fully recognize its metamorphic character, although he did observe that blue-amphibole was a common constituent (1894, p. 206). Furthermore, lawsonite, which is always abundant, had yet to be described (Ransome, 1895), although he gives the optical properties of an "unknown mineral" in the rock which is clearly lawsonite.

For the most part the altered diabase preserves undisturbed igneous textures of three main types: (a) granular and slightly ophitic, (b) fine-grained porphyritic and, (c) variolitic. Textural types (a) and (b) are developed in all exposures and are representative of the coarser interior and chilled marginal phases respectively. Type (c) is more restricted in its development and confined to certain phases of the western exposures of diabase, particularly near Point Knox.

(1) *The main sheet*: (*a*) *granular and sub-ophitic phases.*—Samples of the altered diabase near Point Simpton serve as typical examples of the main sheet which is very uniform in composition over its whole outcrop.

In general the rock is finer-grained than the average diabase and the pyroxene, which is the only original constituent preserved, tends to be granular but also slightly sub-ophitic towards the altered plagioclase (plate 1D and E). The pyroxene is colorless and has the following optical properties: $\alpha =$

1.681, $\beta = 1.687$, $\gamma = 1.711$, $2V_\gamma = 53°$, $\gamma : c = 43°$; the corresponding composition being close to Ca_{40} Mg_{45} Fe_{15} (Hess, 1949, p. 649). Frequently the pyroxene shows marginal alteration to chlorite, glaucophane, and green acmitic-jadeite. In some cases a little jadeite occurs as independent fibrous aggregates which have developed from the material of the groundmass, probably feldspar.

Although the outlines of the original plagioclase crystals are frequently preserved, they are completely altered to dense aggregates of colorless chlorite which is isotropic and has $n = 1.630$. Associated with the chlorite are abundant idiomorphic prisms of lawsonite and occasional feathery aggregates of jadeite (e.g. plate 1G).

The original constituents of the fine-grained groundmass cannot be recognized but, judging by the amount of lawsonite present, it must have been very feldspathic.

Interwoven between the pyroxene crystals and forming a further constituent of the groundmass is crossite in extremely small fibers tightly matted together forming an apparently uniform deep-blue background.

The most significant feature of the altered diabase is the complete elimination of feldspar and its replacement by chlorite, lawsonite, and jadeite. This chloritization of the feldspar bears some resemblance to that described by Vuagnat and Jaffé (1954) from Alpine variolites and pillow-lavas associated with serpentinites, although their rocks do not contain glaucophane-schist type minerals.

An analysis of this phase of the altered diabase is given in table 2, column 2, together with Ransome's original analysis of what is probably the same rock-type (table 2, column 1).

(b) *Fine-grained porphyritic phases.*—Except where it reaches the shore near Point Simpton and between Point Knox and Point Stuart, the junction between altered diabase and adjacent metagraywackes is seldom exposed. When contact phases are exposed they are fine-grained and usually strongly porphyritic.

The constituents of the rock are the same as those in the courser phases but the primary pyroxene occurs as sub-radiate laths or fine brush-like groupings, representing a transitional texture between the sub-ophitic and variolitic types described below.

The altered feldspar phenocrysts are of particular interest since they illustrate the development of chlorite, lawsonite, and jadeite within the former crystal boundaries of the phenocrysts (plate 1F and G).

(2) *Altered diabase west of the serpentinite dike*: (*c*) *variolite.*—The largest mass of altered diabase in this part of the island forms the cliffs at Point Stuart and crops out at various places along the shore to the S S E. While the altered diabase exhibits facies identical to those already described, in the immediate neighbourhood of the lighthouse south of the old Military Post, much of it consists either of intrusive breccia or develops a type of spheroidal structure (Ransome, 1894, p. 201). This latter feature is not pillow-structure and each bulbous projection is little more than 2 to 4 inches in size. The effect is to give the outcrops a rubbly appearance and is a type of auto-

TABLE 2

	1	2	3	4	5	6	7
SiO_2	46.98	46.52	52.89	52.86	48.26	50.31	42.06
TiO_2	—	0.92	1.12	1.49	2.51	0.10	—
Al_2O_3	17.07	13.76	13.20	11.17	12.81	1.15	2.72 (Al₂O₃ + Fe₂O₃)
Fe_2O_3	1.85	2.23	4.93	2.94	4.10	2.02	
FeO	7.02	6.84	3.22	8.93	9.15	3.18	2.88
MnO	—	0.07	0.12	0.03	0.16	0.11	—
MgO	8.29	9.30	5.67	7.70	6.71	22.68	39.53
CaO	12.15	12.16	10.95	4.77	8.76	17.32	nil
Na_2O	2.54	1.91	2.56	5.30	2.93	0.12	—
K_2O	0.53	0.23	0.13	0.02	0.10	0.01	—
H_2O^+	4.86*	5.15	2.09	3.21	3.47	2.82	12.04*
H_2O^-		0.39	0.25	0.25	0.32	0.08	
P_2O_5	0.09	0.10	0.18	0.15	0.36	0.03	nil
CO_2	—	0.21	2.45	0.27	0.01	0.31	—
	101.38	99.79	99.76	99.09	99.65	100.24	99.23
SG	3.20	3.22	3.02	3.11	3.21	3.09	2.61

* loss on ignition

1. "Fourchite" (altered diabase) from main sill, Angel Island. Coarse main phase (Ransome, 1894, p. 231. Analyst, F. L. Ransome).
2. Altered diabase from main sill, Angel Island. Coarse main phase. Analyst, T. W. Bloxam.
3. Variolitic diabase from marginal phase of sill, Point Knox, Angel Island. Analyst, T. W. Bloxam.
4. Glaucophanized marginal phase of the diabase, Point Stuart, Angel Island. Analyst, T. W. Bloxam.
5. Glaucophanized marginal phase of the diabase, Point Simpton, Angel Island. Analyst, T. W. Bloxam.
6. Partially serpentinized pyroxenite, 900 feet N. E. of Point Stuart, Angel Island. Analyst, T. W. Bloxam.
7. Serpentinite, hard nodule in crushed matrix, Angel Island (Ransome, 1894, p. 231. Analyst, F. L. Ransome).

breccia. Ransome (1894, p. 209) considers it probable that these phases of the intrusive were emplaced in a brecciated condition at very shallow depth.

Texturally they are fine-grained rocks with a flinty fracture and contain altered feldspars mainly in the form of spherulites and larger sub-radiate fibrous bundles. all of which have been altered to chlorite. Much of the rock consists of brown glass, some of which represents pyroxene, a few aborescent fibres of which can occasionally be seen. Except where they are sheared the variolitic rocks contain no glaucophane.

An analysis of the variolitic diabase is given in table 2, column 3.

(3) *Marginal glaucophanization of the altered diabase.*—With the exception of the variolites. all varieties of altered diabase contain lawsonite and glaucophane (± jadeite). However. where they have been sheared, glaucophane becomes extremely abundant and schistose glaucophane rocks are produced from the diabase. A good example of this is to be seen on the shore between the old pier and Point Stuart where massive spheroidally weathering altered diabase is traversed almost at beach-level by numerous sub-horizontal shear-planes. The rock becomes increasingly cataclastic and detached blocks and fragments lie in a sinuous web of pale blue glaucophane; the rock-changing in color from dark green to blue. Small vertical shear planes and faults

which cut the diabase are often completely filled with massive clumps of glaucophane.

Two analyses of strongly sheared and glaucophanized diabase are given in table 2, columns 4 and 5.

PILLOW LAVA

The only exposure of pillow-lava on the island occurs on the sea-cliff at Point Blunt, just below a small lighthouse (Ransome, 1894, p. 202). The pillow-lava is in fault contact with conglomeratic metagraywackes to the west and east and lies beneath metagraywacke forming the cliff-slope above.

The pillows are ellipsoidal in shape and vary in size from about one to three feet. The tops are convex and the bottoms concave, fitting around, or sending downward protuberances into spaces between lower pillows. Wilson's (1940) criteria indicate that the lavas are the right way up, but the adjacent metagraywackes dip at high angles.

In thin sections the pillow-lavas have a variolitic texture and are almost identical to the variolitic phases of the altered diabase, with fine brush-like and spherulitic groupings of feldspar set in a matrix of brown glass. Like that in the altered diabase, the feldspar has been largely replaced by chlorite.

The matrix between the pillows consists mainly of calcite in which are scattered globular aggregates of brown glass similar to that forming the pillows. Associated with the glass and occupying branching veins are irregular patches of pumpellyite (cf. Bloxam, 1958; 1959, p. 102).

SERPENTINITE AND PYROXENITE

Traversing the western part of the island is a prominent almost vertical dike-like sheet of serpentinite which trends approximately N N W and attains a maximum width of about 500 feet. The major boundaries of the serpentinite are usually faults and the term "dike" is used more in a descriptive sense since the marginal metasediments are generally vertical, suggesting that the serpentinite may well have been a concordant sheet or sill.

The serpentinite is always strongly sheared, particularly at its contacts, and consists of greenish slickensided masses within which are nodules of less sheared serpentinite (table 2, column 7). Both types are almost completely serpentinized and consist of a dense aggregate of colorless twinned clinochlore which have $\beta = 1.591$, $\gamma - \alpha = 0.008$, $2V_\gamma \sim 10°$, and X parallel to the elongation. With one or two exceptions, pseudomorphs are rare and, when present, are always after pyroxene, no olivine, or evidence of its former presence, having been detected (Ransome, 1894, p. 222). The few opaque minerals consist mainly of parallel streaky clusters of iron-ore and occasional deep brown crystals of chrome-spinel (picotite).

Partially serpentinized specimens of pyroxenite have been obtained from the dike. The analyzed rock (table 2, column 6) consists of diallagic pyroxene up to 5 mm in length, partially replaced by serpentine which also appears to invade the rock along a network of branching veinlets. The optical properties of this pyroxene are identical with that in the altered diabase (p. 562-563).

GLAUCOPHANE-SCHISTS ASSOCIATED WITH THE INTRUSIVE IGNEOUS ROCKS

General statement.—In addition to the extensive developments of jadeite-bearing metagraywacke which carry variable, but generally small amounts of blue-amphibole, there are a group of schistose glaucophane-rich rocks which owe their origin in part to processes controlled largely by proximity to both the altered diabase and the serpentinite. While the relationship of the glaucophane-schists to the diabase and serpentinite is very similar, much more glaucophane-schist is associated with the serpentinite than with the diabase (fig. 2).

Ransome (1894) noted that "sandstones and cherts" in contact with the altered diabase and serpentinite had been converted to glaucophane-schists. He states that "In no single instance has any schist been found upon the island that does not bear the above relation either to the fourchite (altered diabase) or the serpentinite" (1894, p. 211). It will be recalled, however (p. 558), that Ransome had overlooked the rather less obvious metamorphic character of graywackes over nearly the whole of the island.

(1) *Glaucophane-schists associated with the altered diabase.*—Glaucophane-schist forms an apparently continuous zone adjacent to the lower and upper surfaces of the altered diabase (Ransome, 1894, p. 195). However, many of the exposures described by Ransome are no longer available due to subsequent building on the island.

Actual contacts have not been found inland, but the presence of glaucophane-schist between jadeitic-metagraywacke country rock and the altered diabase can be reasonably inferred by sporadic exposures of schist along the approximate line of junction (Ransome, 1894, p. 211). At its widest the glaucophane-schist zone is seldom greater than about 6 feet, but may swell to some 12 feet.

Contacts between the altered diabase and metasediments are exposed on the shore near Point Simpton, and also to the west where the sheet reaches the shore again between Point Ione and Point Stuart. At Point Simpton the bottom of the sheet becomes progressively glaucophanized and sheared towards the metagraywackes beneath, and contains numerous inclusions of glaucophanized graywacke (table 3, column 4). The contact itself is largely a mélange comprising sheared and glaucophanized diabase and metagraywacke, riddled with veins and pods of glaucophane, quartz, and calcite. The graywacke below has been converted to tough blue glaucophane-schist consisting of abundant fibrous glaucophane, lawsonite, and subordinate actinolite which define the schistosity, together with mica and streaky clusters of brown sphene (plate 1H). Quartz is present, some of which probably represents recrystallized chert fragments. No jadeite occurs (table 3, column 3).

About 12 inches further down, the rock becomes paler in color and less schistose; glaucophane decreases in amount and aggregates of "dusty" green and partially glaucophanized acmitic-jadeite appear. Quartz is more abundant in the form of recrystallized chert fragments, and the rock is referred to as "transitional glaucophane-schist" in table 3, column 2. About 3 feet below the contact the transitional glaucophane-schist merges into normal buff-colored jadeite-bearing metagraywacke with a little crossite (table 3, column 1).

TABLE 3

	1	2	3	4
SiO_2	69.77	60.63	57.18	48.26
TiO_2	0.41	1.21	1.06	2.51
Al_2O_3	14.82	15.98	13.77	12.81
Fe_2O_3	1.21	1.11	0.89	4.10
FeO	1.35	3.62	6.01	9.15
MnO	0.03	0.11	0.18	0.16
MgO	2.38	4.07	6.56	6.71
CaO	1.99	4.34	5.11	8.76
Na_2O	3.89	3.59	4.41	2.93
K_2O	1.01	1.00	0.87	0.10
H_2O^+	2.96	3.36	3.23	3.47
H_2O^-	0.20	0.31	0.26	0.32
P_2O_5	0.08	0.01	0.08	0.36
CO_2	0.10	0.42	0.61	0.01
	100.20	99.76	100.22	100.06
SG	2.89	2.96	3.15	3.21

1. Jadeite-bearing metagraywacke, 3 feet below altered diabase, Point Simpton (see table 1, column 4).
2. Quartz-glaucophane-schist (from graywacke), transitional glaucophane-schist, 1 foot below altered diabase, Point Simpton. Analyst, T. W. Bloxam.
3. Glaucophane-schist (from graywacke), contact phase with altered diabase, Point Simpton. Analyst, T. W. Bloxam.
4. Glaucophanized marginal phase of the diabase, Point Simpton (see table 2, column 5).

It is probable that the above assemblages (quartz-glaucophane-lawsonite; quartz-jadeite/acmite-glaucophane-lawsonite and quartz-jadeite-lawsonite-crossite) may owe their development to differences in bulk chemical composition rather than large changes in pressure. Hence in rocks with progressively more Fe and Mg the place of jadeite is taken by jadeite-acmite and eventually glaucophane (cf. Brothers, 1954, p. 620; Bloxam, 1956, p. 496; 1959, p. 102; Fyfe, Turner and Verhoogen, 1958, p. 176).

West of the serpentinite dike, and about 1,000 feet E N E from Point Stuart, the altered diabase is in contact with metacherts which form a thick band in the metagraywackes. Large wedges of disrupted metachert have been caught up by the instrusive diabase which is also full of smaller metachert fragments (Ransome, 1894, p. 217). As at Point Simpton, the marginal diabase has been extensively glaucophanized together with the associated metacherts which have been altered to flinty dark-bluish schists with regularly alternating bands of paler bluish-pink suggestive of original bedding. The metacherts are highly siliceous and consist essentially of an even-grained quartz mosaic riddled with stilpnomelane and riebeckite. The habit of the stilpnomelane is characteristic of that in many other Franciscan metacherts and consists of a number of ragged fibres arranged in small sheaf-like or "bow-tie" bundles. The mineral is frequently replaced by riebeckite which often preserves the form of the stilpnomelane aggregates. The paler bands are richer in lawsonite and contain glaucophane together with very small inter-locking granules of garnet, probably manganese-rich (Bloxam, 1959, p. 104).

(2) *Glaucophane-schists associated with the serpentinite.* (a) *General relationships.*—Serpentinite contacts on the island are less favorably exposed and when they do occur are always faults. Ransome (1894) observed that glaucophane-schists were also developed marginal to the serpentinite *dike and*

that many large masses of glaucophane-schist occured on the *upper* (west) side of the dike which he considered to be hading at about 35° to the south-west. The present writer was unable to confirm this hade, the dike appearing nearly vertical in the cliff sections examined. Ransome also oversimplified the structure and omitted numerous NNW trending faults which make interpretation of the relationships extremely difficult. Nevertheless, wherever glaucophane-schists appear they occur either directly in association with serpentinite or in circumstances from which this relationship can be reasonably inferred.

Inland exposures are poor but outcrops of glaucophane-schist are nearly always interposed between the metagraywackes and serpentinite along its western boundary. Cliff sections along the southern shore are extensively faulted, so that within a few feet, there may be rapid alternations of serpentinite, glaucophane-schist and metagraywacke (fig. 3). These rapid variations may not be entirely tectonic but could represent original interfingering between the intrusive serpentinite and sediments which has been further complicated by faulting along the serpentinite contacts (e.g. Wilson, 1943, p. 196.)

In addition to glaucophane-schists developed marginal to the serpentinite, numerous massive blocks of glaucophane-schist and occasionally metagraywacke occur as inclusions within the serpentinite. While some may represent rafts of sediment caught up during the emplaceemnt of the serpentinite, the majority are probably tectonic inclusions (Brothers, 1954, p. 623.)

All the major faults post-date the Franciscan sedimentary and igneous rocks and the metamorphism, and, while they cannot be definitely dated on Angel Island, are probably related to post-Jurassic to Recent diastrophism during the evolution of the California Coast Range (Reed and Hollister, 1951).

(b) *Detailed relationships.*—The best locality for examining these relationships is along the shore about 1,000 feet ESE from the lighthouse at Point

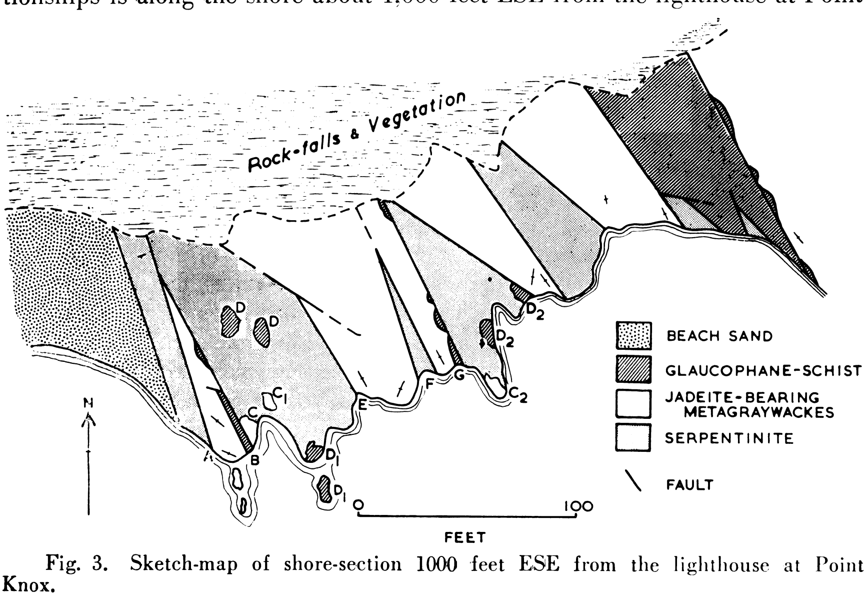


Fig. 3. Sketch-map of shore-section 1000 feet ESE from the lighthouse at Point Knox.

Knox, beginning at the eastern end of a sandy bay. A sketch map of the locality is given in figure 3.

Rising above the sand at the end of the sandy bay is a sheared wedge of serpentinite bounded on either side by faults which bring it into contact with a vertical strip of jadeite-bearing metagraywacke to the east (fig. 3A). Thinly laminated chert bands containing riebeckite and stilpnomelane also occur in the metagraywacke. Interposed between these metasediments and another faulted mass of serpentinite is a zone of fault breccia containing broken-up glaucophane-schist derived from metagraywacke (fig. 3B). A small wedge of shattered metagraywacke bounded in part by serpentinite lies on the eastern side of the fault (fig. 3C), and a similar, but larger mass (fig. $3C_1$), is completely surrounded by the serpentinite. A little further up the sea-cliff some large masses of glaucophane-schist (D) are also enclosed by the serpentinite (tectonic inclusions), while others form a small promontary near sea-level (fig. $3D_1$). The serpentinite terminates eastwards against a fault (fig. 3E), which introduces a wider belt of jadeite-bearing metagraywacke cut by a small fault-wedge of serpentinite (fig. 3F); followed by another fault introducing more serpentinite (fig. 3G). Along this fault-zone discontinuous pods of brecciated glaucophane-schist are exposed similar to those in locality B, except that they have originated from cherts and contain abundant quartz, stilpnomelane, and riebeckite. The adjacent serpentinite encloses one large mass of metagraywacke and two of glaucophane-schist (fig. 3, C_2 and D_2).

INTERPRETATION OF THE CONTACT RELATIONSHIPS

(1) *Altered diabase contacts.*—Ransome (1894) considered that the development of glaucophane-schists from sedimentary formations marginal to the diabase was the result of contact alteration associated with the *emplacement* of the basic magma. It has been demonstrated, however, that the diabase has also been metamorphosed, hence the metamorphism must post-date the diabase and is not directly associated with its emplacement.

Chemical analyses (table 3) show that the regionally prevalent jadeite-bearing metagraywackes have been modified in chemical composition near the diabase, the principle changes involving loss of Si and gains in total Fe, Mg, Ca, Ti, and possibly a little Na. Very similar chemical changes were noted by the writer at Valley Ford (Bloxam, 1959, p. 110) in association with the glaucophanization of jadeite-bearing metagraywackes.

The evidence is compatable with Turner and Verhoogen's (1951, p. 244) hypothesis that active solutions may have risen along suitable paths afforded by shear planes (e.g. igneous contacts). Their effect has been to modify the composition of the arkosic graywacke into one more appropriate to the development of glaucophane.

(2) *Serpentinite contacts.*—Faulting at the serpentinite contacts largely obscures the original relationships and no complete transition from jadeite-bearing metagraywacke into glaucophane-schist has been observed. Instead, the glaucophane-schist occurs as broken-up lenses in fault-zones between jadeite-bearing metagraywackes and serpentinite. However, by implication, it

is probable that the relationships are the same as those between the glaucophane-schists and diabase.

Ransome's analysis of the serpentinite is given in table 2, column 7. If the serpentinite has in fact been derived from pyroxenite their respective analyses (table 2, columns 6 and 7) indicate considerable changes in composition; Mg and water having been added; some Si and all the Ca removed. It is possible, therefore, that serpentinization of the pyroxenite may have played a direct part in the redistribution of certain elements in its vicinity (Turner and Verhoogen, 1951, p. 244).

It has already been noted (p. 566) that relatively more glaucophane-schist is associated with the serpentinite than with diabase. This may be due in part to the processes outlined above and also to the easier access of solutions, whatever their origin, along shear zones associated with the serpentinite (Turner and Verhoogen, 1951, p. 244).

SUMMARY AND DISCUSSION

(1) Arkosic Franciscan graywackes, which form the major rock-type on Angel Island, have been metamorphosed to glaucophane-poor jadeite-bearing metagraywackes with virtually no change in chemical composition. Jadeite has formed mainly from detrital albite (albite = jadeite + quartz).

(2) The development of the jadeite-bearing rocks may be described as regional in extent and is not related to proximity with basic or ultrabasic intrusions.

(3) A sheet of diabase intrusive into the graywackes has also been metamorphosed and its original feldspar converted to chlorite, lawsonite, and jadeite (± glaucophane). The marginal phases of the diabase are sheared and become progressively enriched in glaucophane.

(4) At contacts with the altered diabase the graywackes have been desilicated and enriched in Fe, Mg, Ca, Ti, and possibly Na; leading to the development of glaucophane-schist. Away from the contact-zone the glaucophanized metagraywackes grade into normal arkosic jadeite-bearing metagraywacke. Similar relationships also occur where the diabase comes into contact with radiolarian cherts.

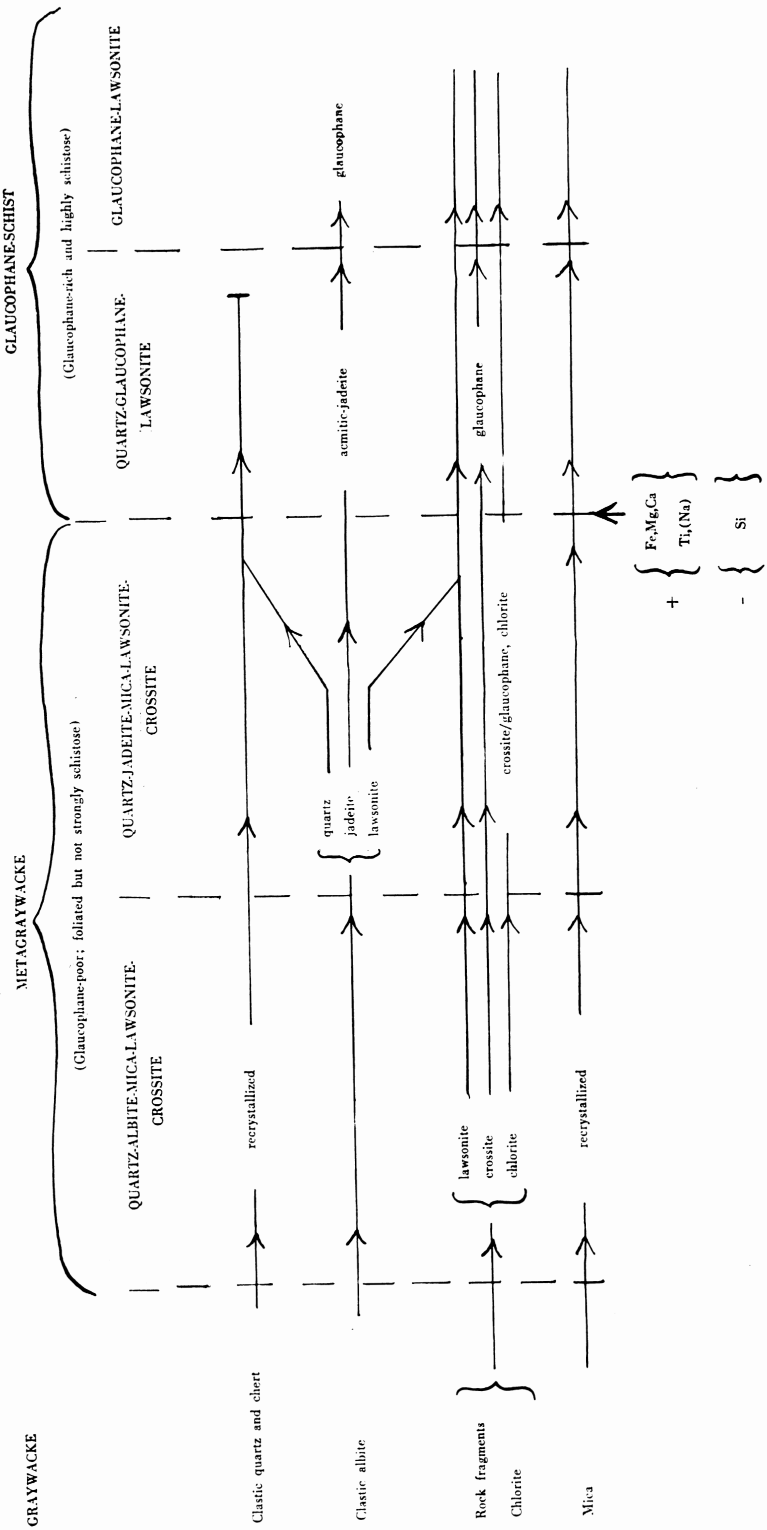
(5) Serpentinite contacts with the graywackes are extensively faulted, but evidence has been presented which suggests that the relationship of glaucophane-schist to serpentinite is the same as that with the altered diabase.

(6) The chemical alteration of graywackes marginal to the diabase and serpentinite is probably due to the activity of hydrothermal solutions of uncertain origin which have been localized along contact zones and associated shear planes. They may be earlier than, or contemporaneous with, the metamorphism, and some may be directly related to serpentinization.

(7) Plagioclase is considered to be unstable in all these metamorphic assemblages, and is replaced by jadeite, lawsonite, and chlorite. Jadeite only appears to be stable in arkosic metagraywackes poor in Fe, Mg and Ca: its place being taken by acmitic-jadeite and glaucophane in rocks with higher proportions of these elements (e.g. glaucophane-schists).

The mineralogical relationships are summarized in table 4.

TABLE 4



GRAYWACKE
METAGRAYWACKE
(Glaucophane-poor; foliated but not strongly schistose)
GLAUCOPHANE-SCHIST
(Glaucophane-rich and highly schistose)
QUARTZ-ALBITE-MICA-LAWSONITE-CROSSITE
QUARTZ-JADEITE-MICA-LAWSONITE-CROSSITE
QUARTZ-GLAUCOPHANE-LAWSONITE
GLAUCOPHANE-LAWSONITE
Clastic quartz and chert
recrystallized
Clastic albite
quartz
jadeite
lawsonite
acmitic-jadeite
glaucophane
Rock fragments
Chlorite
lawsonite
crossite
chlorite
crossite/glaucophane, chlorite
glaucophane
Mica
recrystallized
+
Fe,Mg,Ca
Ti,(Na)
-
Si

The early investigations of Ransome (1894) and Lawson (1895) established the fact that in many parts of California glaucophane-schists of the Franciscan were intimately associated with intrusive bodies of serpentinite; they were considered to have been produced by contact metamorphism and metasomatism accompanying the emplacement of the ultrabasic magma. The glaucophane-schist-serpentinite association in California still appears to be valid on the evidence of more recent field mapping. Wilson (1943, p. 197) states that . . . "The origin of the (glaucophane) schists by pneumatolytic action accompanying the ultra-basic intrusions seems demonstrated by the proximity of the schists to these intrusive bodies, and their gradation into unaltered sediments both along and across the strike". Similar conclusions have been reached by Taliaferro (1941; 1943) who found that the elements most commonly introduced into the marginal rocks were Na, Mg, Ca, Ti and Al; the metamorphism and metasomatism being genetically connected with the ultrabasic magma (see also Crittenden, 1951, p. 25-26). Crittenden notes that . . . . "The most extensive areas of glaucophane-bearing rocks in the San Jose-Mount Hamilton area are those associated with the long narrow serpentine sill . . . . (and) occur as narrow lenses mostly along the western, presumably upper, margin of the sill, and as irregular areas interfingering with the serpentine and sediments". The similarity between these observations and those made on Angel Island is apparent.

Turner and Verhoogen (1951, p. 244) and Fyfe, Turner and Verhoogen (1958, p. 225) conclude that the development of glaucophane-schist by hydrothermal metamorphism at intrusive contacts or more remote points situated on zones of dislocation is well established (cf. Borg, 1956). In addition the effects of later movements often complicates the original relationships and numerous authors have confirmed the plastic mobility of serpentinite in fault-zones and along tight isoclinal fold axes (Wilson, 1943, p. 196-197; Taliaferro, 1943; Gealey, 1951).

As more data accumulate it is becoming clear that extensive areas of Franciscan graywacke, hitherto regarded as unmetamorphosed, have been altered to jadeite-bearing metagraywackes (Bloxam, 1956; 1959; McKee, 1958). Similar rocks have also been described from Celebes (de Roever, 1955) and Japan (Seki and Shidô, 1959). In California glaucophane-rich schists may represent a particular phase of the widespread metamorphism in areas of appropriate lithology, or in rocks suitably modified in chemical composition.

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REFERENCES

Bloxam, T. W., 1955, Glaucophane-schists and associated rocks at two Californian localities: Geol. Soc. America Bull. (Abst.), v. 66, p. 1644-1645.

———, 1956, Jadeite-bearing metagraywackes in California: Am. Mineralogist, v. 41, p. 488-496.

———, 1958, Pumpellyite from South Ayrshire: Mineralog. Mag., v. 31, p. 811-813.

———, 1959, Glaucophane-schists and associated rocks near Valley Ford, California: Am. Jour. Sci., v. 257, p. 95-112.

Borg, I. Y., 1956, Glaucophane schists and eclogites near Healdsburg, California: Geol. Soc. America Bull., v. 67, p. 1563-1584.

Brothers, R. N., 1954, Glaucophane schists from the North Berkeley Hills, California: Am. Jour. Sci., v. 252, p. 614-626.

Crittenden, M. D., 1951, Geology of the San Jose-Mount Hamilton area, California: Calif. Dept. Nat. Res., Div. Mines Bull. 157, p. 1-74.

de Roever, W. P., 1955, Genesis of jadeite by low-grade metamorphism: Am. Jour. Sci., v. 253, p. 283-298.

Fyfe, W. S., Turner, F. J., and Verhoogen, J., 1958, Metamorphic reactions and metamorphic facies: Geol. Soc. America Mem. 73, p. 1-259.

Gealey, W. K., 1951, Geology of the Healdsburg Quadrangle, California: Calif. Dept. Nat. Res., Div. Mines Bull. 161, p. 1-50.

Hess, H. H., 1949, Chemical composition and optical properties of common clinopyroxenes, part 1: Am. Mineralogist, v. 34, p. 621-666.

Lawson, A. C., 1895, A contribution to the geology of the Coast Ranges: Am. Geologist, v. 15, p. 342-356.

McKee, B., 1958, Jadeite alteration of sedimentary and igneous rocks: Geol. Soc. America Bull., (Abst.), v. 69, p. 1612.

Ransome, F. L., 1894, Geology of Angel Island: Univ. Calif. Pub. Dept. Geology, v. 1, p. 193-235.

———, 1895, On lawsonite, a new rock-forming mineral from the Tiburon Peninsula, Marin County, California: Univ. Calif. Pub. Dept. Geology, v. 1, p. 301-312.

Reed, R. D., and Hollister, J. S., 1951, Geology of California: Am. Assoc. Petroleum Geologists, Tulsa.

Seki, Y., and Shidô, F., 1959, Finding of jadeite from the Sanbagawa and Kamuikotan metamorphic belts, Japan: Japan Acad. Proc., v. 35, p. 137-138.

Taliaferro, N. L., 1941, Geologic history and structure of the central Coast Range of California: Calif. Dept. Nat. Res., Div. Mines Bull. 118, p. 119-163.

———, 1942, Geologic history and correlation of the Jurassic of south-western Oregon and California: Geol. Soc. America Bull., v. 53, p. 71-112.

———, 1943, The Franciscan-Knoxville problem: Am. Assoc. Petroleum Geologists Bull., v. 27, p. 109-219.

Turner, F. J., and Verhoogen, J., 1951, Igneous and metamorphic petrology: New York, McGraw-Hill.

Vuagnat, M., and Jaffé, F., 1954, Sur les ophisphérites de la région des Gets (Haute-Savoie): Archives des Sci. Soc. de physique et de Histoire Nat. de Genève, v. 7, p. 5-14.

Williams, J. F., 1891, The igneous rocks of Arkansas: Ann. Rpt. Geol. Survey Arkansas for 1890, v. 2.

Wilson, I. F., 1943, Geology of the San Benito Quadrangle, California: Calif. Jour. Mines and Geology, v. 39, p. 183-270.

Wilson, M. E., 1941, Noranda district, Quebec: Geol. Survey Canada Mem. 229, p. 1-162.