American Journal of Science

JANUARY 1945

ECLOGITE FROM THE CALIFORNIA GLAUCOPHANE SCHISTS.*

GEORGE SWITZER.

ABSTRACT. One of the varied rock types making up the California glaucophane schists is true eclogite, corresponding to typical eclogite in mineral composition, chemical composition, texture, and specific gravity. The California glaucophane schists, and therefore the eclogite, were formed under conditions of moderate temperature and pressure, by hydrothermal contact metamorphism. The California eclogite is thus a mode of occurrence of this rock of a different type from those previously recognized by most writers.

INTRODUCTION.

It was first suggested by Ransome (1894) that the glaucophane schists of the California Coast Ranges were formed along the periphery of intrusive serpentine bodies, from rocks of the Franciscan formation, by contact metamorphism. Several papers by other investigators give evidence to support the theory of a contact metamorphic origin for these unusual rocks. The most recent paper on this subject is that of Taliaferro (1942), in which is given a detailed account of the occurrence and mode of formation of the glaucophane schists. There now seems little doubt that contact metamorphism brought about by serpentine intrusives is the most reasonable explanation for the origin of these rocks.

The term glaucophane schist is broadly used to include a wide variety of rock types, some of which contain no glaucophane. All of these are intimately associated in the field and undoubtedly were formed nearly contemporaneously and through the same genetic process.

Holway (1904) designated as eclogite one of the rock types

* Contribution from the Department of Mineralogy and Petrography, Harvard University, No. 265.

found in the California glaucophane schists. His determination was based upon one chemical analysis of a rock composed essentially of garnet and green pyroxene. No chemical analyses were made of the mineral components of the rock. Because of the contact metamorphic origin of the glaucophane schists, Holway's usage of the term eclogite has been questioned by some later investigators. For example, Taliaferro states (1942, page 1590):

"Holway compared them with Scandinavian eclogite and stated that they were derived from intrusive gabbros. The green pyroxene (diopside) was called omphacite and the actinolite smaragdite. The eclogites of Norway and the Alps are the result of plutonic metamorphism and are everywhere associated with granulites, gneisses, and other completely metamorphosed rocks. The great difference in the mode of occurrence and association of the true eclogite and the Franciscan schists was not commented on by Holway. . . ."

It is true that in recent years the term eclogite has become almost synonymous with highest pressure and temperature conditions of metamorphism. In the facies classification of Eskola, eclogite is placed in the highest pressure-temperature group of all the metamorphic rocks. In the classification of Grubenmann-Niggli, eclogite is considered to belong to the katabzone, or extreme depth zone of metamorphism.

However, it seems to the writer that the fact has sometimes been overlooked that eclogite refers to a rock composed of garnet and pyroxene having certain specified ranges in composition, irrespective of mode of origin.

During a study of the California glaucophane schists the writer found several occurrences of a rock corresponding to Holway's eclogite. A detailed study of these rocks showed them to be true eclogites in every respect. In this paper the word eclogite is used to denote a rock that consists essentially of (a) the pyroxene, omphacite and (b) a garnet in which almandite and pyrope are dominant. This is in agreement with Haüy's original definition.

FIELD RELATIONS.

The most notable occurrence of eclogite found is one mile east of the Junction School, on the Mill Creek road, near
Healdsburg, Sonoma County. Here is an area several square miles in extent covered with scattered outcrops of glaucophane schists of many types. The eclogite is restricted to a single outcrop approximately 50 x 50 feet. The whole schist area is long and narrow, extends in a northwest-southeast direction, and is bordered on the south by a serpentinite sill striking approximately N. 50° W. and dipping 70° NE.

A second noteworthy occurrence of eclogite examined by the writer is near Reed's Station, Tiburon Peninsula, Marin County. This occurrence is restricted to a few small outcrops scattered over an area approximately 100 x 100 feet. Surrounding the eclogite outcrops is a larger area of various types of glaucophane schists. The glaucophane schist area is in turn in contact with a serpentinite sill, which, standing nearly vertically, makes up the backbone of the peninsula.

Other smaller occurrences of eclogite were found at Jenner, on the south side of the mouth of the Russian River, Sonoma County; two miles east of Occidental, Sonoma County; and on the Syke Ranch, on the south fork of the Eel River, 10 miles northeast of Laytonville, Mendicino County.

**Petrography.**

The California eclogite is megascopically deep green in color, more or less uniformly dotted with red garnets. Microscopically it is granoblastic, the grain size ranging from 0.05 to 2.0 millimeters. Garnet and omphacite are the most conspicuous minerals. Glaucophane, sphene, rutile, chlorite, and hornblende are present in small amounts.

The mode of an average specimen is approximately as follows: garnet 28 per cent, omphacite 57, glaucophane 2, hornblende 3, chlorite 4, sphene 4, rutile 2.

The average specific gravity of eclogite from several localities in Sonoma and Marin counties is 3.43.

**Mineralogy.**

*Omphacite:* The pyroxene from eclogite found near Healdsburg, Sonoma County, California, was separated to a purity of 99 per cent and analyzed by Mr. F. A. Gonyer. The result
George Switzer—Eclogite

Table I.

Pyroxene from California Eclogite.

<table>
<thead>
<tr>
<th></th>
<th>1.</th>
<th>2.</th>
<th>3.</th>
<th>4.</th>
<th>5.</th>
<th>6.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>53.31</td>
<td>0.888</td>
<td>1.776</td>
<td>0.888</td>
<td>1.94</td>
<td>1.95</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.26</td>
<td>0.003</td>
<td>0.006</td>
<td>0.003</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>10.52</td>
<td>0.103</td>
<td>0.309</td>
<td>0.206</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>4.11</td>
<td>0.026</td>
<td>0.078</td>
<td>0.052</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>FeO</td>
<td>2.84</td>
<td>0.040</td>
<td>0.040</td>
<td>0.040</td>
<td>0.09</td>
<td>1.10</td>
</tr>
<tr>
<td>MnO</td>
<td>0.05</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>8.42</td>
<td>0.208</td>
<td>0.208</td>
<td>0.208</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td>14.50</td>
<td>0.258</td>
<td>0.258</td>
<td>0.258</td>
<td>0.56</td>
<td></td>
</tr>
<tr>
<td>Na₂O</td>
<td>5.90</td>
<td>0.095</td>
<td>0.095</td>
<td>0.190</td>
<td>0.41</td>
<td>0.97</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.05</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂O(+)</td>
<td>0.16</td>
<td>0.009</td>
<td>0.009</td>
<td>0.018</td>
<td>0.04</td>
<td></td>
</tr>
</tbody>
</table>

100.12  2.781  f = 2.16

1. Omphacite—from eclogite near the Junction School, Mill Creek area, Healdsburg Quadrangle, California. F. A. Gonyer, analyst. Analysis first published by Birch (1943).

2. Molecular ratio.


4. Positive atoms of the ratio in column 2.

5. Ratios of column 4 each multiplied by the factor \( f \), in order to bring the total oxygen to 6.

6. Isomorphous groups of atoms combined to yield the formula \((\text{Ca,Na})(\text{Mg,Fe}^\text{II},\text{Fe}^\text{III},\text{Al})\text{SiO}_4\).

of the analysis is given in Table I. The one per cent impurity was chiefly sphene.

In Table II the California pyroxene is compared with pyroxene from three other localities. It is apparent from this comparison that the California pyroxene is a typical eclogite pyroxene, the soda-rich variety commonly called omphacite.

Garnet: The garnets of the glaucophane schists of California have been described in detail by Pabst (1931) who found that there is considerable range in their composition. The proportion of almandite is especially constant, varying from 48 to 56 per cent. The grossularite content varies from 8 to 21 per cent, andradite from 4 to 24 per cent, and pyrope from 10 to 20 per cent. The California eclogite garnets fall within the composition ranges defined by Eskola (1921) and Heritsch (1926) as being characteristic of eclogite garnets.

Associated minerals: In addition to omphacite and garnet
Table II.
Composition of Pyroxene from Eclogites.
Metal Atoms on Basis of Total Oxygen Number of 6.

<table>
<thead>
<tr>
<th></th>
<th>1.</th>
<th>2.</th>
<th>3.</th>
<th>4.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.94</td>
<td>1.97</td>
<td>1.98</td>
<td>1.93</td>
</tr>
<tr>
<td>Ti</td>
<td>0.01</td>
<td>0.03</td>
<td>0.01</td>
<td>1.99</td>
</tr>
<tr>
<td>Al</td>
<td>0.45</td>
<td>0.42</td>
<td>0.44</td>
<td>0.50</td>
</tr>
<tr>
<td>Fe&quot;&quot;</td>
<td>0.11</td>
<td>0.08</td>
<td>0.16</td>
<td>0.08</td>
</tr>
<tr>
<td>Fe&quot;</td>
<td>0.09</td>
<td>0.10</td>
<td>1.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Mg</td>
<td>0.45</td>
<td>0.35</td>
<td>0.35</td>
<td>0.50</td>
</tr>
<tr>
<td>Ca</td>
<td>0.56</td>
<td>0.59</td>
<td>0.50</td>
<td>0.64</td>
</tr>
<tr>
<td>Na</td>
<td>0.41</td>
<td>0.29</td>
<td>0.88</td>
<td>0.27</td>
</tr>
<tr>
<td>K</td>
<td>0.02</td>
<td>0.01</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

\[ \alpha = 1.673^* \]
\[ \beta = 1.679 \]
\[ \sigma = 1.691 \]
\[ \text{Sign} = (+) \]
\[ 2V = 60^\circ \]
\[ Y = b \]
\[ \text{Orientation} = Z:z=39^\circ, Z:x=43^\circ, Z:y=36^\circ, Z:x=42^\circ \]
\[ \text{Sp. Gr.} = 3.34\pm0.02, 3.31, 3.31, 3.30 \]

*Indices in column 1 ± 0.002.

1. **Omphacite**—near the Junction School, Mill Creek Area, Healdsburg Quadrangle, California. F. A. Gonyer, analyst. Analysis first published by Birch (1948).


3. **Omphacite**—Fay, France. Raoult, analyst (Brière, 1920).


Several other minerals are found in varying amounts in the eclogite. These other minerals are not of contemporaneous origin with omphacite and garnet, but were formed at a later stage in the genetic history of the rock. The eclogite constituents, in the approximate order in which they were formed, are as follows: garnet and omphacite, hornblende, muscovite, clinozoisite, actinolite, glaucophane, pumpellyite, lawsonite, albite, quartz, rutile, sphene, chlorite, and pyrite.

Omphacite and garnet were formed together, the garnet having formed as euhedral crystals in a granular pyroxene groundmass. There is a small amount of muscovite present which is commonly concentrated about the garnet crystals.
A second set of minerals is clearly later than the main eclogite. The most abundant of these are hornblende, glaucophane, rutile, sphene, chlorite, and pyrite. The occurrence of these minerals is almost entirely restricted to narrow seams or fractures irregularly traversing the massive eclogite. The hornblende is usually concentrated along narrow fractures. Occasionally hornblende has entirely replaced the omphacite with a resultant rock that is a typical garnet-amphibolite. Glaucophane is, in the same way, strikingly concentrated along fracture planes in the main eclogite mass. It is often found as peripheral zones about hornblende. Chlorite is also strongly concentrated along narrow fractures, with sphene, glaucophane, hornblende, and pyrite. In thin section chlorite can be seen replacing garnet, hornblende, and glaucophane. The sphene has formed in white to pale-yellow anhedrons up to one centimeter in size, associated with smaller amounts of rutile. Pyrite is common and is also restricted in its occurrence to the seams of late formed minerals.

**Derivation.**

One chemical analysis has been made of California eclogite (Holway, 1904). Another has been calculated by the writer using the mode given on page 3, and chemical compositions of the constituent minerals is given in Table I and by Pabst (1931). These analyses are given in Table III, with three eclogite analyses from other localities, and one analysis of Franciscan basalt. The California eclogite corresponds well to those of Norway, Switzerland, and Scotland, and to the basalt.

Field relations show clearly that the California eclogite is one of the varied rock types making up the California glaucophane schists. In addition, the eclogite is closely associated with Franciscan basalts and was undoubtedly derived from them by hydrothermal contact metamorphism caused by serpentine intrusives.

There is no evidence to indicate that the Franciscan horizon now exposed at the surface was at any time deeply buried. It seems certain, therefore, that the eclogite was formed under conditions of moderate pressure. Low temperature of the peridotite magma at the time of its intrusion is indicated by complete lack of thermal metamorphism along the contacts where no glaucophane schist is found.
from the California Schists.

**Table III.**

ECLOGITE and BASALT ANALYSES.

<table>
<thead>
<tr>
<th></th>
<th>1.</th>
<th>2.</th>
<th>3.</th>
<th>4.</th>
<th>5.</th>
<th>6.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>44.15</td>
<td>46.5</td>
<td>50.21</td>
<td>41.5</td>
<td>44.06</td>
<td>46.60</td>
</tr>
<tr>
<td>TiO₂</td>
<td>trace</td>
<td>3.6</td>
<td>1.69</td>
<td>1.2</td>
<td>2.29</td>
<td>2.87</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>10.18</td>
<td>13.5</td>
<td>13.78</td>
<td>15.9</td>
<td>17.68</td>
<td>15.28</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>11.92</td>
<td>3.8</td>
<td>1.49</td>
<td>3.4</td>
<td>3.40</td>
<td>3.98</td>
</tr>
<tr>
<td>FeO</td>
<td>13.04</td>
<td>8.0</td>
<td>11.32</td>
<td>16.2</td>
<td>9.96</td>
<td>8.17</td>
</tr>
<tr>
<td>MnO</td>
<td>0.18</td>
<td>0.4</td>
<td>n.d.</td>
<td>0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>16.18</td>
<td>7.5</td>
<td>6.69</td>
<td>4.2</td>
<td>7.19</td>
<td>5.4</td>
</tr>
<tr>
<td>CaO</td>
<td>4.51</td>
<td>13.5</td>
<td>11.09</td>
<td>12.4</td>
<td>11.58</td>
<td>10.68</td>
</tr>
<tr>
<td>Na₂O</td>
<td>5.11</td>
<td>3.6</td>
<td>2.12</td>
<td>2.6</td>
<td>2.92</td>
<td>2.26</td>
</tr>
<tr>
<td>K₂O</td>
<td>2.09</td>
<td>0.44</td>
<td>0.1</td>
<td>0.91</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>H₂O (+)</td>
<td>0.95</td>
<td>0.24</td>
<td>0.17</td>
<td>3.63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂O (-)</td>
<td>0.13</td>
<td>trace</td>
<td>0.12</td>
<td>0.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P₂O₅</td>
<td>F</td>
<td>n.d.</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cl</td>
<td>0.07</td>
<td>0.07</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SO₄</td>
<td>0.13</td>
<td>0.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>0.05</td>
<td>0.06</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sp.Gr. 3.442 3.61 3.54 2.85

---

1. **Eclogite**—Coyote Creek, six miles northeast of San Martin, Santa Clara County, California. Composed of garnet 40 per cent, omphacite 40 per cent, actinolite, glaucophane, and white mica together 20 per cent. C. B. Allen, analyst (Holway, 1904).

2. **Eclogite**—near the Junction School, Mill Creek area, Healdsburg Quadrangle, California. Composition calculated from analyzed mineral constituents and mode. (Specific gravity measured by F. Birch.)

3. **Eclogite**—hills west of the “Postman’s Path” to Ardintou, Glenelg. H. R. Alderman, analyst (Alderman, 1936).

4. **Eclogite**—Duen type, Vanelosdaien, Sondmore, Norway. Analysis calculated from mode of analyzed minerals (Eskola, 1921).

5. **Eclogite**—Sulztal, Ötztal, Tyrol (Hezner, 1903, p. 446).

6. **Basalt**—near the mouth of Duvuol Creek, two miles north of Camp Meeker, Sonoma County, California. P. A. Gonyer, analyst.

**Conclusion.**

The known occurrences of eclogite have recently been summarized and classified into the following six types (Davidson, 1943):

1. Schlieren and lenses in garnet-bearing anorthosite.
2. Schlieren and lenses in garnetiferous charnockite, pyroxene-granulite or pyroxene-gneiss.
3. Lenticular masses in granite-gneisses and migmatites.
4. Schlieren and segregations in peridotite and dunite.
George Switzer.

(5) Sheet-like masses, associated with amphibolite, in paragneiss.

(6) Nodules, associated with peridotite and other ultrabasic tyes, in kimberlite pipes of South Africa.

To these well-recognized types of occurrence should be added the California type:

(7) Irregular masses, associated with glaucophane-bearing rocks, formed by hydrothermal contact metamorphism under moderate temperature and pressure conditions. Intrusive peridotite sills and dikes were the metamorphosing agents.

ACKNOWLEDGMENTS.

This paper represents a portion of a general study of the glaucophane schists of California that was made possible by financial aid from two sources, the Holden Fund of the Department of Mineralogy, Harvard University, and Mr. M. Vonsen, of Petaluma, California. For this assistance the writer is deeply grateful. Professors Charles Palache and Esper S. Larsen, of Harvard University, have been most generous with aid of many sorts.

REFERENCES.


YALE UNIVERSITY,
NEW HAVEN, CONNECTICUT.