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GLAUCOPHANE-SCHISTS AND ASSOCIATED ROCKS NEAR VALLEY FORD, CALIFORNIA

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ABSTRACT. Large residual masses of Franciscan glaucophane-schist, eclogite, and associated metamorphic rocks rest upon a basement of Franciscan graywackes and metagraywackes. The residual metamorphic blocks are probably relict masses from a former cover. Various stages in the transformation of graywackes and cherts into glaucophane-rocks have been observed in both basement rocks and residual masses. Progressive glaucophanization of residual blocks of eclogite also occurs, the final mineralogical and chemical composition approaching that of glaucophane-rocks derived from graywackes. Chemical changes accompanying the metamorphism of the graywackes involve an addition of Fe, Mg and Ca, together with a decrease in Si and Na. These changes contrast with those which have produced glaucophane-rocks from the eclogites. The mineralogical character of the glaucophane-schists suggests affinities with the greenschist or epidote-amphibolite facies, but the instability of albite and the presence of hydrous minerals with high density indicates certain conditions perculiar to the glaucophane-schist facies; possibly high water-vapor pressure.

INTRODUCTION AND GENERAL RELATIONSHIPS

The rocks to be described occur in the Sebastopol Quadrangle, 7½ miles north, 17° east of Valley Ford, Sonoma County, on the Valley Ford-Freestone highway (Gealey, 1950; Bloxam, 1955). It is a locality well known for excellent exposures of glaucophane-schist, eclogite, and associated rocks of the Franciscan (Jurassic) formation (Switzer, 1950). The area forms a small part of the Coast Range belt of Franciscan rocks, extending south towards San Francisco and northwards into the Healdsburg Quadrangle (fig. 1).

At Valley Ford the rocks can be divided into three major groups: (a) Basement rocks of the Franciscan which are mainly graywackes, but include metagraywackes, glaucophane-schists, and some igneous rocks. The metamorphic rocks are confined to the area east of a fault which brings them into contact with the graywackes.

(b) Residual masses of Franciscan chert, metachert, glaucophane-schist, eclogite, and associated rocks, resting upon the basement graywackes and metagraywackes. Some of the metamorphic rock-types are common to both basement rocks and residual masses.

(c) A cover of soft unconsolidated marine sands and clays of the Merced Formation (Pliocene), which has in places been stripped off to reveal rocks of the previous two categories.

The residual metamorphic rocks are well exposed and rise above the low-lying ground composed of relatively soft graywackes and metagraywackes (plate 1A). The resulting differential erosion has, in most cases, obscured the original contact relationships. Franciscan metamorphic rocks in this type of setting appear to be common in many parts of California (Gealey, 1950; Borg, 1956).

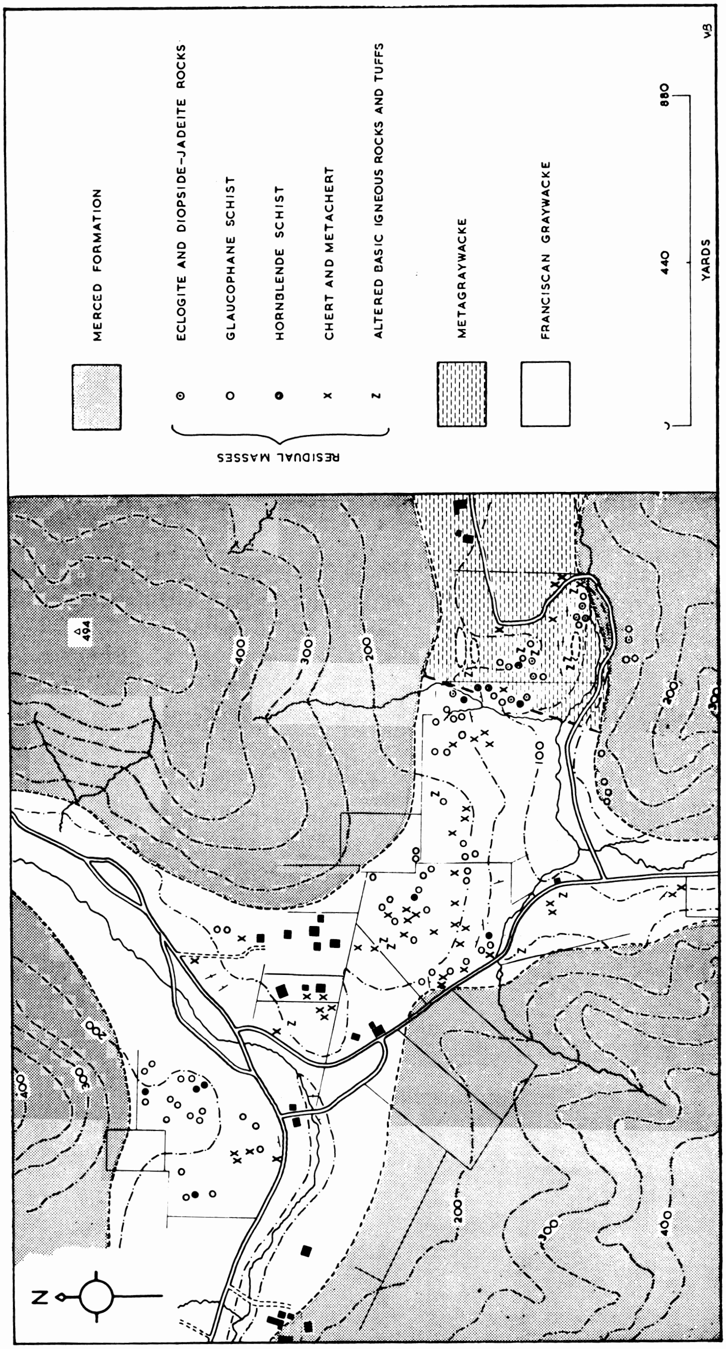
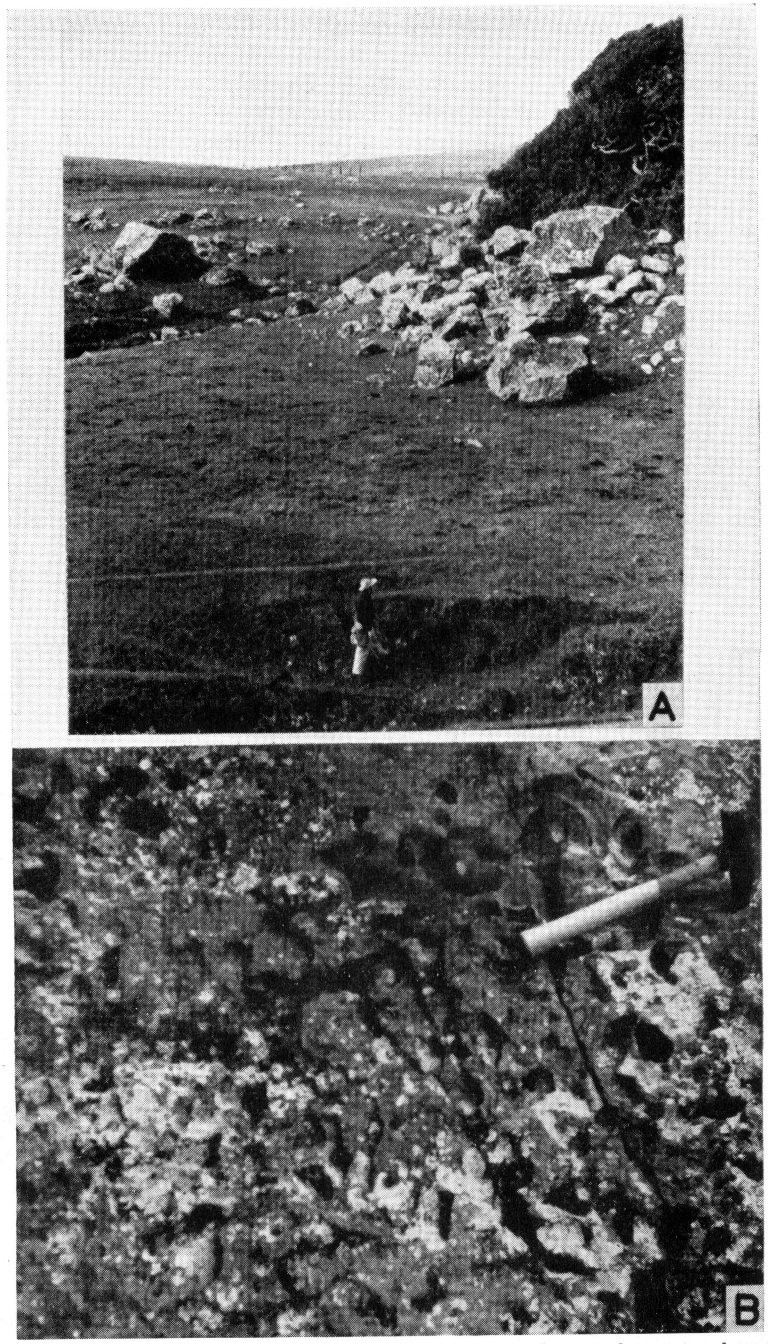


Fig. 1. Geological map of the area near Valley Ford, Sonoma County, California. Major buildings are shown, together with the principal field boundaries as in the fall, 1954.

PLATE 1



A. Residual blocks of Franciscan glaucophane-schist, metachert and associated metamorphic rocks, Valley Ford. The observer is standing on unaltered basement Franciscan graywackes.

B. *Pholas* borings in glaucophane-schist, Valley Ford.

BASEMENT ROCKS

Franciscan graywackes.—In general exposures of the basement rocks are poor and confined to creeks, highway-cuttings, and small quarrys. The dominant rock-type is arkosic graywacke with local pebbly beds. They are strongly folded with fold-axes trending north to north-northwest and plunging at about 10° in the same direction. This structural trend at Valley Ford agrees with the dominant strike of the Franciscan rocks over much of northern California.

The graywackes consist essentially of angular quartz and chert detritus, together with frequent basic igneous fragments, commonly variolitic basalts. Fresh soda-plagioclase, sericite, chlorite, and carbonaceous or shaley material are always present, with soda-plagioclase constituting some 30 percent of the rock in many cases (302/74).*

An analysis of a typical Valley Ford graywacke is given in table 1, 1; where the low value for total Fe, Mg and Ca is indicated. This arkosic tendency appears to be a general feature of the Franciscan graywackes and has been noted by Taliaferro (1942, p. 83) and Bloxam (1956, p. 494).

Some of the apparently unaltered basement graywackes exhibit, under the microscope, signs of incipient metamorphism (302/69). Fragments of variolite and shaley material develop small needles of pale green amphibole, while some of the angular quartz fragments are penetrated by radiating needle-like clusters of a green mineral, too small for precise determination, but

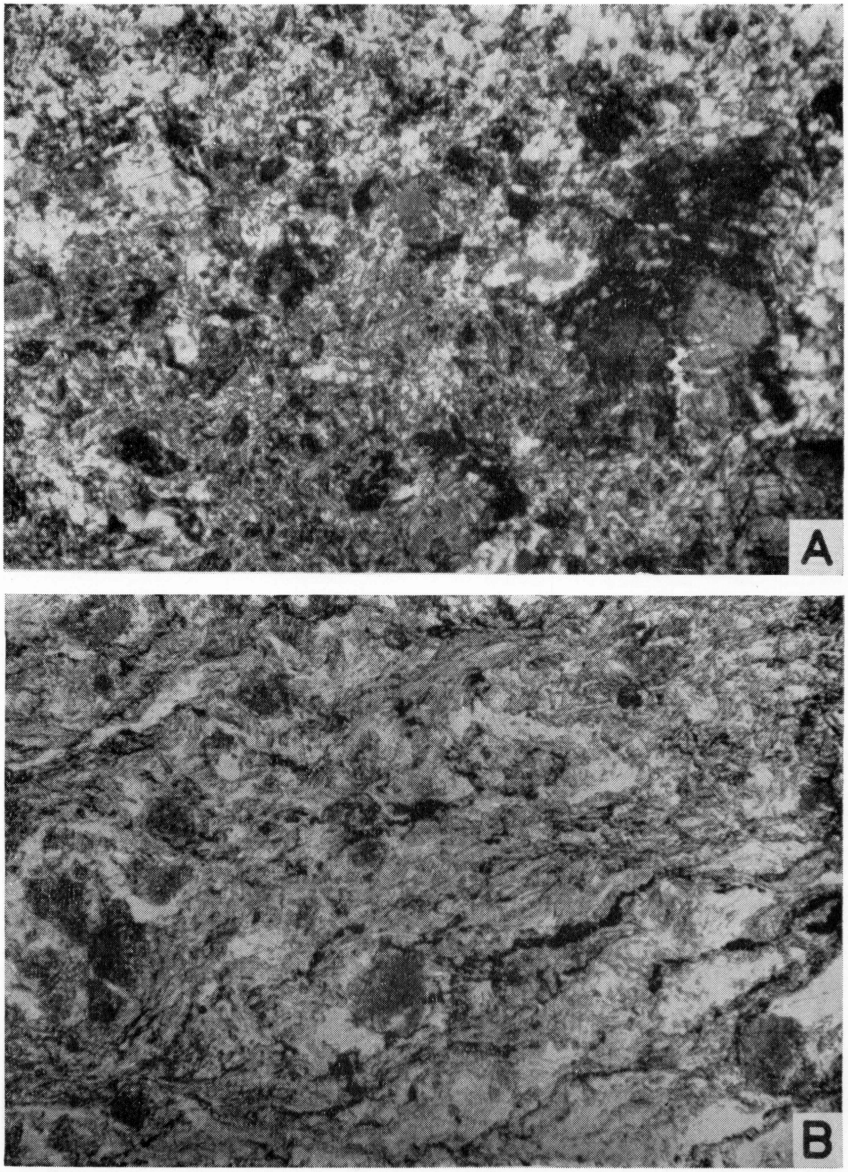
TABLE 1

	1	2	3	4	5	6
SiO_2	71.18	69.14	62.35	49.12	49.17	47.99
TiO_2	0.44	0.37	0.40	0.61	2.51	2.62
Al_2O_3	13.14	15.08	14.43	14.99	12.19	12.50
Fe_2O_3	1.05	1.51	1.25	0.97	1.10	3.40
FeO	2.37	0.84	3.76	9.21	10.88	11.12
MnO	0.06	0.03	0.04	0.07	0.29	0.31
MgO	2.25	1.08	3.40	6.58	6.83	6.11
CaO	1.48	2.79	5.97	10.65	10.76	12.16
Na_2O	4.31	5.31	2.78	2.58	2.47	2.98
K_2O	1.11	1.28	1.98	0.90	0.32	0.21
H_2O^+	1.91	1.96	3.65	4.11	3.58	0.44
H_2O^-	0.32	0.08	0.05	0.19	0.27	0.08
CO_2	0.15	0.00	0.07	0.00	0.02	nil
P_2O_5	0.08	0.12	0.00	0.12	0.00	0.00
	99.85	99.59	100.13	100.10	100.39	99.92
SG	2.70	2.91	3.02	3.15	3.20	3.47

1. Franciscan graywacke (302/74), Valley Ford (Bloxam, 1956, p. 493. *Anal.* E. H. Oslund)
2. Quartz-jadeite metagraywacke (302/138e), Valley Ford (Bloxam, 1956, p. 493. *Anal.* E. H. Oslund)
3. Quartz-glaucophane-lawsonite-schist (302/33), Valley Ford. *Anal.* T. W. Bloxam
4. Glaucophane-lawsonite-pumpellyite-schist (302/3), Valley Ford. *Anal.* T. W. Bloxam
5. Glaucophane-omphacite-garnet-schist (302/143b), Valley Ford. *Anal.* T. W. Bloxam
6. Eclogite (302/143c), Valley Ford. *Anal.* T. W. Bloxam

* Numbers refer to specimens in the Department of Geology, University of California, Berkeley.

PLATE 2

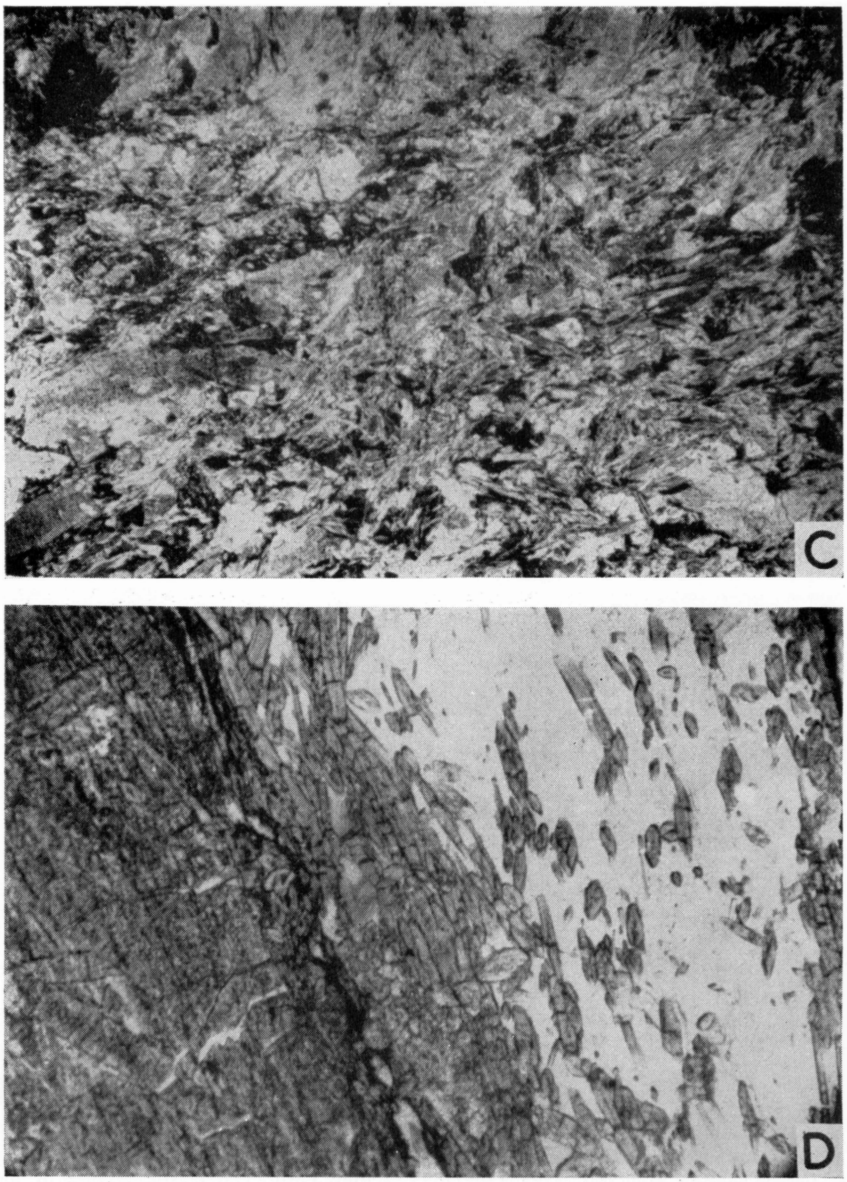


A. Jadeite-bearing metagraywacke (302/138), Valley Ford. The clastic texture of the graywacke is still preserved in this almost unfoliated specimen. Ordinary light ×8.

B. Quartz-(jadeite)-glaucophane-lawsonite-schist (302/33), Valley Ford. The specimen is a glaucophanized jadeite-bearing metagraywacke with turbid relicts of jadeite in a foliated web of glaucophane, lawsonite and muscovite. Ordinary light ×8.

whose habit resembles that of pumpellyite in the metacherts (p. 103). Patches of chlorite in the matrix occasionally develop an extremely narrow border of

PLATE 2

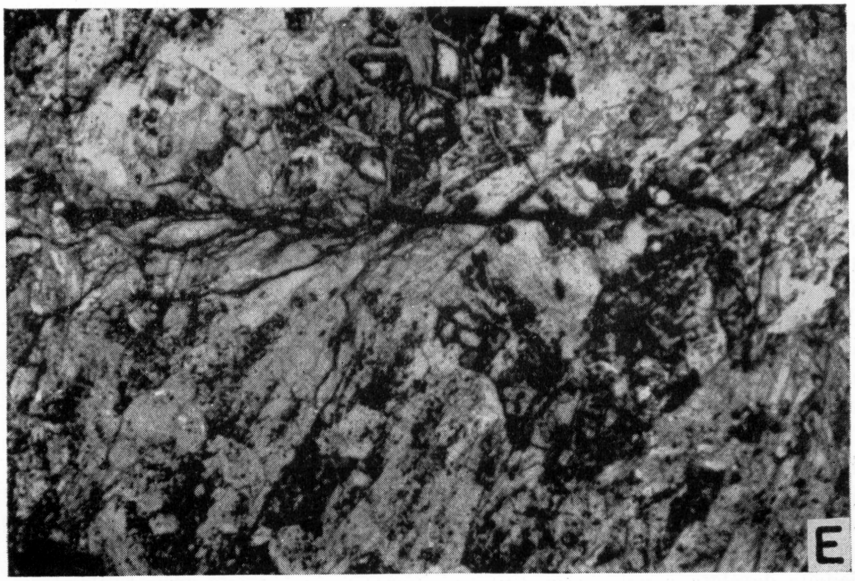


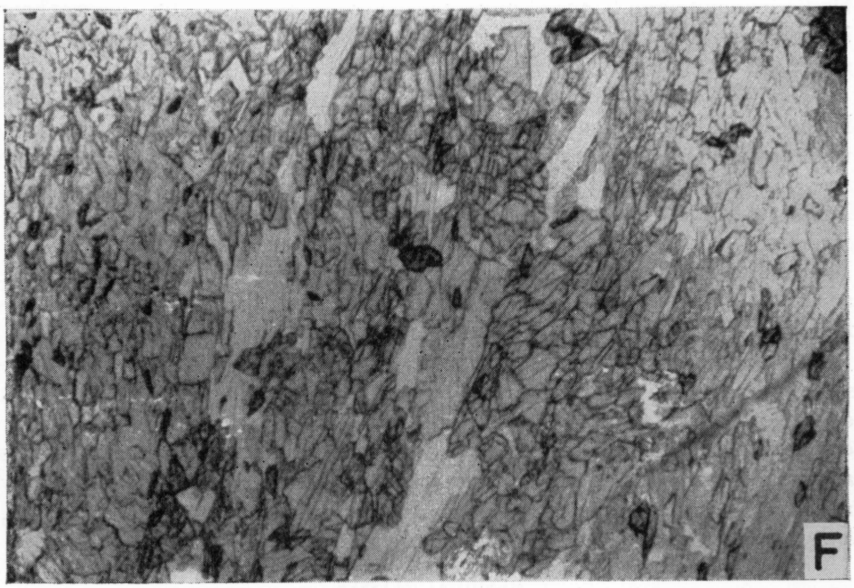
C. Glaucophane-lawsonite-pumpellyite-(muscovite, chlorite)-schist (302/3), Valley Ford. The rock is derived from a graywacke. Ordinary light ×8.

D. Metachert (302/57), Valley Ford. Contrasting bands of lawsonite (left) and quartz-glaucophane (right). Ordinary light ×8.

a faintly pleochroic fibrous blue mineral which may be glaucophane but, due to its small size, complete optical data could not be obtained.

PLATE 2





E. Altered eclogite (302/46), Valley Ford. Crystals of eclogite-garnet partially altered to lawsonite, pumpellyite and iron-ore. Stout crystals of glaucophane with crossitic margins are abundant, together with dark granular sphene. Ordinary light ×10.

F. Altered eclogite (302/24), Valley Ford. Glaucophane-omphacite-epidote-schist, the centre of the field being occupied by a thin schlieren of relict omphacite. Ordinary light ×8.

Metagraywackes and derived glaucophane-rocks.—The metagraywackes containing jadeite are confined to the area east of a fault which defines the line of a north-south trending creek. In a small waterfall near the head of the creek, and at various points downstream, extensive brecciation can be seen in the graywackes. The adjacent metagraywackes trend east-west with almost vertical foliation and enclose thin lenses of less altered graywacke, together with some altered and sheared igneous rocks (see below).

The jadeite-bearing metagraywackes from this, and other localities in California, have been described previously (Bloxam, 1956). They are the products of low-temperature metamorphism of graywackes and retain, to varying degrees, the clastic textures and minerals of the parent graywacke (table 1, 2 and plate 2A). In addition to jadeite (table 3, 1) the rocks contain varying amounts of glaucophane and lawsonite which generally define relict bedding and suggest derivation from more argillaceous bands. Larger blades of mica develop from an earlier sericitic mica (302/138).

A progressive increase in the amount of glaucophane and lawsonite can be observed in many of the basement metagraywackes (plate 2B). Glaucophane continues to crystallize from chloritic material in the groundmass and also at the expense of the jadeite which assumes a "dusty" appearance and exhibits marginal alteration to glaucophane (table 1, 3). In some cases the jadeite develops a pale green tint and increases in birefringence to 0.019, indicating a change in composition. The glaucophane is accompanied by idioblastic lawsonite and bands of mica. In some specimens (302/65) glaucophane is less prominent and jadeite crystals are imbedded in a groundmass of pale green, almost isotropic, chlorite.

Igneous rocks.—Thin lenses of variolitic basalt and tuff occur within the basement graywackes and metagraywackes. Those associated with the graywackes are composed of a brown glassy matrix charged with abundant iron-ore and riddled with microlitic needles of plagioclase (302/114). The plagioclase forms sub-radiate clusters and spherical aggregates; the rock strongly resembling the glassy variolites of Angel Island, San Francisco Bay (Ransome, 1894). Many of the variolites are brecceiated and veined with quartz, albite and calcite; while others contain varying amounts of chert and argillaceous fragments, exhibiting transitions into tuffs.

Igneous rocks associated with the basement metagraywackes are of the same type but have been extensively sheared and metamorphosed. Abundant crystallization of pumpellyite is characteristic in these rocks. The pumpellyite occurs as a dense matt of small fibres which form a complex network of veins and infillings between the broken fragments of glassy variolite, but only rarely replace the fragments themselves (302/15). Varying amounts of glaucophane, lawsonite and late albite veins may also be present.

RESIDUAL MASSES

A characteristic feature of the area are masses, principally metamorphic rocks, scattered over the surface formed by the basement graywackes and metagraywackes. These masses vary in size from small boulders to crags 20 feet high (plate 1A). Their contacts with the underlying rocks are exposed in some places and are perfectly sharp, suggesting that the masses cannot be precisely *in situ.*

The macroscopic fabric elements of the residual masses were plotted on a stereographic projection in order to evaluate their structure in relation to the basement rocks. However, no uniform structural pattern common to the various masses could be obtained, let alone any correlation with the structure of the basement rocks. Nevertheless, the distribution of the various blocks is not entirely random since the eclogites are confined to the south-east corner of the area, and the greatest concentration of chert and metachert occurs in the central region.

Considerable changes in both texture and mineralogy may occur within the compass of a single crag, making it possible to follow in some detail the relationships between the various metamorphic types.

The residual masses can be divided into the following groups: (i) chert, (ii) metachert, (iii) altered igneous rocks, (iv) eclogites, (v) glaucophane-schists, and (vi) epidote-amphibolites.

Chert.—The cherts range in color from red to dark green, the former being dominant, and are generally well bedded but shatter easily due to the development of numerous fractures normal to the bedding. The bedding is defined by thin leaves composed of an admixure of chert and shaley material.

In thin sections the cherts contain abundant radiolarian tests within a cryptocrystalline groundmass of quartz. Many are very impure (302/43), and contain finely dispersed chlorite stained with iron, together with much fine-grained unidentifiable subisotropic material. Recrystallization of quartz has generally occurred to varying degrees with resulting destruction of the radiolarian tests. In some cases the cherts have the appearance of micro-breccias; angular fragments of cryptocrystalline chert stained red with a fine limonitic dust being cemented by coarse vein-quartz (302/66).

Metacherts.—The earliest signs of alteration in the cherts (apart from recrystallization of the quartz) is the development of quartz-veins containing tiny stellate clusters of pumpellyite (302/67). At the same time the fine limonitic dust develops into larger aggregates with which are associated small sheaves of stilpnomelane. The crystallization of stilpnomelane is often accompanied by tiny curved fibres of riebeckite which riddle the quartz mosaic (302/50).

With the development of riebeckite the rock assumes a blue color which in some rocks alternates with flesh-pink bands rich in garnet (302/132). The garnet forms small idiomorphic crystals imbedded in the quartz mosaic, together with riebeckite and some crossite. An analysis of this garnet is given in table 2.1, from which it will be seen to approach spessartine in composition. Garnet-bearing metacherts of this type are common in the Franciscan and many similar rocks have been collected from Tiburon Peninsula (San Francisco Bay), and elsewhere.

Specimen series (302/57) collected from a single crag show transitions from brecciated chert with fractures filled with glaucophane and lawsonite, to banded quartz-glaucophane-lawsonite-schists. In the latter almost monomineralic bands of lawsonite alternate with bands of quartz-glaucophane (plate 2D).

In general the strongly banded and siliceous nature of the metacherts make them distinctive rocks in the field and, if one makes the not unreasonable assumption that all were derived from parent rocks of uniform highly siliceous composition, their origin is seldom in doubt.

Altered igneous rocks.—Blocks of altered variolitic basalts and tuffs are of frequent occurrence and are identical with the pumpellyitized variolites described from the basement metagraywackes (p. 102). Indeed, it is not always easy to determine whether some small blocks of altered variolite belong to the basement rocks or are residuals.

A few isolated boulders of carbonated serpentinite were observed among the residual masses but, in common with the latter, they cannot be regarded as precisely in situ. However, their possible significance will be considered subsequently (p. 108).

Eclogite.—Garnet-pyroxene rocks which are referred to eclogite are developed east of the fault where numerous large slabs rest upon the basement metagraywackes. Most of the eclogites exhibit varying degrees of deformation, but there are many exposures of fresh granular eclogite containing bright green pyroxene and evenly distributed red garnets (302/143). An analysis of eclogite from this locality is given in table 1, 6. In some exposures the relative proportions of pyroxene and garnet may vary within a distance of a few inches, so that pyroxene and garnet-rich phases develop. Muscovite and chlorite which are probably of secondary origin are always present, together with rutile and sphene. The chlorite has a rather distinctive radiate habit in thin sections and is a type characteristic of both the California eclogites and some glaucophane-

TABLE 2

	1	2		3		4	
SiO_2	37.39	38.01	Si	3.008		3.003	
TiO_2	0.42	0.62	Ti	0.048		0.023	
Al_2O_3	20.18	19.83	Al	1.915	1.992	1.844	2.019
Fe_2O_3	0.47	2.62	Fe‴	0.029		0.152	
FeO	5.47	23.68	Fe″	0.367		1.563	
MnO	25.96	0.81	Mn	1.770		0.052	
MgO	1.32	3.23	Mg	0.154	3.031	0.585	3.131
CaO	8.58	11.00	Ca	0.740		0.931	
	99.79	99.80					
SG	4.14	4.04					
n	1.798	1.801					

Almandine	55.93
Pyrope	11.11
Spessartine	1.81
Andradite	8.39
Grossularite	22.75
	99.99

1. Spessartine garnet from metachert, Valley Ford. *Anal.* T. W. Bloxam
2. Garnet from eclogite, Valley Ford. *Anal.* T. W. Bloxam
3. Metal atoms in 1 on the basis of 6 oxygens
4. Metal atoms in 2 on the basis of 6 oxygens, and molecular composition

schists (Switzer, 1950). The pleochroism is from colorless to green, N_β = 1.617. $N_\gamma - N_\alpha = 0.006$, $2V_\gamma = 0°$ or very small.

The pyroxene is an acmitic diopside-jadeite or omphacite (table 3, 2) with variable optical properties, even in one thin section, and only average values can be quoted (table 4, 2). It is apparent that this green pyroxene is quite distinct chemically and optically from the colorless jadeite-rich pyroxene in the metagraywackes. No clear optical distinction can be made between pyroxenes referred to omphacite and many other aluminous pyroxenes (e.g. fassaite). Alderman (1936) gives the following optical data for the omphacites: N_β = 1.67-1.70, Z:c = 36-42°, 2V = 58-82° and SG = 3.30-3.36. However, the optics of many omphacites, including those from California, may depart from these values; particularly in respect to refractive index and extinction angle.

TABLE 3

	1	2	3
SiO_2	60.64	53.12	53.31
TiO_2	1.29	0.31	0.26
Al_2O_3	18.17	10.31	10.52
Fe_2O_3	3.68	4.55	4.11
FeO	0.53	3.00	2.84
MnO	0.07	0.08	0.05
MgO	1.09	7.54	8.92
CaO	2.13	15.03	14.00
Na_2O	11.36	5.81	5.90
K_2O	0.25	0.03	0.05
H_2O^+	0.78	0.13	0.16
H_2O^-	0.11	0.06	—
	100.10	99.97	100.12
SG	3.27	3.30	3.34

	4			5		
Si	1.929		2.000	1.917		2.000
Al	0.440	0.071		0.444	0.083	
		0.369	0.991		0.361	1.016
Ti	0.006			0.006		
Fe‴	0.078			0.112		
Fe″	0.089			0.086		
Mn	0.005			0.002		
Mg	0.444			0.449		
Ca	0.561		0.988	0.552		1.000
Na	0.427			0.410		
K	—			0.038		

	6	7	8
Jadeite	77.68	26.26	28.38
Diopside	7.46	50.97	55.10
Acmite	12.39	12.92	11.95

1. Jadeite from metagraywacke, Valley Ford (Bloxam, 1956, p. 494. *Anal.* E. H. Oslund. Mineral contains 12.55% quartz inclusions)
2. Acmitic diopside-jadeite from eclogite, Valley Ford. *Anal.* T. W. Bloxam
3. Acmitic diopside-jadeite from eclogite, Healdsburg (Birch, 1943, p. 272. *Anal.* F. Gonyer)
4. Metal atoms in 2. on the basis of 6 oxygens
5. Metal atoms in 3. on the basis of 6 oxygens
6. Molecular percent end-members in 1.
7. Molecular percent end-members in 2.
8. Molecular percent end-members in 3.

Tilley (1938) has distinguished the omphacites from other aluminous pyroxenes of omphacite-type on the basis of SiO_2 (52-55.5%), and the coordination of the aluminum which, in the omphacites, largely replaces the Y group. From the analysis and structural formula for the Valley Ford eclogite pyroxene (table 3, 4), both SiO_2 and the co-ordination of aluminum are in agreement with omphacite.

An analysis of the eclogite garnet is given in table 2, 2 and compares with analyses of garnet from other California eclogites (Birch, 1943; Borg, 1956) although it differs in having slightly more Ca and lower Mg. The composition of this and other garnets from California eclogites and glaucophane-schists lies within, or very close to, the field of "eclogite garnet" (Eskola, 1921; Pabst, 1931, 1955; Borg, 1956).

Within a single exposure of eclogite the effects produced by deformation can be examined in some detail. The initial stages are largely mechanical and produce a crude flaser-structure defined by streaks of broken pyroxene and garnet. The development of glaucophane may be apparent macroscopically at this stage, but as the deformation increase blue streaks of the mineral become common. Within a few inches breakdown of the granular eclogite yields a crudely foliated glaucophane-rock with variously preserved remnants of eclogite garnet and pyroxene which form discontinuous lenses or schlieren. Some of the eclogites contain conspicuous radiating clusters of fibrous glaucophane, many over 2″ long (302/143).

TABLE 4

	1	2	3
α	1.659 colorless	1.673 pale green	1.688 pale green
β	1.663 colorless	1.688 pale green	1.692 pale green
γ	1.670 colorless	1.696 green	1.710 pale yellow
$\gamma-\alpha$	0.011	0.023	0.022
$2V_\gamma$	86°	72°	70-82°
γ:c	53° (Y=b)	58° (Y=b)	44-50°
Disp.	Very strong	Moderate	Moderate (r>v)

1. Jadeite from metagraywacke, Valley Ford (Bloxam, 1956, p. 490)
2. Acmitic diopside-jadeite, Valley Ford
3. Acmitic diopside-jadeite, Healdsburg (Optical data from Borg, 1956, p. 1571)

Glaucophane-schists derived from eclogites.—As described above, glaucophane develops in association with the deformation of the eclogites. Further mineralogical changes can be observed in thin sections where the green eclogite pyroxene exhibits marginal replacement and pseudomorphism by glaucophane ($2V_a = 47°$, Z:c $= 4°$) in the form of moderately stout prisms which are often zoned, passing into deeper blue crossite ($2V_a = 0$-$30°$). The crossite may in turn have a marginal rim of blue-green hornblende (302/46). In some rocks aggregates of small granular epidote crystals occur.

The eclogite garnet generally persists after the disappearance of the pyroxene and, even in glaucophane-rocks where a strong superimposed schistosity and new minerals have developed, the distribution of the garnets, or their alteration products, preserve a vague remnant of eclogite texture. Mineralogical changes in the garnet are numerous and the mineral has been replaced, and even pseudomorphed by any, or more than one, of the following minerals: chlorite, lawsonite, pumpellyite, and occasionally glaucophane (plate 2E).

Rutile from the eclogite often develops rims of sphene which may be mantled by calcite. The subsequent history of the eclogite chlorite is not clear, but some at least has been observed altered to pumpellyite. Mica appears to be the only constituent of the eclogite that remains unaffected, although some recrystallises forming smaller crystals parallel to the schistosity. The precise composition of the mica requires further chemical investigation since the K_2O content of the eclogite and derived glaucophane-schist (table 1, 5 and 6) is lower than one would expect from the amount of mica present, assuming the latter to be muscovite.

The final mineral assemblage is typically represented by glaucophane/crossite-lawsonite-pumpellyite-mica-schists. Rocks of comparable mineralogy may also be derived from graywackes (below) so that in the absence of definite relict textures and minerals the origin of many glaucophane-schists at Valley Ford cannot readily be determined (plate 2F).

Glaucophane-schists derived from graywackes.—The development of glaucophane-schist from jadeite-bearing metagraywackes has been described from the basement rocks (p. 102). Similar rock-types occur as residual masses and one large crag may display various stages in the development of glaucophane and associated minerals (plate 2C).

Eventually the composition and mineralogy becomes similar to that of the altered eclogites, however the texture tends to remain finer in grain-size (table 1, 4). Glaucophane forms rather sinuous bundles of small fibres which are bent around idioblastic crystals of pumpellyite and lawsonite. Garnet has not been observed in these rocks (cf. Borg, 1956, p. 1572). There are some chemical differences between these rocks and those of definite eclogitic origin; in particular the minor oxides TiO_2 and MnO are consistantly lower (p. 111).

Epidote-amphibolites.—Rocks containing an amphibole other than glaucophane are common. Their mineralogy is relatively simple consisting essentially of epidote, hornblende and albite (302/23). Pumpellyite may occasionally be present in small amount, but lawsonite never occurs. Two types of amphibole have been observed; one strongly colored in thin section, and the other an almost colorless variety. The former is the same amphibole that occurs as rims or patches in association with glaucophane and crossite in the glaucophane-schists (p. 106). This mineral appears to be the same as "carinthine" (hornblende) described by Murgoci (1904) from the California glaucophane-rocks and has the following optical properties: X = colorless, Y = green, Z = deep blue-green, $N_\beta = 1.660$, $N_\gamma - N_\alpha = 0.024$, $2V_\alpha = 73\text{-}75°$ and Z:c = 17-20°. Hutton (1940) has described an actinolite ($Al_2O_3 = 3.88\%$) from albite-stilpnomelane-actinolite-schist in New Zealand which has optical properties very similar to the Valley Ford amphibole. The colorless amphibole has not been observed in association with glaucophane and has very weak pleochroism in pale yellows and a $2V_{\alpha} = 80\text{-}84°$, suggesting affinities with soda-tremolite or edenite.

Albite and epidote are always present, the former often in two generations, the first defining the foliation while the second forms later veins and irregular aggregates.

A few epidote-amphibolites contain relict glaucophane mantled by the blue-green hornblende. These rocks usually exhibit evidence of later brecciation and may represent retrograde glaucophane-rocks. However, there is no evidence indicating that all the epidote-amphibolites were so derived since many occur as lenses and schlieren within masses of glaucophane-schist against which they exhibit sharp boundaries.

MERCED FORMATION (PLIOCENE)

Horizontal or very gently dipping soft marine sands and clays of the Merced Formation form the higher ground around Valley Ford. The base of the Merced is exposed at one locality (see below) while elsewhere its base can be mapped with reasonable accuracy using topographic features. It is probable, however, that the present surface of Franciscan rocks corresponds very closely to the pre-Merced erosion surface.

Contact between the Merced and underlying rocks is exposed in the creek immediately below the bridge at the extreme southeast corner of the map. A vertical section of about 25 feet of Merced is exposed which is fine-grained throughout. A few blocks of glaucophane-schist not more than 1 to 2 feet long are imbedded in the Merced at its base but are quite absent at higher levels. Traverses over adjacent outcrops of Merced failed to reveal any incorporated blocks of glaucophane-schist.

ORIGIN OF THE RESIDUAL MASSES

The presence of numerous crags and boulders of Franciscan metamorphic rocks resting upon unaltered Franciscan graywackes indicates that the former cannot be precisely *in situ*. However, since the general metamorphic character of some of the residual masses conforms to that of the basement metagraywackes, and the distribution of certain rock-types is not entirely random (p. 103), the blocks do not appear to have undergone extensive transport. The enormous size of many of the blocks also tends to preclude large-scale transport.

It is probable that the blocks occupied their present positions before Merced times since many of the glaucophane-schist crags exhibit numerous *Pholas* borings (plate 1B) and horizontal wave-cut ledges produced by marine conditions; presumably the Merced sea. While several explanations are possible the writer is of the opinion that the residual masses formed an original cover of extremely hard and resistant metamorphic rocks, remnants of which remained as "collapsed" relicts upon a pre-Merced erosion surface which cut progressively lower into much softer graywackes and metagraywackes beneath.

In California the glaucophane-schist metamorphism may occur at various levels in the thick geosynclinal belt of Franciscan rocks. The metamorphism is frequently, but not exclusively, associated with subjacent bodies of serpentinite (Ransome, 1894; Taliaferro, 1943). While no serpentinite occurs *in situ* at

Valley Ford. a few blocks of carbonated serpentinite (p. 104) may represent remnants of former ultrabasic intrusions.

CHEMICAL AND MINERALOGICAL RELATIONSHIPS

From an examination of the textural and mineralogical features of the metamorphic rocks two modes of origin are indicated; the first from graywackes. cherts and igneous rocks, and the second from eclogites. The abundance of the latter type indicates that eclogite must have been originally present in considerable amounts (Borg. 1956). The observed mineralogical relationships and transformations are summarized in table 5.

TABLE 5

Graywacke		Jadeite-metagraywacke		Glaucophane-schist
Quartz fragments	→	Quartz mosaic	→	– –
Soda-plagioclase	→	Jadeite, Quartz	→	Glaucophane
Chlorite, Mica, Clay minerals, Igneous fragments	→	Chlorite, Mica, Glaucophane, Lawsonite, Pumpellyite, Sphene	→	

Eclogite		Glaucophane-schist
Garnet	→	Relict garnet, Chlorite, Lawsonite, Pumpellyite, Glaucophane
Omphacite	→	Relict omphacite, Glaucophane/crossite, ?Chlorite
Chlorite	→	Chlorite, Pumpellyite
Mica	→	Mica
Rutile, Sphene	→	Sphene, Calcite

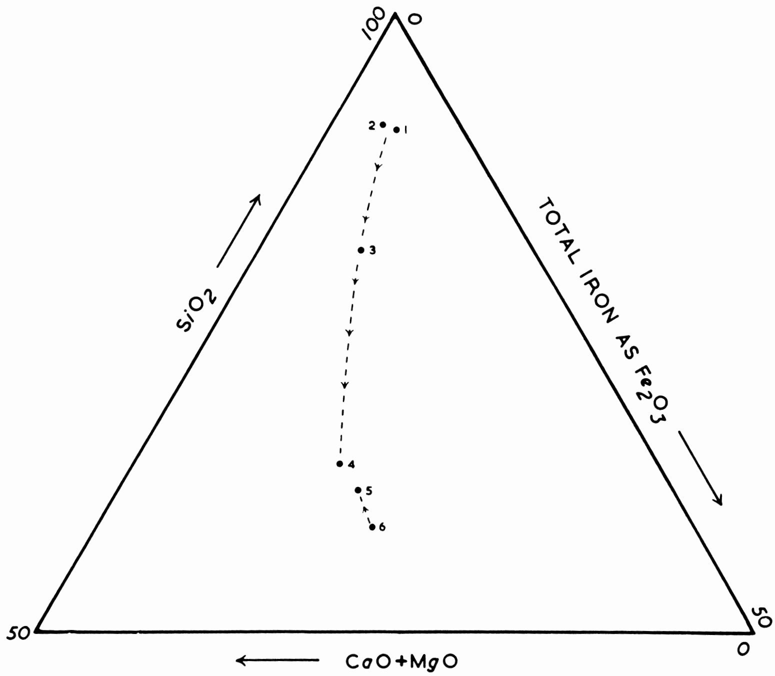


Fig. 2. Triangular diagram illustrating the major changes in composition during glaucophanization of the graywackes and eclogite at Valley Ford. The analyses plotted correspond to the numbers in Table 1.

All the rock analyses have been plotted on a ternary diagram (fig. 2) in terms of SiO_2, total iron as Fe_2O_3 and $MgO + CaO$; these showing the greatest variation among the major oxides. There is virtually no change in bulk composition during the development of quartz-jadeite metagraywacke from graywacke. Hence jadeite forms under conditions appropriate to the glaucophane-schist facies in rocks of rather restricted chemical composition (low Fe, Mg and Ca). The succeeding phases in which more glaucophane develops, some at the expense of the jadeite, are accompanied by an increase in Fe, Mg, Ca and a decrease in Si and Na. This trend continues towards a final assemblage which is commonly glaucophane-lawsonite-pumpellyite-schist. These changes in bulk composition could be due either to differences in the original composition of the graywackes, or to metasomatism. While the former possibility cannot be entirely excluded, the extremely constant chemical composition of the Franciscan graywackes (p. 98) appears to be reflected through analyses 1-4, table 1: particularly TiO_2, Al_2O_3 and MnO. This, in conjunction with evidence from relict textures and transitional phases suggests metasomatism rather than large differences in original composition.

The initial chemical composition of the eclogites must be one which is more appropriate to the development of glaucophane-schist since only small changes in composition are involved in their transformation; the final product approaching the composition and mineralogy of the glaucophanized graywackes. Of the minor oxides, both TiO_2 and MnO are consistently higher than in the metagraywackes.

The absence of albite in the greater majority of glaucophane-rocks at Valley Ford, and the progressive elimination of omphacite and eclogite garnet, indicates that these minerals are unstable in the glaucophane-schist facies. However, manganese garnets are apparently stable in association with glaucophane (p. 103; Miyashiro and Banno, 1958). The eclogites must therefore have formed prior to, and under different conditions, from those of the glaucophane-schist facies (Turner, 1951). In general the mineralogical character of the glaucophane-schists has affinities with the greenschist facies (Turner, 1951; Miyashiro and Banno, 1958), but the instability of albite and the presence of hydrous minerals with high density, notably glaucophane, lawsonite and pumpellyite, suggests certain conditions perculiar to the glaucophane-schist facies, possibly high water-vapor pressure (Yoder, 1950).

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