The Colebrooke Schist of Southwestern Oregon and its Relation to the Tectonic Evolution of the Region

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By R. G. COLEMAN

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THE COLEBROOKE SCHIST OF SOUTHWESTERN OREGON AND ITS RELATION TO THE TECTONIC EVOLUTION OF THE REGION

By R. G. Coleman

ABSTRACT

The Colebrooke Schist occupies a triangular area of about 100 square miles within the Coast Range province of southwestern Oregon. Late Cretaceous thrusting on serpentinite "tectonic sheets" has placed much of the Colebrooke Schist on top of Mesozoic eugeosynclinal and miogeosynclinal sedimentary rocks such as the Galice, Otter Point, and Dothan Formations, and the Myrtle Group. Eocene conglomerates of the Umpqua Formation containing clasts from both the Colebrooke Schist and serpentinite rest unconformably on the Colebrooke Schist and its thrust contacts with the underlying Mesozoic sedimentary rocks.

Graywackes of the Otter Point and Dothan Formations are chemically and lithologically similar. Structural and stratigraphic evidence suggests that these graywackes may have been deposited at the same time. The large amount of volcanic debris and associated submarine volcanic centers within the westernmost exposed margin of the Otter Point suggests that it may represent the eastern flank of a Late Jurassic island arc.

The serpentinite "tectonic sheets" are derived from harzburgites and dunites. The highly sheared serpentinites contain tectonic inclusions of glaucophane schist, diabase, gabbro, and Colebrooke Schist. The serpentinites may represent parts of the oceanic mantle that were transported to their present position by repeated tectonic movements.

The Colebrooke Schist is predominantly metamorphosed thin-bedded shale and sandstone and associated minor pillow lavas, tuff, and chert. The mineral assemblages of the pelitic and basaltic rocks reflect metamorphism intermediate between blueschist and greenschist facies. The metabasalts typically contain actinolite, epidote, albite, chlorite, (pumpellyite). The mineral assemblage for the pelitic rocks consists of quartz, chlorite, phengitic mica, albite, lawsonite, and epidote. Bulk chemical compositions of Colebrooke pelitic schists and Galice sedimentary rocks are similar to but distinct from Dothan and Otter Point graywackes. The high silica and aluminum, together with low calcium and sodium of the Colebrooke and Galice Formations, make them compositionally different from typical graywackes.

Two periods of deformation can be recognized in the Colebrooke Schist: S_1, related to metamorphic recrystallization with development of foliation parallel to the original sedimentary bedding, and S_2, characterized by folding at high angles to original bedding and foliation. Axes of the S_2 folds are generally north-south with recumbent folds exhibiting vergence to the east. The structural data are consistent with eastward thrusting of the Colebrooke Schist.

Analyses for Rb, Sr, K, and strontium isotopes on the Colebrooke, Galice, Dothan, and Otter Point Formations show a similarity in source materials. The low initial Sr^{87}/Sr^{86} values (Colebrooke Schist, 0.7065 ± 0.0011 (1σ); Galice Formation, $0.7051 \pm 0.0011 (1\sigma)$; Dothan Formation, $0.7050 \pm 0.0007 (1\sigma)$; Otter Point Formation, $0.7050 \pm 0.0007 (1\sigma)$) are intermediate between those for oceanic basalts (0.7035) and the composition of sea water during the Jurassic (0.7070), as determined from the isotopic composition of strontium in primary fossil carbonate. These data suggest that a reconstructed source terrane for the Colebrooke, Galice, Otter Point, and Dothan Formations would be mainly reworked eugeosynclinal sedimentary and volcanic rocks or oceanic volcanic material; the amount of detritus derived from a significantly older continental crust would be small. On a strontium evolution diagram, isotope data from the Colebrooke Schist show excessive scatter, but in a gross sense the data are compatible with a metamorphic age of approximately 130 m.y. (million years), or Early Cretaceous.

The Colebrooke Schist represents fine-grained pelitic sediments deposited presumably during the Late Jurassic in a deep-ocean environment west of the present continental margin. During the Early Cretaceous, these marine sediments were recrystallized under conditions intermediate between blueschist and greenschist facies. Late Cretaceous thrusting, perhaps related to ocean floor spreading, has transported the Colebrooke Schist eastward as plates on top of younger Mesozoic sedimentary rocks, the eastward part of the Colebrooke protolith.

INTRODUCTION

The Colebrooke Schist of southwestern Oregon, first described by Diller (1903), occupies an important position relative to the geologic history of this area. The Colebrooke Schist has been described in general terms in several reports (Diller, 1903; Dott, 1965; Koch, 1966; Baldwin, 1968); none of these, however, considered the entire outcrop area of the schists, nor were detailed petrographic or structural studies attempted. The purpose of this study is to examine the Colebrooke Schist in detail to relate it to the geology of the region. Important problems relative to this study are: (1) What was the protolith before metamorphism? (2) What metamorphic facies does the schist represent, and what were the probable pressure-temperature conditions during metamorphism? Is there any metamorphic zonation? (3) What was the style of deformation during and following metamorphism? (4) What is the relation between the serpentinites and Colebrooke Schist? (5) What is the age of metamorphism?

The investigation of these problems began in 1960 as part of a study on metasomatism related to serpentinites of southwestern

Oregon. Areal mapping of the Colebrooke Schist was begun in 1963 and continued through 1968. During this period approximately 250 samples from the Colebrooke Schist were collected for petrographic study. In order to establish mineral asemblages and possible metamorphic zonation (fig. 1), the author selected samples for a full areal coverage of the schist. These same samples were the basis for detailed petrographic and chemical studies. In 1965, B. L. Wood, New Zealand Geological Survey, made a reconnaissance structural study of the Colebrooke Schist along the Rogue River from Agness to the Lobster Creek Bridge.

ACKNOWLEDGMENTS

I am grateful to colleagues who have contributed directly and indirectly to this report. Norman J Page, U.S. Geological Survey, and Bryce Wood, New Zealand Geological Survey, assisted me in parts of the fieldwork. Ewart Baldwin, University of Oregon, offered suggestions concerning geologic problems of the study. David Jones, U.S. Geological Survey, identified the fossils collected, and his knowledge of Oregon Mesozoic stratigraphy was helpful. Robert Dott, University of Wisconsin, whose special knowledge of southwest Oregon geology enabled him to make a particularly helpful analysis of the original draft, reviewed the manuscript. Preston Hotz, U.S. Geological Survey, also reviewed the manuscript and offered information about his geologic fieldwork in southwest Oregon. Edward Clifton, Ralph Hunter, and Larry Phillips, U.S. Geological Survey, discussed with me their work on the marine geology of the south Oregon coast, which was done at the same time as this study. Zell Peterman, U.S. Geological Survey, did a study of the strontium isotopes and their relation to origin and age of the sedimentary and metasedimentary rocks. Porter Irwin and Clark Blake, U.S. Geological Survey, gave me valuable information about correlation of units between Oregon and California.

REGIONAL SETTING

The Colebrooke Schist occupies an approximately triangular area of 100 square miles within the Gold Beach, Port Orford, Agness, and Collier Butte 15-minute quadrangles (pl. 1). The area is within the Coast Range province, which is bounded on the west by the Pacific Ocean and on the east by the Klamath Mountain province. The province is characterized by strong relief that averages approximately 2,000 feet; the highest elevation is approximately 4,600 feet. The Rogue River bisects the triangular outcrop of the Colebrooke Schist and is joined on the eastern boundary of the outcrop by the Illinois

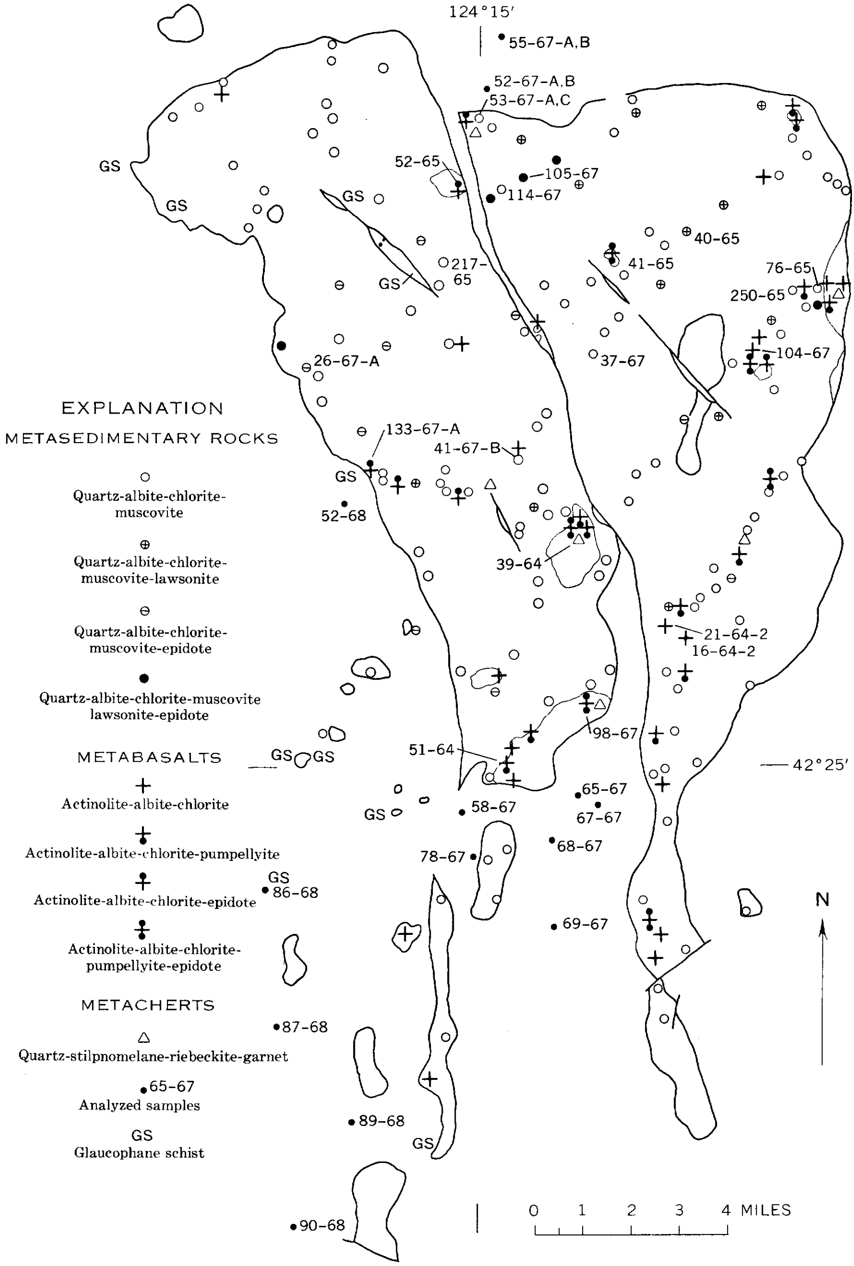

Figure 1.—Location and mineral assemblages of samples from the Colebrooke Schist.

River. In the south, the westward drainage is by the Pistol and Chetco Rivers; in the north, by the Elk River. The region is heavily timbered or brush covered. Access along the coast is by Highway 101, from which numerous logging roads extend eastward. Recent logging road construction within the National Forest lands provides excellent exposures and access to previously remote areas.

The eastern boundary of the area is represented by a thick sequence of Tertiary sandstones that occupies a narrow downfaulted trough (Baldwin, 1965). In the southeast, graywackes of the Dothan Formation form northward-extending salients into the southern boundary of the Colebrooke Schist. The Galice Formation forms the northeastern boundary; west of the Mountain Well fault, the Colebrooke is bounded by Lower Cretaceous rocks. The Otter Point Formation which extends from Sisters Rocks south to the Pistol River, marks the western boundary of the schist. Large serpentinite sheets are directly under or juxtaposed against the Colebrooke in the Signal Buttes area and along its entire eastern contact. A smaller serpentinite body screens part of the contact of the Colebrooke with the Galice to the north. Isolated patches of Colebrooke Schist are present structurally on top of serpentinite and Lower Cretaceous and Upper Jurassic rocks. North of the outcrop area, in the Langlois quadrangle, a large isolated mass of Colebrooke Schist appears to rest on the Otter Point, but is partially screened by serpentinite.

The pattern of the Mesozoic units in this area is complicated by the juxtaposition of sedimentary and metasedimentary rocks and serpentinites. Geologic units in the area are the subject of controversy of long standing between geologists mapping in Oregon and those mapping in California. The purpose of this report is not to settle the controversy but to interpret the origin of the Colebrooke Schist. To this end, however, the history of the controversy is sketched.

The Colebrooke Schist was first recognized by Diller (1903) during his mapping of the Port Orford 30-minute quadrangle. He believed the Colebrooke was derived from pre-Cretaceous sedimentary rocks and by inference he related the Colebrooke Schist to similar schists exposed along the south fork of the Trinity River in California. Since these California schists were considered to be overlain by rocks containing Devonian fossils, Diller assigned a tentative pre-Cretaceous, and possibly pre-Devonian, age to the Colebrooke Schist. He noted the strong deformation of the Colebrooke and the uniform fine grain of the schists and phyllites. He listed only quartz, plagioclase feldspar, and sericite as the main constituents. Initially then, the Colebrooke Schist was considered to represent the oldest rocks of the Port Orford

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quadrangle, and Diller considered the possibility that they represented metamorphosed pre-Devonian sedimentary rocks. A reconnaissance survey by Butler and Mitchell (1916) of the geology and mineral resources of Curry County, which somewhat defined the areal extent of the Colebrooke Schist, referred to the Colebrooke as a quartz-white mica schist and commented on the folded and contorted nature of its deformation. Butler and Mitchell believed that the Dothan graywackes unconformably overlie the schists; as the Dothan was then considered to be Jurassic, they concluded that the Colebrooke Schist was at least pre-Jurassic and, citing Diller, possibly pre-Devonian.

The results of Diller's pioneer work in southwestern Oregon interested California geologists, who made excursions into Oregon to reconcile the paradox of the Jurassic and Cretaceous stratigraphy of these areas. Louderback (1905) suggested that the Mariposa Formation was equivalent to the Galice "slates" and that the Colebrooke was derived from the Galice. Taliaferro (1942) followed this lead but, curiously, suggested that the Colebrooke Schist, the Abrams Mica Schist, and Salmon Hornblende Schist of northern California are pre-Silurian and could be Precambrian. Thus one sees the tendency of geologists of this era to regard metamorphic rocks as being ancient merely because they are metamorphosed. Perhaps as a mapping convenience, Wells and Peck (1961) considered the Colebrooke Schist to be equivalent to the Upper Jurassic Rogue Formation. Baldwin (1959, 1964), in a synthesis of Oregon geology, was indecisive regarding the Colebrooke Schist, as he first considered it equivalent to the Triassic Applegate Group and later suggested it was equivalent to the Jurassic Rogue and Dothan Formations. Irwin (1960), in a synthesis of northern California geology, suggested equivalency for the later named South Fork Mountain Schist, the Weitchpec Schist of Hershey (1904), the Kerr Ranch Schist of Manning and Ogle (1950), and the Colebrooke Schist. Wells and Peck (1961), in their compilation of the Oregon State map, show the Colebrooke Schist to be derived from the Rogue and Galice Formations.

Between 1903 and 1961 virtually no new information was added to Diller's early very sketchy description of the Colebrooke Schist. However, this lack of new information on the Colebrooke was no deterrent to continuing discussions of its place in the regional geology of southwestern Oregon and northern California. In 1959, Professor R. H. Dott, Jr., began a systematic study of the Jurassic and Cretaceous stratigraphy of southwest Oregon. Mapping by graduate students from the University of Wisconsin under Professor Dott provided the first new data on the Colebrooke Schist since Diller's work. Dott's (1965) summary report on this mapping described the new information on the Colebrooke Schist in general terms. Dott concluded that the Colebrooke Schist grades southward directly into the Dothan Formation and that the Colebrooke grades northward into slates of the Galice Formation. Two whole-rock K-Ar radiometric dates of 125 and 138 m.y. (million years) on the Colebrooke Schist were interpreted by Dott to indicate metamorphism related to the Nevadan orogeny (135–145 m.y.). Dott's (1965) general statements were further documented by Koch (1966), in a map that includes the northwestern part of the Colebrooke Schist. Koch did not significantly augment the sparse published details of Colebrooke petrography, although he did indicate that in addition to quartz, white mica, and albite (the minerals Diller had listed), that graphite, chlorite, epidote, and glaucophane are also present. He was first to recognize metachert and metavolcanic rocks in the Colebrooke Schist. Significantly, Koch also recognized isolated blocks of blueschist and amphibolite similar to those earlier described by Diller (1903). Koch did not definitely establish the metamorphic facies of the Colebrooke Schist, nor did he relate its internal features to the regional structure. He did, however, suggest that the Colebrooke may be in thrust contact with the Otter Point Formation. He also regarded the Colebrooke to be the metamorphic equivalent of the Rogue-Dothan-Galice complex.

Blake, Irwin, and Coleman (1967) included the Colebrooke Schist in discussing regional blueschist metamorphism in northern California and Oregon. They considered the Colebrooke Schist to belong to the blueschist facies, and metamorphic fabric to be equivalent to the Chl subzones 2 and 3 of the greenschist facies of Otago, New Zealand, as described by Hutton (1940). Coleman's discovery of an occurrence of lawsonite and minor amounts of glaucophane prompted the inclusion of the Colebrooke in this discussion of regional metamorphism, because the Colebrooke Schist, South Fork Mountain Schist, Weitchpec Schist of Hershey (1904), Kerr Ranch Schist of Manning and Ogle (1950), and the extension of these metamorphic rocks south to the Yolla Bolly-Black Butte area in the Coast Ranges were considered to represent the same type of metamorphism. In California, textural and mineral zonation of the rocks indicated an increase in metamorphic grade toward the thrust fault separating the Klamath Mountain and Great Valley provinces from the Coast Range province. The metamorphism was generally considered to be related to the regional overthrusting in California, with the metamorphic grade increasing upward to the sole of the thrust. This concept of overthrusting in the Klamath region, first proposed by Irwin (1964), has been valuable in working out the complex geology of this area.

Buchia, a Late Jurassic (Tithonian) and Early Cretaceous pelecypod, has been reported (Ghent, 1963) from the metasedimentary rocks in California, and radiometric dating of these rocks by Rb/Sr and K-Ar techniques has yielded ages of 105 to 123 m.y. (Peterman and others, 1967; Suppe, 1969). On the other hand, K-Ar ages on the Colebrooke Schist show apparent ages of 125 to 138 m.y. for the metamorphism (Dott, 1965). Thus, there seems to be a fundamental difference between the radiometric ages of the South Fork Mountain and Colebrooke Schists. Baldwin (1968, 1969) recently considered the equivalency of the Colebrooke Schist and concluded that the Rogue, Dothan, and Galice Formations are the same age. A single whole-rock K-Ar age of 149 m.y. (Dott, 1965) on a dacite flow interstratified with Dothan graywacke was accepted by Baldwin, and on this basis, the Rogue, Dothan, and Galice are considered pre-Portlandian in age. Baldwin considers the Colebrooke to be derived from both Galice and Dothan protoliths. At the completion of this study, there are still conflicting opinions regarding the age of the Colebrooke Schist and its protolith. The general age correlations and stratigraphy are shown in figure 2.

GENERAL GEOLOGY

In this report, discussion of the geology of the region precedes the more detailed discussion of the Colebrooke Schist, to give the reader an understanding of the geologic setting. The discussion will mainly concern the petrographic characteristics of the units exposed in the area. Not enough information is available for a detailed structural and stratigraphic analysis of the Colebrooke Schist.

GALICE FORMATION

The Galice Formation was first described in the Galice quadrangle (Diller, 1907), where it is best exposed along the Rogue River and Galice Creek. Diller mapped the Galice in an arcuate belt extending from Roseburg south to the California border. Several geologists (Maxson, 1933; Cater and Wells, 1953; Wells and others, 1946; Irwin, 1960) reported that the Galice extends southward into northwestern California, occupying a western Jurassic sedimentary belt of the Klamath Mountains. Mapping by Wells and Walker (1953) and by Wells, Hotz, and Cater (1949) showed that the Galice is coextensive with the Dothan Formation and occupies the eastern part of the Jurassic eugeosynclinal belt of Oregon; the Dothan Formation occupies the western part. Although Diller (1903) recognized slates within the Port Orford quadrangle, it was not until recent mapping by Dott (1966), Koch (1966), and Baldwin (1969) that these extensive areas of slate were shown to represent the Galice west of the Dothan Formation in both

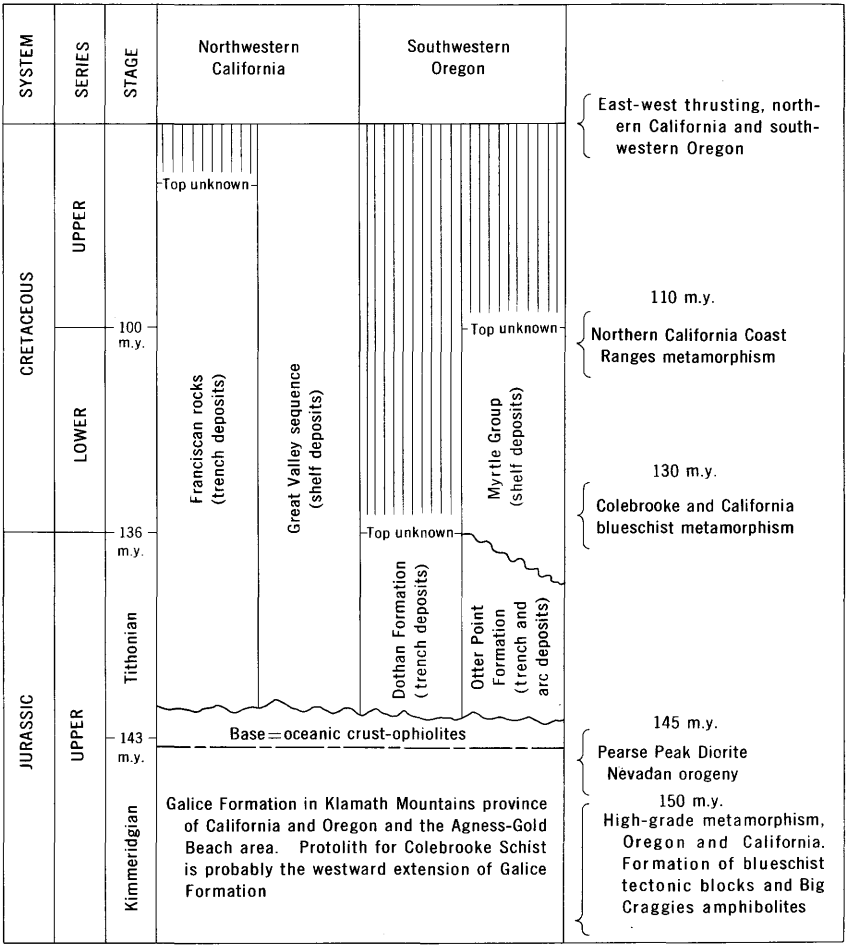

FIGURE 2.—Time-stratigraphic chart showing general correlation between metamorphic rocks of northwestern California and southwestern Oregon. Modified after Bailey, Irwin, and Jones (1964).

the Agness and Port Orford quadrangles. Fossils from the Galice of the Klamath Mountains indicate that it is Late Jurassic in age (Diller, 1907; Hotz, 1970). At the section along Galice Creek, the Galice is primarily thin-bedded black shales and siltstones with occasional lenses of conglomerate and sandstone. Associated with the Galice are extensive volcanic rock units that range in composition from basalt to andesite. These volcanic rocks are flows and pyroclastic units in which low-grade regional greenschist metamorphism has obscured much of the original volcanic character. The volcanic rocks between the Galice and Dothan Formations were called the Rogue Formation by Wells and Walker (1953).

The light-gray sandstone units contrast sharply with the black shale laminae. A well-developed slaty cleavage is so characteristic of the Galice that its rocks are often called slates.

Microscopic inspection of rocks from all parts of the Galice reveals that it is nearly completely recrystallized, even though sedimentary features are preserved. The new minerals are primarily albite, chlorite, rutile, sphene, mica, and carbonate. In the pebble conglomerates, detrital clastic material is predominantly chert, phyllite, and sandstone; a little volcanic debris is locally present. In the shaly laminae, carbonaceous material is abundant and is altered to graphite. The recrystallized components of the Galice exhibit a strong preferred orientation. This preferred orientation and the degree of recrystallization are similar to those described by Hutton (1940) in the Chl subzone 2 within the Alpine schists of New Zealand. Earlier authors (Diller, 1903; Wells and Walker, 1953) did not regard the Galice as a metasedimentary rock, but its character in the Agness quadrangle suggests that it recrystallized in response to low-grade greenschist metamorphism contemporaneous with deformation.

The Galice west of the Dothan outcrop belt is confined to two areas (pl. 1), the larger of which extends north from the South Fork of Lobster Creek nearly to Powers and is terminated on the west by the Mountain Well fault and on the east by the Coquille River fault. The smaller area occurs where the Pearse Peak Diorite intrudes and alters a small window of Galice surrounded by Lower Cretaceous sedimentary rocks. The Galice in these two areas is intruded by numerous dikes and plugs of diorite and dacite informally called diorite of the Pearse Peak type, which is restricted to the Galice Formation.

Numerous serpentinites invade the Galice Formation along faults; some have developed calcium metasomatic borders related to their emplacement. At Iron Mountain, a large mass of serpentinite appears to have been thrust on top of the Galice (pl. 1).

The Galice Formation in these two areas is composed of rhythmically layered shales and sandstones that exhibit graded bedding. The individual laminae in the thinnest shale layers average about ½ cm (centimeter) thick. Most of the fine sandstone units are not more than 2 cm thick; the massive sandstone units are not more than 10 cm thick. The basal fine pebble conglomerates of some massive sandstones have an average pebble size of less than 5 mm (millimeter).

The Galice Formation has higher silica and lower calcium content than the graywackes of the Otter Point and Dothan (table 1). The scarcity of volcanic debris and high content of sedimentary clasts suggest that the Galice was derived from reworked older sedimentary rocks that were slowly deposited during a time of little tectonic activity.

TABLE 1.—*Chemical and spectrographic analyses of metasedimentary rocks from the Galice Formation*

[Rapid rock chemical analyses by Paul Elmore, G. W. Chloe, James Kelsey, J. L. Glenn, S. D. Botts, Hezekiah Smith, Lowell Artis; spectrographic analyses by Chris Heropoulos]

	52-RGC-67-A	52-RGC-67-B	55-RGC-67-A	55-RGC-67-B	134-RGC-67	135-RGC-67	139-RGC-67-A	139-RGC-67-B
Chemical analyses (weight percent)								
SiO_2	70.0	81.3	72.1	67.5	71.5	84.6	64.7	68.9
Al_2O_3	12.0	7.6	12.3	15.0	12.3	6.1	15.4	12.3
Fe_2O_3	.79	.66	.66	1.3	.82	.63	1.6	1.6
FeO	4.1	2.4	3.4	3.7	3.8	1.7	4.7	2.4
MgO	2.4	1.8	2.1	2.5	2.3	1.1	2.7	1.7
CaO	2.0	.80	.90	.30	1.3	1.0	1.7	3.5
Na_2O	2.4	1.6	2.5	1.7	3.2	1.2	2.1	3.0
K_2O	1.6	.80	1.6	2.8	.90	.90	2.1	1.3
H_2O^-	.18	.09	.08	.19	.18	.13	.34	.09
H_2O^+	2.6	1.7	2.7	3.2	2.4	1.5	3.4	2.1
TiO_2	.55	.36	.62	.72	.51	.26	.75	.68
P_2O_5	.17	.11	.30	.18	.18	.19	.29	.16
MnO	.04	.08	.05	.00	.04	.12	.04	.00
CO_2	.78	.18	.05	<.05	.39	.08	<.05	2.1
Total	100	99	99	99	100	100	100	100
Sulfide sulfur as S	0	.06	0	.22	0	.04	.04	0
Specific gravity bulk	2.71	2.66	2.64	2.70	2.64	2.66	2.70	2.66
Specific gravity, powder	2.72	2.72	2.72	2.72	2.72	2.72	2.72	2.72
Semiquantitative spectrographic analyses (ppm)								
B	70	50	70	100	30	50	70	70
Sr*	211	166	123	97.8	233	97.4	166	212
Rb*	48.1	32.0	54.2	86.7	32.7	37.7	70.8	40.5
Ba	1,000	500	700	1,000	500	700	500	700
Co	15	10	15	10	15	7	7	15
Ni	100	70	100	70	70	20	50	100
Cu	70	50	70	200	70	70	100	70
Cr	150	70	150	150	100	50	100	200
Pb	20	7	15	20	10	7	30	15
Y	20	15	20	20	20	15	30	20
Yb	3	3	2	2	2	1.5	3	2
Sc	20	10	15	15	15	7	20	15
Nb	10	7	7	10	10	7	15	7
Ga	15	15	15	20	15	7	20	15
Zr	200	100	200	200	200	100	300	300
V	150	100	150	200	150	100	200	150

* Determined by isotope dilution and X-ray fluorescence. Analyst, Zell Peterman.

Sample	*Description and location*
52-RGC-67-A	Medium-gray fine-grained graywacke; Lobster Creek, Agness quadrangle.
52-RGC-67-B	Medium-gray fine-grained conglomerate; Lobster Creek, Agness quadrangle.
55-RGC-67-A	Medium-light-gray fine-grained graywacke; North Fork Lobster Creek, Agness quadrangle.
55-RGC-67-B	Medium-gray shaly fine-grained sandstone; North Fork Lobster Creek, Agness quadrangle.
134-RGC-67	Medium-gray fine-grained sandstone; Panther Mountain, Agness quadrangle.
135-RGC-67	Light-gray fine-grained pebble conglomerate, Panther Mountain, Agness quadrangle.
139-RGC-67-A	Light-gray to black interbedded fine-grained sandstone and shale, Sucker Creek, Powers quadrangle.
39-RGC-67-B	Medium-light-gray fine-grained graywacke; Sucker Creek, Powers quadrangle.

The base of the Galice could not be found in the Agness or Port Orford quadrangles. The abundance of serpentinite and mafic volcanic material within the Galice supports the idea that these sediments were deposited on oceanic crust. Lower Cretaceous sedimentary rocks rest unconformably on the folded Galice in the northwest corner of the Agness quadrangle, and to the south the Colebrooke Schist has been thrust over the Galice on serpentinite sheets. The Iron Mountain serpentinite may be a remnant of this serpentinite sheet.

Diller (1903) and Dott (1966) have reported the occurrence of *Buchia concentrica* in Galice slates along Sucker Creek just north of the Agness quadrangle. On the basis of this fossil evidence and a K-Ar date of $\approx$145 m.y. for the Pearse Peak intrusives, it seems likely that the Galice Formation in this area is of Late Jurassic (late Oxfordian and early Kimmeridgian) age.

DOTHAN AND OTTER POINT FORMATIONS

For this discussion, the Dothan and Otter Point Formations are considered to be the same age (fig. 2). There is no direct stratigraphic or fossil evidence to substantiate this; however, the fieldwork disclosed an unbroken gradation from the Otter Point Formation along the coast into the Dothan Formation inland. No major unconformity or structural break between the formations was recognized, even though a major fault separating the Dothan and Otter Point was shown by Wells and Peck (1961) and Dott (1965). South of the area described here, there does seem to be evidence for a structural boundary between the Dothan and Otter Point Formations (R. H. Dott, oral commun., 1969).

The Dothan Formation is a thick graywacke to shale unit of major importance in southwestern Oregon, bordering the Klamath Mountains province from the Oregon border to Roseburg. It was first named by Diller (1907) for its exposures on Cow Creek in the Riddle quadrangle. The lack of fossils throughout its broad exposure has led to disagreement about its age and correlative units in Oregon and California. Initially Diller (1907) considered the Dothan equivalent to the Franciscan Formation of California and suggested a Late Jurassic age. Other published opinions were that the Dothan was either equivalent to or older than the Galice. Age concepts are summarized by Irwin (1964), who concluded that the Dothan is equivalent to the Franciscan. Dott (1965) and Koch (1966), having mapped in the area in and around the Colebrooke Schist, considered the Dothan to be older than the Galice and suggested a Late Jurassic (Oxfordian to Kimmeridgian) age. Their opinion is based mainly on a single whole-rock K-Ar age of 149 m.y. on a dacite flow within the Dothan reported by Dott (1965). Later investigation of this dacite flow by the author revealed equivocal field relations; lack of intrusive contacts or in-place occurrence of the dacite greatly diminishes any significance of a radiometric date from a stream cobble. A recent find of Upper Jurassic fossils in a landslide area along the Chetco River by Ramp (1969) provides new evidence that at least part of the Dothan Formation is the same age as the Otter Point Formation. Hotz (1969) has indicated that there is no stratigraphic continuity between the Dothan and Galice. Volcanic rocks of the Rogue Formation, which apparently underlie the Galice, are in thrust-fault contact with (or thrust over) the Dothan Formation and may represent oceanic crust (ophiolites).

The Otter Point Formation was first defined by Koch (1966). The type locality is at Otter Point, just north of Gold Beach. Koch discovered Tithonian fossils within the coastal section of the Otter Point and considered the formation to be latest Jurassic in age. He was impressed by the large amount of volcanic material within the Otter Point along the coast, present as pillow lava units and pyroclastic debris in the graywackes. The lavas and volcanic debris range in composition from basalts to keratophyres. The present study has shown that strata containing volcanic detritus of the same character continue without interruption eastward into the Dothan Formation and that the quantity of volcanic rock debris decreases as interbedded shale increases.

The Dothan Formation underlies nearly all of the Collier Butte quadrangle (pl. 1). It occupies a 14-mile-wide belt extending from the Gardner Ranch eastward. Westward from near the Gardner Ranch, it grades imperceptibly into the Otter Point Formation. Structural breaks or unconformities may be present, but the lack of marker beds makes this uncertain. The Dothan extends northward from near the Gardner Ranch along a salient following the north fork of the Pistol River (pl. 1). Another salient projects northward to Game Lake in the drainage area of Collier Creek. Dott (1965) considered these salients of Dothan graywackes to be the protolith of the Colebrooke Schist and believed that there was a complete gradation from graywacke to schists. The eastern boundary of the Dothan graywackes is a major thrust fault that has brought the Klamath block over rocks of the Coast Range province (Irvin, 1964; Blake and others, 1967; Hotz, 1969). The western extension of these graywackes is obscure because allochthonous sheets of Colebrooke Schist on serpentinite sheets rest on the autochthonous Dothan and Otter Point graywackes. Serpentinites of the Signal Hill and Carpenterville areas were earlier considered to be localized along a fundamental deep vertical fault separating the Dothan and Otter Point Formations (Dott, 1965; Wells and Peck, 1961).

The graywackes are massive with shale interbeds; the ratio of shale to sandstone increases in the Dothan Formation from west to east. Volcanogenic clastic components are much greater in the Otter Point graywackes than in the Dothan graywackes. The graywackes are

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dark greenish gray to light gray, depending on the amount of volcanic clastic material. Generally, these graywackes retain their original sedimentary textures except along the eastern thrust zone along the Klamath Mountains or near the thrust fault contacts of the allochthonous sheets. In all samples examined, the matrix has been completely recrystallized. Clastic fragments of quartz, feldspar, and rock are dominant detrital materials. Staining reveals that Otter Point graywackes contain as much as 3 or 4 percent potassium feldspar, whereas Dothan graywackes contain no detrital potassium feldspar. The bulk of the feldspars appears to be albite, although exceptional samples appeared to be more calcic. The lithic clasts are a mixture of mafic volcanics (basalt, spilite, andesite, keratophyre) and reworked shales or graywackes. Volcanic clasts predominate in the Otter Point, whereas specimens from the Dothan contain less and less volcanic debris the farther eastward they are collected. The graywackes near Signal Buttes and Sugar Loaf characteristically contain abundant shale chips up to 5 cm long. Serpentinite and chromite with attached serpentine are minor but persistent clasts, along with epidote and green-brown hornblende. The recrystallized matrix of the Dothan graywackes contains fine-grained chlorite, white mica, and pumpellyite, whereas laumontite is commonly present in the Otter Point graywackes.

The chemical character of the Dothan (table 2) and Otter Point (table 3) graywackes is nearly identical with that of the Franciscan graywackes of California.

The abundant evidence of volcanic activity in the Otter Point Formation suggests that these sedimentary rocks were deposited near an active volcanic arc west of the present coast, whereas the Dothan was deposited in the axial part of a trench along the continental edge. The presence of zeolites (laumontite) along the coast and pumpellyite farther eastward suggests that these sedimentary rocks have undergone a regional low-grade metamorphism, the intensity increasing eastward (Blake and others, 1967).

MYRTLE GROUP

In the Roseburg quadrangle, southwestern Oregon, sedimentary rocks that have thick basal conglomerates and contain the pelecypod *Buchia* were originally called the Myrtle Formation by Diller (1898). More recent work (Imlay and others, 1959, and Koch, 1966) has shown that these rocks are widespread throughout southwestern Oregon as small discrete occurrences. The Myrtle Formation was elevated to the Myrtle Group by Imlay, Dole, Wells, and Peck (1959) to include their newly named Riddle and Days Creek Formations, to which they assigned Late Jurassic and Early Cretaceous ages, respectively. Koch

(1966) subdivided similar rocks along the Oregon Coast into two distinct formations: Humbug Mountain Conglomerate (Lower Cretaceous) and Rocky Point Formation (Lower Cretaceous). In this report, the term Myrtle Group will be used for all isolated occurrences of sedimentary rocks whose lithology is similar to previously described Myrtle Group rocks and which contain Buchias ranging in age from Late Jurassic to Early Cretaceous (Jones, 1960, 1969). This use is similar to that in California, where the Great Valley sequence represents shelf deposits and ranges in age from Late Jurassic to Early Cretaceous.

The Myrtle Group sediments are extensive in the northern part of the area. They are bisected on the east by the Mountain Well fault and are covered on the south by the Colebrooke Schist-serpentinite sheets (pl. 1). In the eastern part of the area, there are five isolated areas of Myrtle Group sedimentary rocks. The two largest are the Agness and Horsesign Butte synforms, resting on serpentinite tectonic sheets. The Jacoby Butte area contains a small area of Myrtle Group rocks resting on serpentinite. In the upper reaches of Lawson Creek, a small selvage of Myrtle Group sedimentary rocks is imbricated between the Colebrooke Schist and serpentinite. In all of these isolated occurrences. the stratigraphy is similar to shelf-type sediments, and the *Buchia* zones suggest an age range from Tithonian to Valanginian (Jones, 1969). East of the Mountain Well fault in the Agness quadrangle, a large synform of Myrtle Group rests unconformably on the Galice Formation (pl. 1); according to Dott (1966), these rocks are correlative with the Humbug Mountain Conglomerate but contain Tithonian fossils similar to those of the type locality of the Myrtle Group (Imlay and others, 1959) near Roseburg.

The Myrtle Group sedimentary rocks contain basal conglomerates of well-rounded chert pebbles and variable amounts of volcanic and plutonic igneous rocks. The basal conglomerates grade upward into rhythmically bedded sandstone and mudstones containing numerous shell-bearing horizons. The Myrtle Group sedimentary rocks seem to represent a near-shore environment typical of shelf facies with only minor deep-water turbidites. The similarity of these rocks to those of the Great Valley sequence in California has been described by Jones (1969).

The only places where the base of the Myrtle Group can be seen undisturbed and exposed are in the Barklow Mountain area (southern half of Coquille quadrangle and in the headwaters of the Elk River. Dott (1966) has shown that the Myrtle Group is here deposited directly on folded Galice slates; however, there is only minor Galice clastic material within the basal conglomorates

TABLE 2.—*Chemical and spectrographic analyses of graywackes from the Dothan Formation*

[Chemical analyses by Paul Elmore, G. W. Chloe, James Kelsey, J. L. Glenn, S. D. Botts, Hezekiah Smith, Lowell Artis; spectrographic analyses by Chris Heropoulus]

	58-RGC-67	65-RGC-67	67-RGC-67	68-RGC-67	69-RGC-67	78-RGC-67	89-RGC-67	90-RGC-67	93-RGC-67	53-RGC-68	54-RGC-68	55-RGC-68	56-RGC-68	58-RGC-68
Chemical analyses (weight percent)														
SiO_2	64.7	65.6	63.7	65.4	65.4	63.1	68.9	71.3	65.4	67.4	65.9	66.2	67.7	68.7
Al_2O_3	12.9	13.8	13.9	13.0	12.8	13.6	13.8	12.9	13.9	14.9	15.3	15.8	14.2	14.4
Fe_2O_3	1.4	.89	1.0	1.1	.72	.87	.68	.84	1.0	2.1	2.0	1.5	1.8	2.1
FeO	4.4	4.1	3.0	4.3	3.8	4.3	4.2	3.6	4.4	2.8	3.5	3.5	3.2	2.8
MgO	3.0	2.7	2.0	2.2	3.6	2.4	2.0	1.6	3.0	2.0	2.5	2.2	2.3	2.1
CaO	3.0	2.3	4.4	3.8	3.3	4.0	1.1	1.2	2.7	2.2	1.7	1.9	2.6	1.6
Na_2O	3.9	3.2	3.6	3.4	4.4	4.2	3.0	4.3	4.4	3.5	3.6	3.8	3.2	2.5
K_2O	1.1	1.2	1.4	1.1	.90	1.3	1.4	.60	.60	1.2	1.5	1.4	1.3	1.4
H_2O^-	.51	1.1	.69	.69	.32	.51	.37	.22	.27	.33	.38	.30	.22	.62
H_2O^+	3.1	2.9	2.9	2.5	2.8	2.7	2.9	2.5	2.7	2.3	2.7	2.4	2.5	2.5
TiO_2	.68	.68	.51	.62	.49	.77	.59	.51	.68	.65	.67	.60	.62	.57
P_2O_5	.15	.19	.12	.19	.16	.19	.15	.15	.18	.16	.16	.16	.15	.15
MnO	.08	.04	.08	.08	.08	.08	.00	.04	.08	.07	.08	.09	.07	.07
CO_2	.82	1.2	2.6	1.4	1.3	1.9	.15	.10	.22	.11	$<.05$	.11	.10	.30
Total	100	100	100	100	100	100	99	100	100	100	100	100	100	100
Sulfide sulfur as S	0	0	0	0	0	0	0	0	0	---	---	---	---	---
Specific gravity, bulk	2.64	2.65	2.65	2.65	2.65	2.66	2.67	2.68	2.69	2.71	2.70	2.70	2.73	2.69
Specific gravity, powder	2.72	2.70	2.72	2.72	2.72	2.72	2.73	2.72	2.72	---	---	---	---	---

Semiquantitative spectrographic analyses (ppm)

B	15	70	50	50	----------	50	50	30	15	20	30	30	20	50
Sr *	172	145	300	112	206	445	111	145	211	298	313	344	290	167
Rb *	43.5	42.9	55.6	37.0	36.3	37.4	56.6	27.9	25.8	41.1	46.0	44.7	42.6	51.8
Ba	200	200	200	200	150	150	500	300	200	700	700	700	700	700
Co	15	15	15	15	20	15	15	15	15	10	15	15	15	10
Ni	50	100	70	70	100	70	200	50	50	30	50	30	70	70
Cu	70	100	70	70	50	50	70	70	50	50	70	70	70	70
Cr	100	70	70	100	200	150	70	50	70	70	70	70	150	100
Pb	10	10	10	----------	10	7	30	15	10	10	10	10	10	10
V	200	150	150	150	150	200	150	150	200	100	150	100	100	100
Y	20	20	20	20	20	30	20	20	20	20	20	20	20	20
Yb	3	3	2	2	2	2	2	2	2	2	2	2	2	2
Sc	20	20	15	15	20	20	15	15	15	20	20	20	20	15
Nb	10	15	15	10	15	15	10	10	10	10	10	10	10	10
Ga	15	15	15	15	20	15	15	15	20	15	15	15	15	15
Zr	200	150	150	150	150	300	200	150	150	200	200	200	200	200

*Determined by isotope dilution and X-ray fluorescence. Analyst, Zell Peterman.

Sample	*Description and location*
58–RGC–67	Medium-gray graywacke pebble comglomerate; Hunter Creek, Gold Beach quadrangle.
65–RGC–67	Medium-gray fine-grained graywacke; Sugarloaf Mountain, Collier Butte quadrangle.
67–RGC–67	Medium-dark gray medium-grained graywacke; Sugarloaf Mountain, Collier Butte quadrangle.
68–RGC–67	Medium-gray medium-grained graywacke; Elko Camp, Collier Butte quadrangle.
69–RGC–67	Medium-light-gray coarse-grained graywacke; Headwaters of the Pistol River, Collier Butte quadrangle.
78–RGC–67	Medium-gray coarse-grained graywacke; Pyramid Rock; Gold Beach quadrangle.
89–RGC–67	Medium-dark gray fine-grained veined graywacke; Vulcan Peak area, Chetco Peak quadrangle.
90–RGC–67	Medium-dark-gray fine-grained veined graywacke; Red Mountain Prairie, Mount Emily quadrangle.
93–RGC–67	Medium-light-gray coarse-grained graywacke; Mouth of South Fork, Chetco River, Mount Emily quadrangle.
53–RGC–68	Medium-gray medium-grained graywacke; southeast ridge Brandy Peak, Marial quadrangle.
54–RGC–68	Medium-dark-gray fine-grained graywacke; Bear Camp Ridge, Marial quadrangle.
55–RGC–68	Medium-dark-gray medium-grained graywacke; Bear Camp Pasture, Marial quadrangle.
56–RGC–68	Medium-dark-gray medium-grained graywacke; Chief Creek Ridge, Marial quadrangle.
58–RGC–68	Medium-dark-gray fine-frained graywacke; Bob's Garden, Marial quadrangle.

TABLE 3.—*Chemical and spectrographic analyses of graywackes from the Otter Point Formation*

[Analyses by Paul Elmore, G. W. Chloe, James Kelsey, J. L. Glenn, S. D. Botts, Hezekiah Smith, Lowell Artis; spectrographic analyses by Chris Heropoulos]

	52-RGC-68	86-RGC-68	87-RGC-68	89-RGC-68	90-RGC-68	93-RGC-68
Chemical analyses (weight percent)						
SiO_2	64.2	63.0	65.9	67.1	66.2	69.4
Al_2O_3	13.2	13.5	13.8	12.9	13.0	10.2
Fe_2O_3	2.3	2.4	1.9	1.8	1.7	1.6
FeO	3.0	3.8	3.4	3.2	3.2	2.7
MgO	4.1	4.8	3.2	4.0	3.5	3.4
CaO	3.9	2.6	2.2	1.6	2.6	2.9
Na_2O	2.7	3.8	4.4	3.5	3.3	2.6
K_2O	1.3	.84	1.0	1.2	1.3	1.1
H_2O^-	.95	.89	.39	.65	.53	1.2
H_2O^+	2.8	2.4	2.5	2.7	2.7	2.5
TiO_2	.67	.79	.59	.62	.60	.52
P_2O_5	.19	.22	.12	.16	.16	.12
MnO	.08	.08	.11	.07	.07	.07
CO_2	.46	.71	.55	.22	1.0	1.6
Total	100	100	100	100	100	100
Specific gravity, bulk	2.66	2.67	2.63	2.68	2.69	2.52
Specific gravity, powder.	---	---	---	---	---	---
Semiquantitative spectrographic analyses (ppm)						
B	20	15	15	30	30	30
Sr*	491	323	177	224	237	121
Rb*	33.4	14.9	28.9	33.2	36.5	32.5
Ba	700	500	200	500	500	500
Co	15	20	15	15	15	15
Ni	150	150	100	150	100	150
Cu	70	70	70	70	70	70
Cr	200	300	200	300	200	500
Pb	10	n.d.	10	10	10	n.d.
V	150	200	150	150	150	150
Y	20	20	20	20	20	20
Yb	2	2	2	2	2	2
Sc	20	30	20	20	20	20
Ga	15	15	15	15	15	15
Zr	150	150	150	150	100	150
Nb	10	10	10	10	10	10

*Determined by isotope dilution and X-ray fluorescence. Analyst, Zell Peterman.

Sample	*Description and location*
52-RGC-68	Medium-dark-gray coarse-grained graywacke; Kimball Hill, Gold Beach quadrangle.
86-RGC-68	Medium-dark-gray fine-grained graywacke; Hunter Creek, Gold Beach quadrangle.
87-RGC-68	Medium-gray medium-grained graywacke; Big South Fork Hunter Creek, Gold Beach quadrangle.
89-RGC-68	Medium-dark-gray medium-grained graywacke; Headwaters of Big South Fork Hunter Creek, Gold Beach quadrangle.
90-RGC-68	Medium-dark-gray medium-grained graywacke; Pistol River, Gold Beach quadrangle.
93-RGC-68	Medium-gray coarse-to medium-grained graywacke; Otter Point, Gold Beach quadrangle.

of the Barklow Mountain locality. And the Agness and Horsesign Butte synforms resting on serpentinite contain no clastic ultramafic debris. Instead, there are obvious calcium metasomatic contacts and strong shearing at the contact of the Myrtle Group sedimentary rocks with serpentinite. The scarcity of Galice and serpentinite debris in the basal conglomerate and the calcium metasomatic contacts along serpentinite boundaries suggest that some of the Myrtle Group may be allochthonous. The displacement of these rocks may have occurred during Late Cretaceous thrusting.

UPPER CRETACEOUS AND TERTIARY SEDIMENTARY ROCKS

A small patch of unnamed Upper Cretaceous clastic rocks is present in the Cape Sebastian area (Howard and Dott, 1961). The Tertiary Umpqua and Tyee Formations were first described by Diller (1898, 1903) in southwestern Oregon; Baldwin (1965) has presented a recent account of these formations. The Umpqua and Tyee Formations make up a thick section of marine sandstones of Eocene age.

The Umpqua and Tyee occur in the eastern part of the Agness quadrangle, where they occupy a synform separated from older rocks on the west by the Coquille River fault zone (Baldwin, 1965). Two small areas of Umpqua sandstones are found at Boulder Creek and Indigo Creek (pl. 1).

The base of the Umpqua in the Agness area consists of coarse conglomerates containing abundant serpentinite, ultramafic rocks, and mafic debris. The basal conglomerate grades upward into the rhythmically bedded sandstones and shales. In the Boulder Creek area, the Umpqua contains a basal unit that is primarily Colebrooke Schist debris. At Horsesign Butte, small patches of Umpqua containing "iron sand" lenses are deposited directly upon the Myrtle Group synform and serpentinite. The Upper Cretaceous and Eocene sedimentary rocks apparently were deposited in structural lows. Their onlap of thrust faults and their unconformity on the Myrtle Group provide clear evidence that some of the thrusting was Late Cretaceous.

SERPENTINITE

The serpentinites of this area are widespread but highly erratic in distribution (pl. 1). Numerous small bodies crop out in and around Gold Beach and north along the coast; the largest is Vondergren Hill. The Signal Buttes serpentinite exposure forms a lobe approximately 2 by 9 miles. The largest continuous exposure is centered in the Collier Butte quadrangle. It extends from Snow Camp to Agness, nearly 20 miles; the greatest width is approximately 7 miles. In the northern part of the Agness quadrangle, the irregular Iron Mountain lobe extends from Lobster Creek 7 miles northward to Sucker Creek. Many of the small serpentinite bodies are associated with fault zones. Where these bodies occupy vertical faults, such as the Coquille River fault, it seems clear that the bodies' shape must be discoid with the major axes parallel to the fault strike. The form of many serpentinite bodies is difficult to ascertain, however, because their contacts with surrounding rocks are commonly obscured by slumping and landslides, especially on the flanks of large topographically high bodies. Description of the form of the serpentinite bodies commonly depends on which emplacement mechanism one chooses to infer.

At least three possible mechanisms for the origin of the serpentinites are worth considering:

1. Ultramafic intrusion followed by serpentinization after igneous emplacement within the crust.
2. Submarine mafic-ultramafic extrusion (ophiolites in the sense of Steinmann, 1926) within eugeosynclinal sediments and later serpentinization.
3. Emplacement on or into crust of oceanic crust-mantle slabs serpentinized during tectonism.

The most likely mode of origin may be deduced from the following observational data. The lithology of the serpentinites is chaotic and can best be described as a mélange. The preserpentinite ultramafic suite consists of harzburgites and dunites with minor orthopyroxenites. There is a broad spectrum from massive serpentinized areas of peridotite to completely sheared and incompetent flaky serpentinite.

Lizardite and clinochrysotile are the main minerals; magnetite is a common accessory, present in highly variable amounts (0.2 to >10 percent). The massive serpentinites derived from dunties and harzburgites may also contain large amounts of brucite. X-ray examination revealed no antigorite. The highly sheared serpentinites appear to contain more clinochrysotile and magnetite than their associated massive serpentinites. The serpentinized ultramafic rocks range in density from 2.40 to 2.98 and average 2.56 (table 4). If density reflects the degree of serpentinization, the peridotites are more than 50 percent by weight serpentinite. The magnetic susceptibility (K) ranges from 0.26 to 16×10^{-3}; remanent magnetism (J) from 0.96 to 127×10^{-4}. These great ranges in magnetic properties must reflect the extreme variability of the crystallization of magnetite during serpentinization.

TABLE 4.—*Physical and mineralogic character of southwestern Oregon serpentinites*

Sample	Location	Mineral assemblage (in order of decreasing abundance	Density	Type	Magnetic properties		Porosity (percent)
					$J\times10^{-4}$	$K\times10^{-3}$	
10-RGC-68	Arntzen's Resort	Lizardite, chrysotile	2.59	Sheared			5.4
11-RGC-68	River Road	do	2.48	Massive	8.09	2.35	1.2
11-RGC-68	do	Chrysotile, lizardite magnetite	2.30	Sheared			
12-RGC-68	Gold Beach Bridge	Lizardite, chrysotile	2.53	Massive	1.32	.30	2.4
12-RGC-68	do	do	2.50	Sheared			
13-RGC-68	Grizzly Peak Road	do	2.57	do			6.2
14-RGC-68	Flycatcher Spring	Lizardite, brucite	2.56	Massive	3.02	.71	1.2
14-RGC-68	do	Chrysotile, magnetite	2.56	Sheared			
15-RGC-68	do	Lizardite, brucite	2.53	do	11.7	.52	1.2
15-RGC-68	do	Lizardite, chrysotile	2.41	do			

TABLE 4.—*Physical and mineralogic character of southwestern Oregon serpentinites*—Continued

Sample	Location	Mineral assemblage (in order of decreasing abundance	Density	Type	Magnetic properties		Porosity (percent)
					$J\times10^{-4}$	$K\times10^{-3}$	
16–RGC–68	Red Flat	Serpentine, olivine, orthopyroxene, brucite	2.81	Massive	4.26	1.86	1.4
16–RGC–68	do	Lizardite, chrysotile	2.61	Sheared			
17–RGC–68	do	Lizardite, brucite, olivine, orthopyroxene, magnetite	2.68	Massive	.96	.65	
18–RGC–68	do	do	2.71	do	28.9	3.67	.7
21–RGC–68	Carpenterville	Lizardite, brucite, orthopyroxene, olivine	2.72	do	127.0	1.465	1.8
23–RGC–68	Pine Flat	Serpentine, orthopyroxene, brucite	2.67	do			
23–RGC–68	do	Lizardite, chrysotile, brucite		Sheared	65.7	16.0	
24–RGC–68	Game Lake	Lizardite, brucite, nagnetite	2.67	Massive			0
24–RGC–68	do	Lizardite, magnetite	2.57	Sheared			
24–RGC–68	do	do	2.67	do	38.8	6.05	
27–RGC–68	Huntley Spring	Serpentine, orthopyroxene, brucite magnetite	2.71	Massive			1.1
27–RGC–68	do	Serpentine, orthopyroxene	2.56	Sheared			
28–RGC–68	do	Lizardite, chrysotile	2.62	Massive	1.24	2.03	.8
29–RGC–68	Snow Camp Road	Chrysotile, lizardite, magnetite	2.65	do	3.09	.48	0
29–RGC–68	do	do	2.33	Sheared			
31–RGC–68	Pine Point	Lizardite, magnetite	2.76	Massive			11.5
31–RGC–68	do	Lizardite, brucite, magnetite, orthopyroxene	2.42	Sheared			
32–RGC–68A	Pine Point Quarry	Lizardite, orthopyroxene	2.62	Massive	1.26	.26	2.3
32–RGC–68B	do	Lizardite, chrysotile	2.50	do			.4
33–RGC–68	Hunter Creek area	Lizardite	2.59	do	4.74	1.73	3.2
33–RGC–68	do	Lizardite, chrysotile	2.47	Sheared			1.2
34–RGC–68	North Bank Rogue River	Lizardite, orthopyroxene olivine	2.56	Massive	2.63	1.055	0
34–RGC–68A	do	Clinochrysotile, magnetite	2.42	Sheared			
34–RGC–68B	do	Lizardite, chrysotile	2.47	do			
35–RGC–68	North Bank Rogue Series	Lizardite, magentite	2.52	Massive	4.47	1.26	.8
35–RGC–68(1)	do	Clinochrysotile, lizardite, magnetite	2.43	Sheared			
35–RGC–68(2)	do	do	2.37	do			
35–RGC–68(3)	do	do	2.40	do			
35–RGC–68(4)	do	Lizardite, chrysotile, magnetite	2.55	do			
35–RGC–68(5)	do	do	2.54	do			
36–RGC–68	Vondergren Hill	Lizardite, chrysotile, orthopyroxene, olivine	2.66	Massive	72.1	1.125	2.2
37–RGC–68	do	Orthoproxene, olivine, lizardite	2.98	do	21.2	.765	1.7
37–RGC–68	do	Chrysotile, lizardite, orthoyproxene	2.52	Sheared			
40–RGC–68	McCready Camp	Lizardite, chrysotile, brucite, magnetite	2.74	Massive	12.4	8.2	2.6
40–RGC–68	do	Clinochrysotile, magnetite	2.63	Sheared			
48–RGC–68	Signal Buttes	Lizardite, chrysotile, magnetite	2.56	Massive	13.5	4.25	0
48–RGC–68	do	Chrysotile, magnetite	2.40	Sheared			
49–RGC–68	do	Lizardite, chrysotile, magnetite	2.56	Massive	23.0	5.57	1.2
49–RGC–68	do	Chrysotile, lizardite, magnetite	2.42	Sheared			

Typical exposures reveal rounded blocks of massive peridotite, 6 inches to 6 feet in diameter, set in a matrix of sheared serpentinite. Primary igneous features such as compositional layering or dikes, if present, are obscured by tectonic disruption and sepentinization. Hand specimens show that these peridotites have textures similar to those described previously (Loney and others, 1971) for alpine-type ultra-

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mafic rocks, that is, a strong preserpentine metamorphic fabric superposed on the primary igneous olivines and pyroxenes. The preserpentine metamorphic fabric developed after igneous formation of the ultramafic rocks and the serpentinite mélange observed in the present outcrop indicate that these ultramafic rocks have undergone several periods of deformation. Intimately associated with these serpentinized ultramafics are irregular areas of diabase, gabbro, and diorite. As their contacts with the serpentinite are highly sheared and the gabbros and diorites show strong internal deformation and alteration, it is difficult to establish for the gabbros and diorites a direct structural or intrusive relation with the enclosing serpentinized ultramafic rocks. These diabase, gabbro, and diorite masses may represent broken fragments of former oceanic crust. In addition, there are numerous exotic rock masses ranging in diameter from a quarter of a mile to several feet, imbedded in serpentinite. These exotic blocks are recognizable Colebrooke Schist, mafic volcanic rocks, glaucophane schists, amphibolites, and other rock types so altered that original rock is unrecognizable. Some of these exotic inclusions within the serpentinite have well-developed calc-silicate metasomatic borders formed during serpentinization (Coleman, 1966, 1967; Barnes and O'Neil, 1969). In addition to these exotic inclusions in the serpentinite, klippen of the Colebrooke Schist and Myrtle Group sedimentary rocks rest on top of the serpentinite. Where contacts between the serpentinite and the surrounding country rock are exposed, serpentinite invariably shows strong shearing and small inclusions of country rock. At some places, local calcium metasomatism is developed in the country rock where it comes into contact with the serpentinite. There was no evidence of igneous intrusion of an ultramafic magma at this level in the crust, as all contacts between serpentinite and country rock were faulted and sheared, with no evidence of contact metamorphic aureole. Regular stratigraphic progression from peridotite, gabbro, diabase, to pillow lava as has been described for ophiolites (Steinmann, 1926) could not be established; however, such a stratigrapic sequence may have existed before tectonism, as all parts of an ophiolite sequence are present as tectonic blocks within the serpentinite.

Several features of the serpentinites suggest severe tectonism. The mélange character of the serpentinite, together with numerous exotic inclusions and calcium metasomatism along contacts, supports tectonism. The mapped outlines of masses demonstrate that serpentinites are tabular units with low dips, except where they occupy vertical faults as in the Coquille River fault zone. The close association of the serpentinites with thrusting is demonstrated by the parallelism between the serpentinite sheets and thrust planes. The irregular and patchy distribution of smaller serpentinite sheets resulted from dissection by erosion of a much larger coextensive serpentinte sheet that probably occupied the zone of major thrust dislocation of the Colebrooke Schist and Myrtle Group sedimentary rocks. Aeromagnetic anomalies related to the exposed serpentinites demonstrate that they are generally thin tabular sheets. However, anomalies most certainly resulting from concealed masses of serpentinite suggest that these tabular bodies may dip steeply into and beneath the Dothan graywackes and that the amount of serpentinite in the upper crust of this area is more extensive than implied by the surface map.

The field evidence strongly supports the idea that these serpentinites represent parts of oceanic crust-mantle tectonically emplaced into the continental crust. The presence of exotic (or tectonic) blocks demonstrates that large-scale dislocations were needed to enclose these blocks completely in the serpentinite. The mélange and sheared nature of the serpentinite could only have been caused by tectonism. These tectonic movements do not preclude the possibility that the peridotites had an igneous origin within the mantle. If serpentinization was contemporaneous with tectonism, with continued hydration the peridotites became more plastic and facilitated regional thrusting and transporting of tectonic inclusions from various parts of the crust.

The age of the serpentinites remains uncertain, as the ultramafic rocks have been tectonically transported, and serpentinization is a continuous process not related to stratigraphy or igneous history. If the diorites and the ultramafic rocks with which they are associated have a contemporaneous igneous origin, then radiometric dating of the diorites may provide a possible minimum age. Dott (1965) reported a single hornblende age of 285 m.y. from his Saddle Mountain Diorite, considered part of the ultramafic complex in this area, rather than a tectonic inclusion. There are no known Paleozoic rocks in this area, but to the east in the Klamath Mountains province there is a thick section of Paleozoic rocks associated with ultramafic rocks (Irwin, 1964; Irwin and Lipman, 1962). Small single grains of serpentinite debris are widely disseminated in the Dothan and Otter Point graywackes. If the source of these detrital fragments in the graywackes is related to the presently exposed serpentinite, the serpentinites may have first been exposed during the Late Jurassic. Further indirect evidence of the age of the serpentinite is afforded by the Nevadan diorite intrusions in the serpentinite at Collier Butte, Iron Mountain, and Game Lake. K-Ar ages on hornblende and biotite indicate a minimum age of 145 m.y. (table 5). The basal conglomerates of the Umpqua Formation near Agness contain abundant pebbles of serpentinite, gabbro, and diorite. From this indirect evidence of the age, it appears that the ultramafic rocks may have crystallized from an igneous melt during Carboniferous time, in either the upper mantle or oceanic crust, perhaps along an ancient oceanic ridge. If the Saddle Mountain Diorite of Dott (1965) is comagmatic with the peridotites, the ultramafic rocks began their conversion to serpentinite during Early Jurassic time, and during Late Jurassic time were intruded by Nevadan diorite of Pearse Peak type. Some of the serpentinite was exposed at the surface during this period and provided minor debris to the Late Jurassic graywackes. The present serpentinite tectonic sheets developed during the Late Cretaceous when the Colebrooke Schist and some Myrtle Group rocks were thrust into their present position. Continued uplift at the beginning of the Tertiary stripped off some of this serpentinite and Colebrooke Schist, and the debris formed part of the basal conglomerates of the Umpqua Formation. Continued tectonic activity along the Coquille River and Mountain Well faults further mobilized the serpentinites into these disturbed zones.

AMPHIBOLITES AND GLAUCOPHANE SCHISTS

Numerous isolated tectonic blocks of coarse-grained gneissic rocks of the blueschist and amphibolite facies are present within the area. These unusual rocks were first recognized by Diller (1898, 1903) and carefully mapped in the Port Orford and Roseburg quadrangles. Diller was puzzled by these isolated occurrences of coarse-grained metamorphic rocks that seldom exceed 100 acres and are commonly less than several square feet in diameter. He concluded that these blocks might represent local metamorphism, although he presented no convincing evidence. Diller (1903) indicated that these isolated meta-

TABLE 5.—*K–Ar ages on minerals from diorite and amphibolite, Gold Beach-Agness area, Oregon*

[Analysts: Lois Schlocker, potassium analyses; Jarel Von Essen, argon analyses and age calculations]

Field No.	Rock type	Mineral	K_2O (percent)		$Ar^{40}{}_{rad}$ (moles/gram)	$\frac{Ar^{40}{}_{rad}}{Ar^{40}{}_{total}}$	Apparent age (m.y.)
19–RGC–65	Diorite, Pearse Peak.	Biotite	2.44, 2.45	2.44	5.285×10^{-10}	0.57	141±4
		Hornblende	.450, .456	.453	9.542×10^{-11}	.69	137±4
34–RGC–65	Diorite, Iron Mountain.	Hornblende	.725, .730	.728	1.620×10^{-10}	.78	145±4
47–RGC–64–1	Quartz diorite, Game Lake.	Muscovite	9.42, 9.30	9.36	2.028×10^{-9}	.80	141±4
54–RGC–65A	Amphiboltic, Big Craggies.	Amphibole	.143, .147	.145	3.362×10^{-11}	.50	151±5

Constants:
K^{40} decay constants: $\lambda_\epsilon = 0.585\times10^{-10}$ year $^{-1}$.
$\lambda_\beta = 4.72\times10^{-10}$ year $^{-1}$.
Abundance ratio: $K^{40}/K = 1.19\times10^{-4}$ atom percent.

morphic rocks do not extend south of the Sixes River; however, numerous new occurrences of such rocks have been found in both the Port Orford and Gold Beach quadrangles. Glaucophane-bearing schists are sparse in the Colebrooke Schist, but isolated blocks of higher grade blueschists of unknown origin have been found along the west side of the serpentinite mass on Signal Buttes and in the North Fork Pistol River on the southeastern side of the Signal Buttes serpentinite mass. Few of these blueschist blocks are more than 50 feet in diameter; many are rounded and show evidence of shearing. The mineral assemblages of the blueschists in this area are as follows:

Glaucophane-epidote-chlorite-quartz.
Glaucophane-epidote-mica-quartz.
Crossite-epidote-mica-chlorite-garnet-quartz.
Crossite-epidote-quartz-lawsonite-albite.
Glaucophane-albite-stilpnomelane.

The mineral assemblages and textures indicates that these blueschists were derived from rocks predominantly of basaltic composition and that they probably formed under metamorphic conditions different from those that produced the Colebrooke Schist.

Other isolated blocks of the amphibolite facies are commonly associated with the blueschist tectonic blocks. At Iron Mountain, a mass of amphibolite approximately 2,300 by 1,000 feet is a tectonic inclusion within serpentinite. A series of smaller amphibolite inclusions are present within serpentinite near the Game Lake Lookout. The Big Craggies form a klippe of amphibolite gneiss approximately 2 by 6 miles in area (pl. 1) upon a thin carpet of serpentinite resting on top of Dothan graywacke. Axial planes of the recumbent isoclinal folds of the amphibolite dip northwest. Only one period of deformation can be established within the amphibolite, but there is considerable evidence of shearing, brecciation, and mylonitization along its contacts with the serpentinite. The amphibolites all show retrogression to lower metamorphic grade. Most of the plagioclase has been altered to epidote-prehnite-sericite; some amphibole has been altered to chlorite. The common primary mineral assemblages recognized in the amphibolites are as follows:

Green hornblende-plagioclase-quartz-magnetite.
Green hornblende-plagioclase-magnetite.
Green hornblende-magnetite.
Green hornblende-clinopyroxene-olivine.
Olivine-hypersthene-clinopyroxene-plagioclase.
Quartz-biotite-garnet-amphibolite.

The mineral assemblage of the common types suggests that the metamorphic rocks belong to the amphibolite facies; however, the presence of orthopyroxene and olivine-bearing ultramafic zones suggests that these amphibolites may be gradational into the granulite facies.

No blueschists have been found associated with these larger amphibolite masses, even though farther west tectonic blocks of both facies are found together. K-Ar dates on muscovite and glaucophane from Tupper Rock, in the town of Bandon, and from tectonic blocks near Winston Bridge in Roseburg, give ages close to 150 m.y., and a single hornblende from the Big Craggies also gives 150 m.y. (M. A. Lanphere, writen commun., 1970; table 5). From these preliminary data, it appears that a blueschist and amphibolite metamorphism developed together in a cryptic terrane not now exposed. To the east in the Kerby and Galice quadrangles, there are amphibolites similar to the amphibolite from Big Craggies; these eastern amphibolites could be a source terrane for the Big Craggies, but no blueschists are found with them. The thrusting that moved the Colebrooke Schist into its present position may have also dislocated the blueschists and amphibolites from their parent terrane. If this terrane was developed 150 m.y. ago, the dislocated masses now exposed must represent a basement not now exposed along the continental border of Oregon. There are amphibolites in the Klamath Mountains province, but they are not associated with blueschists of the type seen along the coast. More detailed work is necessary to fit these unusual masses into the regional geology.

DIORITE OF PEARSE PEAK TYPE

The Pearse Peak Diorite, named by Koch and others (1961) for exposures along the Elk River just north of Pearse Peak, is the largest intrusive mass in the area and is similar to the smaller intrusives throughout the area. This diorite intrudes the Galice Formation and is surrounded by a well-developed hornfels contact zone (Koch, 1966; Dott, 1965). The intrusive body varies in composition from diorite along its outer boundaries to quartz diorite toward the center. The content of hornblende and biotite is highly variable; zoned plagioclase ranges from An_{30} to An_{46} (Kaiser, 1962). Modal analyses show that the intrusive rocks belong to the quartz diorite family. The more mafic types from the border may represent the composition of the parent magmas. Both Dott (1965) and Koch (1966) consider the Pearse Peak to represent the Nevadan event, and their earlier reported K-Ar ages (141–145 m.y.) agree with the 137–141 m.y. ages derived from coexisting hornblende and biotite used in this study (table 5).

Of the numerous smaller intrusive bodies of quartz diorite and dacite porphyry that invade the Galice Formation and serpentinites, the Collier Butte and Iron Mountain stocks are particularly noteworthy. I use the term, "diorite of Pearse Peak type," to include the many intrusive bodies of the same petrology and age as the Pearse Peak Diorite. Serpentinite at the contacts is baked in appearance, and numerous xenoliths of serpentinite are present within the intrusives. The Collier Butte stock is porphyritic, with a fine-grained groundmass showing flow textures, and it is nearly a dacite porphyry. Many other small dikes in the serpentinite and Galice Formation also are dacite porphyries. Some small stocks, such as at Game Lake and near Iron Mountain, appear to have evolved into albitites as a result of desilication within enclosing serpentinites (pl. 1). Where these intrusive bodies have been in active tectonic zones, some have been broken up and undergone calcium metasomatism (Coleman, 1967). A characteristic of the diorite of Pearse Peak type and related intrusive rocks is the widespread alteration of the plagioclase and biotite.

The age data on these various intrusive bodies show that they can all be considered part of the Pearse Peak intrusive event ($\approx$145 m.y.) or Nevadan (Late Jurassic). It is important to stress that none of these intrusive bodies invades the Colebrooke Schist, Dothan, or Otter Point Formations. Where diorite of the Pearse Peak type invades the serpentinite tectonic sheets that overlie the Otter Point and Dothan graywackes, these intrusive bodies are considered to be rootless and not to intrude the underlying graywackes. There is some brecciation and shearing, but no prevalent metamorphic fabric associated with the alteration. The pervasive alteration may be related to a regional low-grade metamorphism. Diorite of Pearse Peak type appears to be correlative with the northern plutonic rocks of the Klamath Mountains province, where Lanphere and others (1968) report that the ages range from 145 to 155 m.y.

COLEBROOKE SCHIST

GENERAL DESCRIPTION

The areal distribution of the Colebrooke Schist is extremely irregular and follows no regional structural trend (pl. 1). The topography produced on the schist terrane is characteristically subdued with low, rounded hills except where metabasalt accumulations have developed a more rugged outcrop pattern, as at Skookumhouse and Quosatana Buttes. The climatic conditions of southwest Oregon have caused a vigorous forest of Douglas-fir to grow on most of the Colebrooke Schist, and because of this heavy growth, good exposures of unaltered rock are restricted to streams, roadcuts, and areas of active logging. The best exposures of the Colebrooke Schist are along the Rogue River, which cuts east-west across the entire exposure and along Lobster Creek in the northern part of the area. A typical surface exposure of schist is characteristically a thin soil zone underlain by broken fragments of schist and phyllite to a depth of 30 feet. Many areas are now actively creeping or have been involved in landslide activity. In the drainage areas of Quosatana Creek and the Rogue River, there are many active landslides. The widespread mass wasting and heavy timber cover prevent detailed or meaningful structural studies of the schist.

There are no persistent stratigraphic markers within the Colebrooke Schist, and all attempts to establish stratigraphic thickness were unsuccessful. If, however, the Colebrooke is an allochthonous plate, it may have a maximum thickness of 3,000 feet and an average thickness of 1,000 to 2,000 feet.

The contacts of the Colebrooke Schist with all surrounding rocks are faulted except where a small patch of the Umpqua Formation is in depositional contact with the Colebrooke at Boulder Creek. These faulted contacts are nearly flat lying and are interpreted as thrusts. Where the thrust surface has been folded, the flat-lying contacts are steep along the flanks of the fold. On the eastern edge of the main area of Colebrooke Schist and sporadically in other areas, sheared tectonic serpentinite is in direct contact with the schist, and the serpentinite commonly contains tectonic blocks of Colebrooke Schist. Numerous small outliers (klippen) of Colebrooke are present in and around serpentine in the Signal Buttes and Snow Camp Mountain areas. These small patches of Colebrooke are probably part of a coextensive plate of Colebrooke Schist rather than local development of schist as suggested by Dott (1965).

The two large segments of Colebrooke Schist are separated by the Mountain Well fault. As a result of earlier thrust faulting and later normal faulting, the Colebrooke Schist is in structural contact with all the surrounding units. Dott (1965) and Koch (1966) considered the contacts of the Colebrooke Schist with the Dothan and Galice Formations to be gradational and the Colebrooke to represent metamorphosed equivalents of these two formations. My interpretation of the field evidence does not substantiate the concept of gradation since the actual contacts either represent fault boundaries, or the Colebrooke Schist is separated by tectonic serpentinite carpets from the Galice and Dothan. Gradational relations were recorded (Blake and others, 1967) in northern California, where the South Fork Mountain Schist is very gradually gradational downward into Franciscan graywacke over at least several thousand feet. No similar gradational zones were established for the Colebrooke Schist, even though narrow shear zones are observed at the faulted contacts.

LITHOLOGY

The Colebrooke Schist is primarily metamorphosed pelitic sedimentary rocks with subordinate amounts of submarine basalt. Graded beds of shale-sandstone layers are the dominant rock type. Subordinate, but consistently present throughout the area, are sandstone beds up to 6 inches thick. In places these sandstone beds grade into pebble conglomerates. The lithology of the pelitic rocks is very similar to that of the Galice Formation, but quite different from the Dothan and Otter Point Formations. Dott (1965) thought several lithologic boundaries extended north from the Dothan into the Colebrooke Schist, but the gradation he inferred may have been his interpretation of complex fault slices of allochthonous and autochthonous rocks. The graded beds and fine-grained nature of the metapelitic rocks, together with the scarcity of limestones, suggest that these sedimentary rocks represent deep-water deposits. The absence of thick massive graywackes characteristic of the Dothan and Otter Point Formations reflects a depositional period of reduced tectonic activity.

Submarine pillow lavas and pyroclastic layers of basaltic composition are erratically distributed throughout the Colebrooke Schist. Three large volcanic centers in the Colebrooke that are now prominent physiographic features are Quosatana and Skookumhouse Buttes and Copper Canyon. These large volcanic piles are mainly pillow lavas, breccias, interstratified pyroclastic rocks, and minor associated chert bodies. The mappable volcanic units are approximately 3 percent of the area of the Colebrooke Schist. Many smaller units not shown on the map were recognized; some of them are submarine basalts and others are pyroclastic rocks interbedded with the pelitic rocks.

STRUCTURE

The Colebrooke Schist has undergone several periods of penetrative deformation related to its recrystallization and tectonic transport. Foliation and linear elements within the pelitic rocks observed at reliable exposures only partially explain the deformation history. Data concerning the structure of the Colebrooke Schist are limited because there are few extensive outcrops, the exposures being limited to streambed and deep roadcuts.

Foliation in the pelitic rocks is parallel to the original bedding, S_1, and related to regional metamorphic recrystallization (fig. 3). This

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is manifested by the alinement of mica and chlorite parallel to the bedding. Where graded bedding is still preserved, S_1 can be readily observed; in the fine-grained shales or more massive graywackes, however, S_1 is difficult to establish. Superposed on S_1 are pervasive S_2 planes that exhibit strain-slip cleavages parallel to the axial planes of folding (figs. 3–5). The S_2 strain-slip cleavages and F_2 folds are

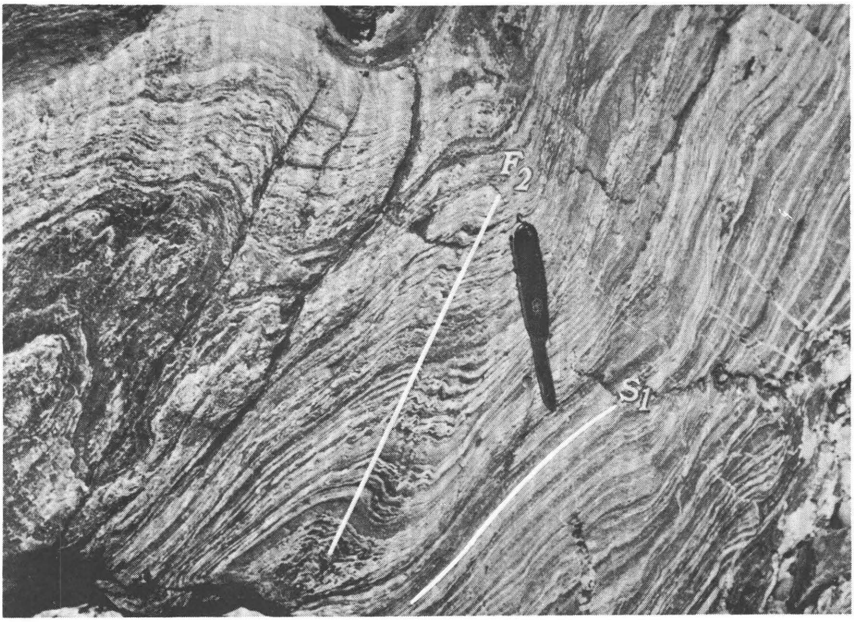


FIGURE 3.—Metasedimentary rocks with preserved graded bedding parallel to S_1 foliation and F_2 folding developed at high angle to S_1. Colebrooke Schist.

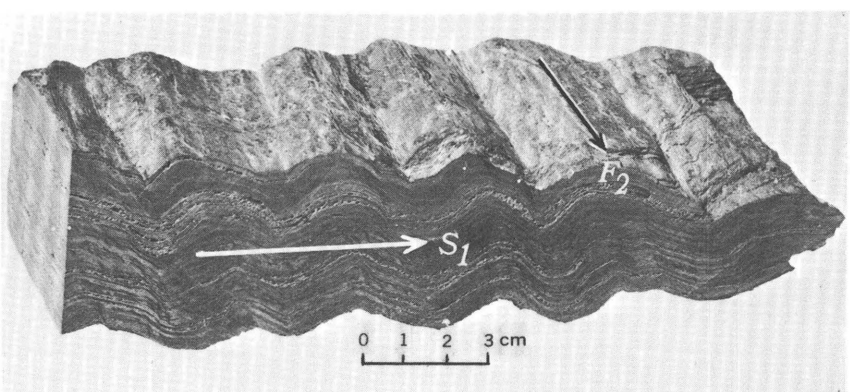
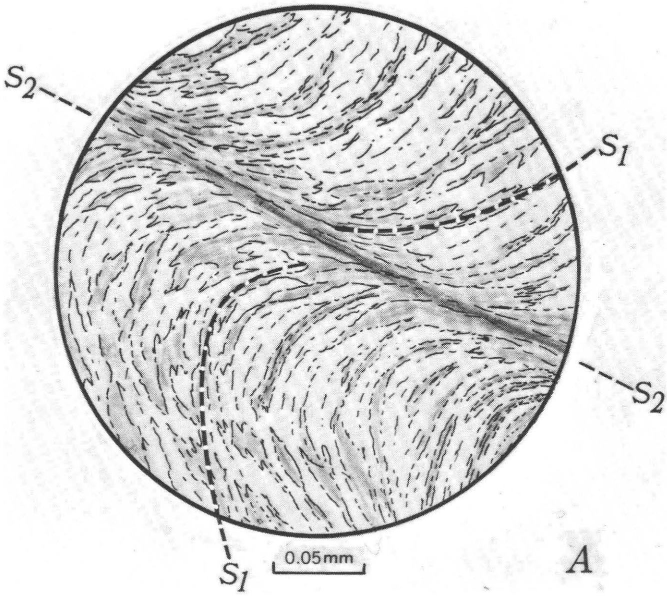


FIGURE 4.—Metasedimentary rocks showing well-developed F_2 folding. Colebrooke Schist.



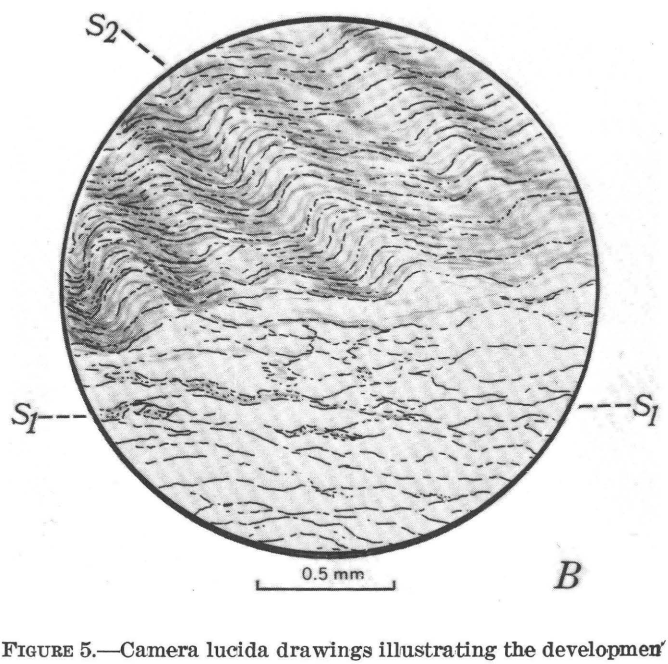


FIGURE 5.—Camera lucida drawings illustrating the developmen of S_2 strain-slip cleavage at high angles to the original foliation plane (A). In the shaly layers the development S_2 is more pronounced (B).

much more pronounced and better developed than S_1 foliation and accompanying F_1 folds. The general linear trend of the S_2 and S_1 intersections is parallel to F_2 folds. F_2 fold axes trend generally north-south in the Colebrooke Schist, except near Sawtooth Rock and Fall Mountain. Here there appear to be rather sharp inflections, and fold axes trend northwest to northeast. By statistical plotting of foliations and lineations, an earlier F_1 folding that trends northeast-southwest can be recognized. Many of the F_2 fold axial planes dip to the west at low angles. This dip and an eastward vergence of the axial planes suggest that strain-slip cleavage developed at a late stage of compressional folding during eastward transportation of the Colebrooke nappes. According to Turner and Weiss (1963, p. 464), strain-slip cleavage is invariably a late structural feature and usually tends to be normal to the principal compressive stress direction. Thus it appears that forces responsible for S_2 strain-slip cleavages and F_2 folds were from either the west or east. The fold axes in the Otter Point and Dothan, like the apparent synform axes of the two allochthonous blocks of the Myrtle Group near Agness, generally trend north-south.

The widespread occurrence of sheared serpentinite as thin sheets under the Colebrooke Schist plate demonstrates that at least some of the tectonic transport was facilitated by the presence of the serpentinite. The contacts between the serpentinite and schist are highly sheared, often showing intimate mixtures of the two units. In the Signal Buttes and Collier Butte areas, smaller isolated allochthonous masses are completely surrounded by serpentinite, and some are completely enclosed as tectonic blocks. The associated serpentinites, even though they may represent subcrustal peridotites, have arrived at their present location by tectonic transport. It is not clear whether the serpentinites were present in the upper crust before the thrusting of the Colebrooke sheets or if the upward tectonic transport of the serpentinites accompanied the thrusting. The S_2 strain-slip cleavage and F_2 folds of the Colebrooke Schist appear to have developed during the thrusting. Umpqua (Eocene) conglomerates containing Colebrooke Schist fragments and serpentinite debris lie unconformably on Colebrooke Schist in the Boulder Creek area. Thus, the age of the thrusting is probably pre-Tertiary.

Later normal faulting has bisected the Colebrooke Schist. The Mountain Well and the Coquille River faults are parallel north-south-trending faults that have elevated the eastern sector of the Colebrooke Schist into a horst. The amount of vertical displacement on these faults is difficult to estimate and may be quite variable. Along the northern part of the Powers-Agness fault, the Eocene Umpqua and Jurassic Galice Formations are brought into contact, whereas the Mountain Well fault shows less displacement at its northern end.

Both faults appear to die out to the south or at least are not recognizable within the Dothan graywackes. Further mapping within the graywackes to the south is needed to determine the extent of the faults.

PETROGRAPHY

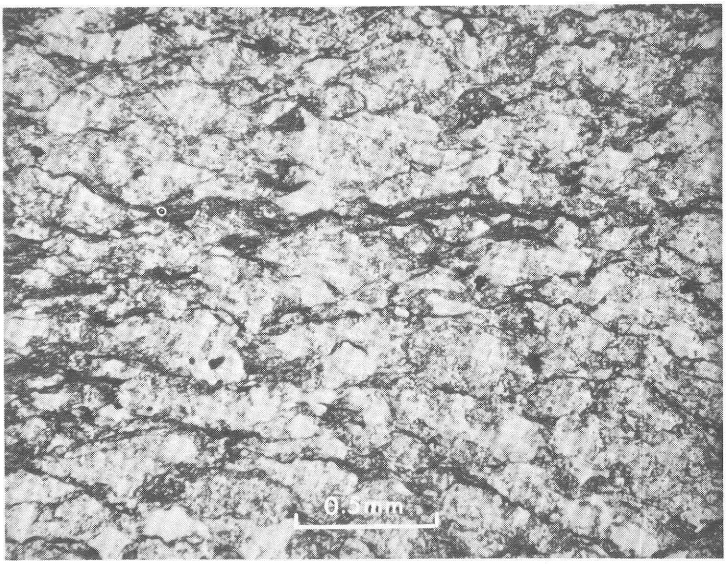
The Colebrooke Schist can be divided into three main rock types for the purpose of petrographic discussion: (1) metasedimentary rocks, (2) metachert, and (3) metavolcanic rocks.

METASEDIMENTARY ROCKS

Metasedimentary rocks are characteristically recrystallized fine-grained schists or phyllites with silvery-gray cleavage surfaces (fig. 6). Shaly beds may retain an almost black color, whereas the coarser sandstones appear nearly identical with a strongly foliated graywacke. The texture of these rocks is determined by the orientation of chlorite and white mica. Recrystallization of the original clastic materials produces a foliation generally parallel to the bedding planes, S_1. The second deformation has bent and broken the metamorphic minerals and, in some instances, minor recrystallization has produced a faint foliation, S_2. Rotation of albite porphyroblasts is common and is presumed to occur during development of S_2 (fig. 7).

Quartz is the predominant mineral in these schists, forming a fine-grained matrix with individual grains less than 0.1 mm. Quartz segregations and veins are abundant (fig. 8*A*, *B*). They are almost monomineralic; a small amount of carbonate is the only other mineral present. F_2 folding has deformed and broken these quartz concentrations, particularly along the axis of folding. Albite ($<An_{10}$) forms porphyroblasts in the foliated groundmass of quartz, chlorite, and white mica (fig. 6). These albite porphyroblasts show simple albite twinning and are crowded with minute inclusions. The outlines are anhedral, interdigitating with the finer matrix.

Chlorite and white mica are in intimate intergrowths, making it difficult to establish their chemical nature by either electron probe or analyses of separates. Using a combination of X-ray and optical techniques, the author found that the chlorites from the pelitic rocks have a density greater than 2.86 with a basal spacing (001) that averages 14.19A. The chlorite is optically negative with a $2V$ between 15° and 20° and an average beta refractive index of 1.612 ± 0.003. According to Albee (1962) and Deer, Howie, and Zussman (1962), these chlorites have an Fe/Fe+Mg ratio of 0.3 with approximately a fourth of the tetrahedral sites occupied by $[Al]^4$. In the nomenclature of Hey (1954), these chlorites belong to the corundophyllite group and appear to be more magnesium rich than chlorites from the greenschist facies of New Zealand (Hutton, 1940). Chlorites from the metabasalts have



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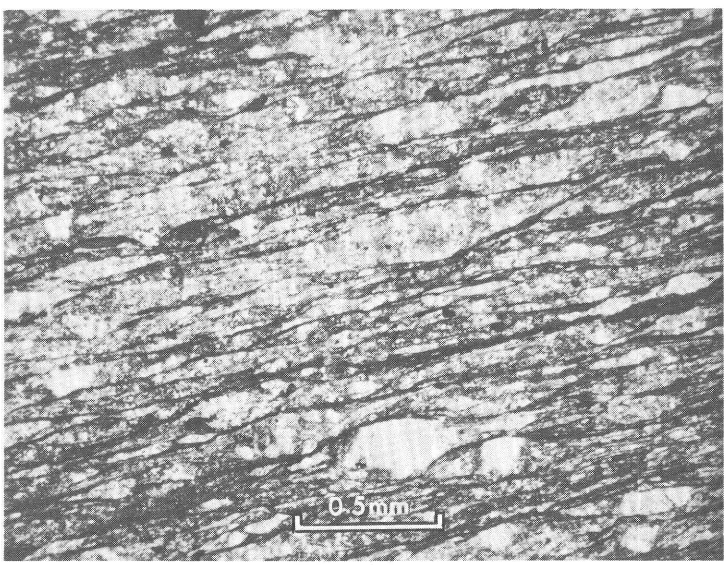
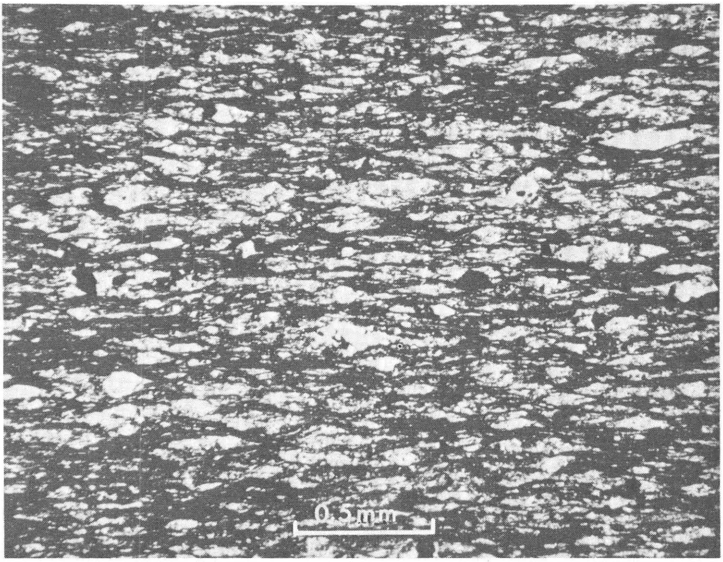


B

FIGURE 6.—Photomicrographs of typical metasedimentary rocks from the Colebrooke Schist. *A*. Schist consisting of quartz, albite, mica, and chlorite. *B*. Schist showing development of porphyroclasts as a result of strain-slip cleavage, S_2, parallel to S_1. Consists of same mineral assemblages as (*A*). *C*. Phyllite containing a large amount of fine-grained graphite derived from original carbonaceous material.



C

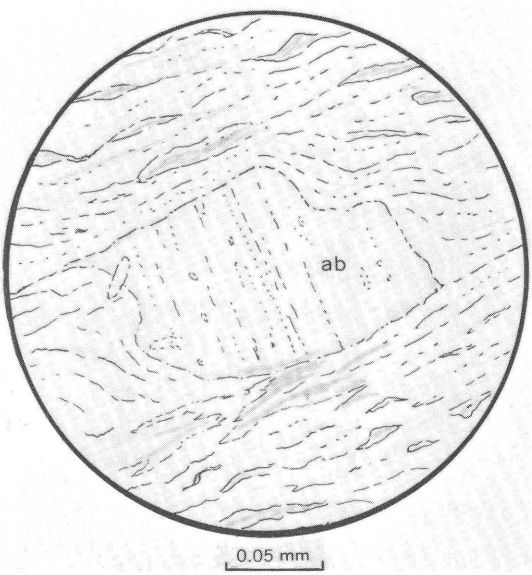
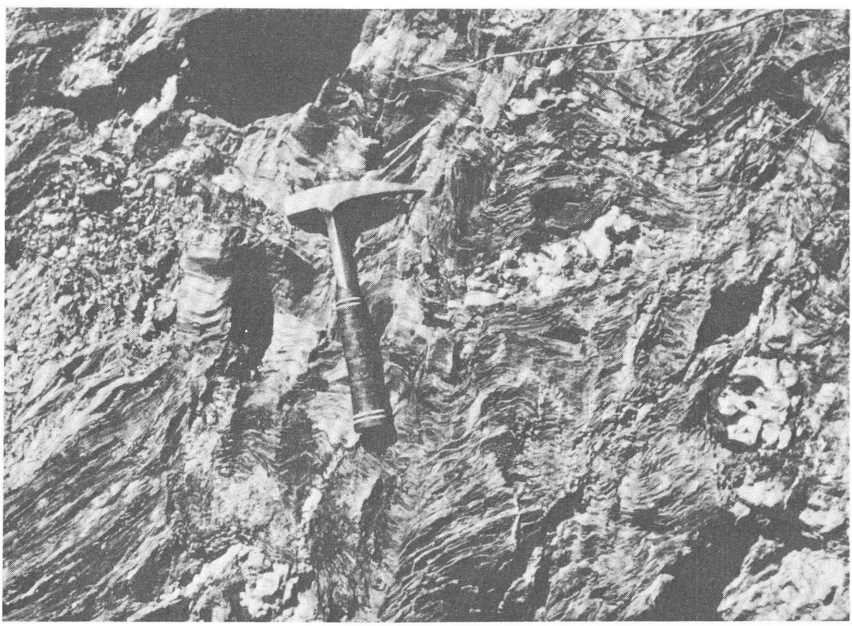


FIGURE 7.—Camera lucida drawing of albite porphyroblast (ab) in the Colebrooke Schist. Rotation of albite produced during second deformation.

A



B

FIGURE 8.—Colebrooke Schist showing: *A*, typical quartz segregations parallel to the foliation, and *B*, distorted and broken segregations within area of complex folding.

an average basal spacing (001) of 14.09 A, suggesting that the amount of tetrahedral aluminum is greater.

The white micas have $2V \approx 30°$ $(-)$ and $\beta = 1.586 \pm 0.003$. Using the X-ray techniques of Cipriani and others (1968), analysts concluded that these white micas are phengitic in composition, as $b_0 > 9.025$ A. Careful examination of the X-ray patterns revealed no evidence of paragonite; the difficulties in establishing the presence of paragonite have been described by Laduron and Martin (1969). As pointed out by Guidotti (1968), the amount of aluminum in the rock controls the formation of paragonite. Since the Al_2O_3 content of the Colebrooke Schist is low (11–15 percent Al_2O_3), one would not expect paragonite to form in these rocks.

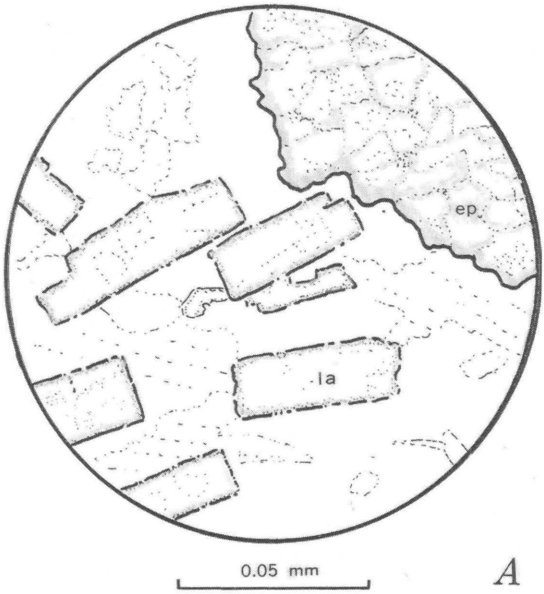
Quartz, chlorite, white mica, and albite are the most important minerals of the pelitic schists and phyllites of the Colebrooke Schist. Lawsonite was identified in 19 of approximately 130 specimens; it rarely accounts for more than 0.1 percent (by volume) of the schists (fig. 1). It is extremely fine grained, forming distinct elongate tabular euhedral crystals. These grains may be 0.1 mm along the prismatic axis, but few are more than 50μ (microns) thick (fig. 9). Characteristically, they contain numerous inclusions, particularly within the central part of the crystal. Less common, but present in significant amounts, is epidote. The epidote appears to be metamorphic rather than detrital, and in several sections epidote and lawsonite coexist. Graphite is a common constituent in the shale units, and, in some places, imparts a nearly black tone to the metashales.

Sphene and tourmaline are common to nearly all sections inspected but are only minor accessory metamorphic minerals. Calcite was identified in only a few specimens; however, near-surface leaching of calcite in the porous schists may be responsible for its scarcity. Aragonite was sought but not found; however, some calcite grains have biaxial optical character with small $2V$. Stilpnomelane is present as a major mineral in pelitic rocks containing volcanic detritus.

METACHERT

Metachert generally associated with the volcanic rocks is not plentiful in the Colebrooke, but its mineral assemblages are significant. These cherts are extremely fine grained with delicate bedding preserved; the strong deformation characteristic of the pelitic rocks is not apparent. The more common mineral assemblages are as follows:

Quartz-stilpnomelane-chlorite-white mica-carbonate.
Quartz-riebeckite-acmite-magnetite-deerite.
Quartz-magnetite-acmite-riebeckite-deerite.
Quartz-chlorite-mica-garnet-pyrite-albite.
Quartz-stilpnomelane-sphene-graphite.



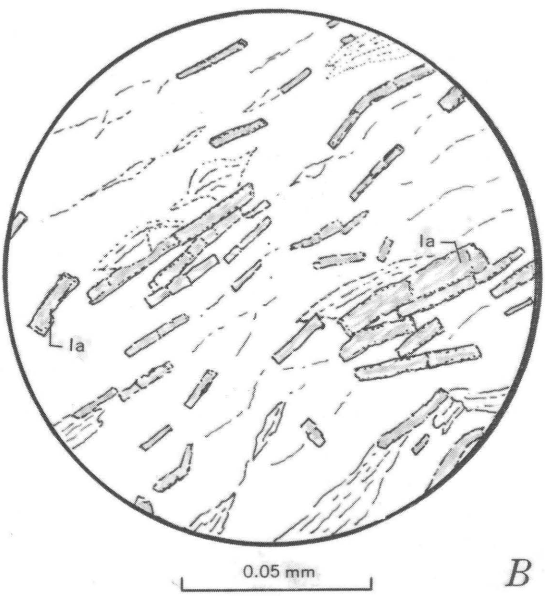
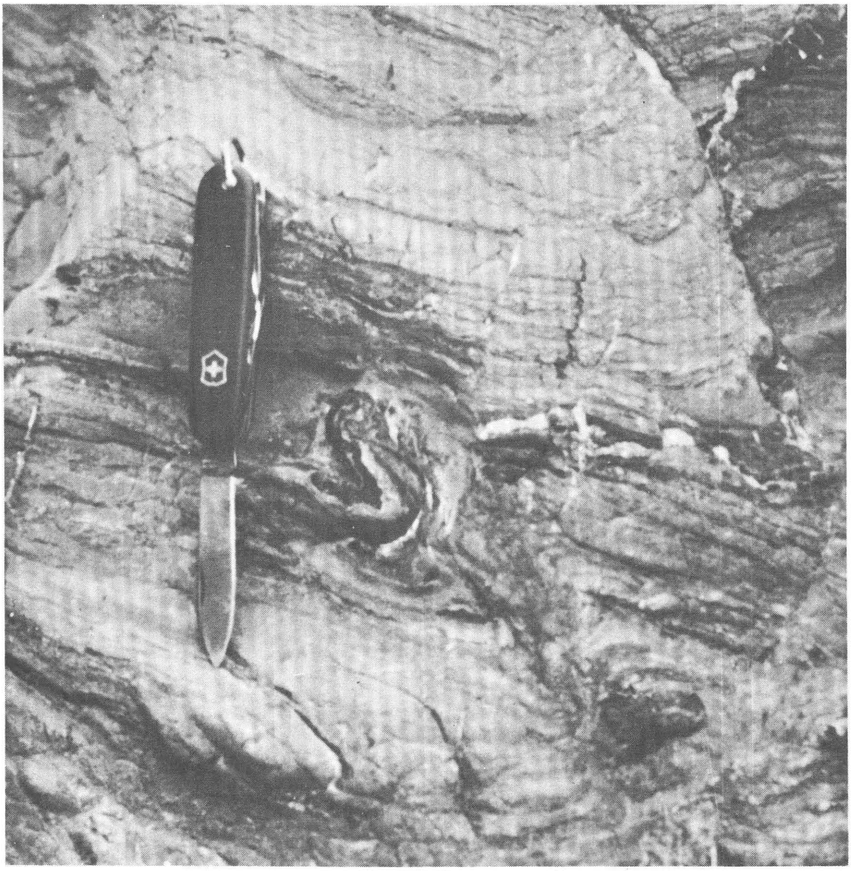


FIGURE 9.—Camera lucida drawing of lawsonite from metasedimentary rocks in the Colebrooke Schist. In some places, lawsonite (la) and epidote (ep) coexist (*A*). Where the F_2 folding has affected the rock, lawsonite may show bending and deformation (*B*).

The prismatic and platy metamorphic minerals within these metacherts exhibit strong preferred orientation, although they are not abundant enough to produce well-defined foliation. Sharp changes in mineral assemblages from layer to layer reflect original compositional variations. Any single metachert unit may show a wide range in mineral assemblages from layer to layer. The metachert near Wildhorse Lookout contains lenses that are nearly 90 percent magnetite. Attempts were once made to mine this material as iron ore, but the lenses were too small (Butler and Mitchell, 1916, p. 95). Riebeckite forms euhedral grains to 0.5 mm in length in common association with fine fibers of deerite and irregular anhedral grains of acmite. Magnetite is present as euhedral to anhedral grains, and where concentrated is nearly massive in appearance. Stilpnomelane, a common constituent, forms lepidoblastic layers intimately associated with chlorite and white mica. In some metacherts, iron sulfides are present instead of magnetite; the two are apparently mutually exclusive. Many of the features exhibited by these metacherts are similar to those associated with blueschist facies rocks in California (Coleman and Lee, 1963).

METAVOLCANIC ROCKS

Metavolcanic rocks are present in larger volcanic piles, in individual flows and dikes, or as discontinuous pyroclastic beds within the pelitic rocks (fig. 10). Within the larger piles, such as Quosatana and Skookumhouse Buttes, there is little evidence of the strong foliations developed in the pelitic rocks; however, the metapyroclastics have well-developed metamorphic fabrics. The original igneous textures of the more massive metavolcanic rocks are preserved, even though the rocks have been completely recrystallized. Pillow structures can be clearly observed in the larger volcanic piles. The pillows are not vesicular at their margins and thus may have been extruded in deep water (Moore, 1965). They are somewhat flattened, but thin sections of the chilled margins reveal the original variolitic texture. Primary igneous pyroxene is the only mineral that survived metamorphism; commonly it has overgrowths of actinolite. The groundmass of the metavolcanic rocks is mainly chlorite, actinolite, albite, stilpnomelane, and sphene, with variable amounts of epidote and pumpellyite. Carbonate is commonly present in veins associated with albite. The hydrous calcium silicates, epidote and pumpellyite, coexist in some specimens; in others, either pumpellyite or epidote occurs alone. No pattern of occurrence could be established for these minerals. It is noteworthy that lawsonite was not found in any of the metavolcanic rocks. Pyrrhotite is a common accessory mineral in the metavolcanic rocks, and it appears to have formed during metamorphism.



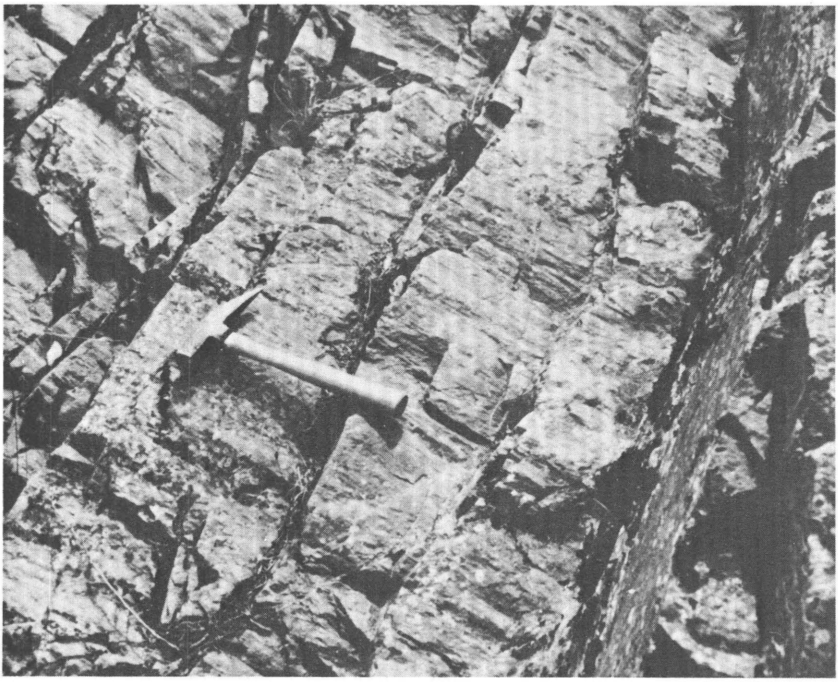
A

FIGURE 10.—Metabasalt within the Colebrooke Schist. *A*. Strongly jointed pyroclastic metabasalts with poorly developed foliation. Direction of lineation parallels hammer handle. *B*. Layered metatuff of basaltic composition consisting primarily of actinolite-albite-epidote. Plastic zone showing small fold contains abundant blue amphibole (crossite).

The metapyroclastic rocks have the same general mineral assemblages. Epidote is the only hydrous calcium silicate found in these rocks. Significantly, crossite was found in two occurrences as small, nearly monomineralic segregations; in no instance, however, do alkali amphibole and lawsonite coexist in the metavolcanics.

MINERAL ASSEMBLAGES AND METAMORPHIC FACIES

The mineral assemblage, quartz-chlorite-white mica-albite, characteristic of the pelitic Colebrooke Schist, is similar to the mineral



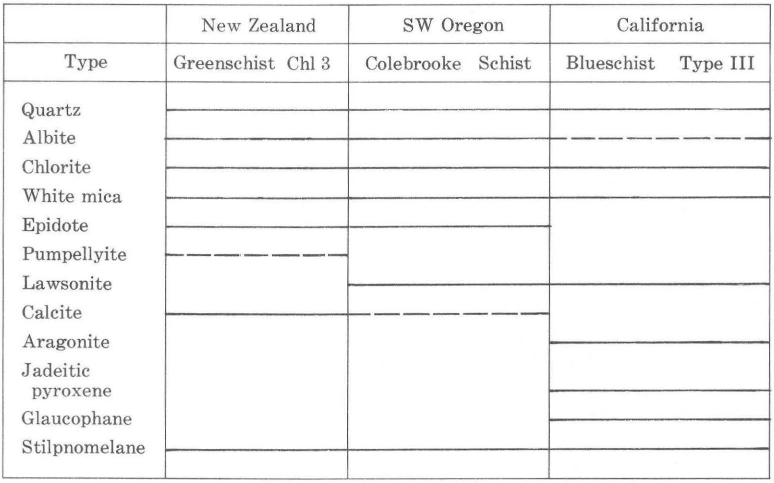
B

assemblage described for the quartzo-feldspathic schists of the Chl 3 subzone in the Wakatipu metamorphic belt of New Zealand (Hutton, 1940); the Colebrooke also contains lawsonite, not reported in the New Zealand rocks (fig. 11). The textural similarities of the Colebrooke Schist and the Chl 3 subzone in New Zealand have been documented (Blake and others, 1967).

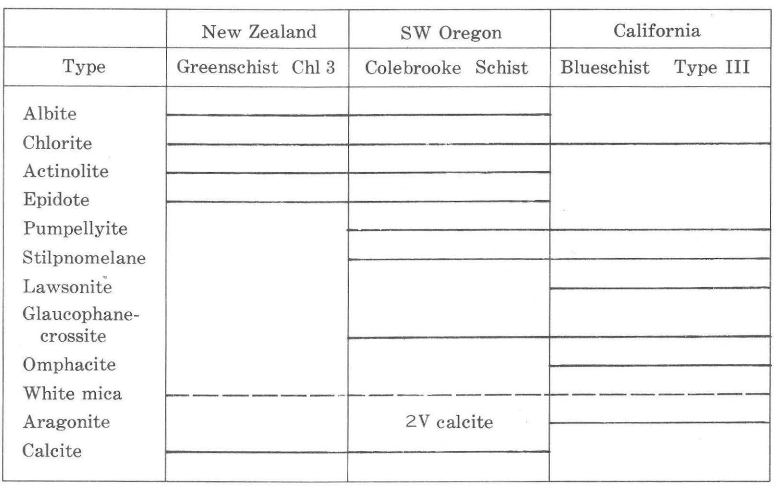
The chlorite-actinolite-albite-pumpellyite-epidote assemblage of the metabasalts is also similar to rocks of similar bulk composition within the Chl 3 subzone of the Wakatipu metamorphic belt except that pumpellyite and crossite are absent in New Zealand rocks. The metabasalt mineral assemblages are more nearly equivalent to the greenschist facies than to the blueschist facies.

In this particular study, it was not possible to discern any areal mineral zonation (fig. 7). Zonation may exist, but the exposures of Colebrooke Schist do not provide evidence of systematic spatial variation in the mineral assemblages.

Comparison (fig. 11) of assemblages of the Colebrooke Schist with the Chl 3 subzone and Type III blueschists (Coleman and Lee, 1963) suggests that Colebrooke rocks were metamorphosed under conditions intermediate between blueschist and greenschist facies. The degree of



Metasedimentary assemblage



Metabasalt assemblage

FIGURE 11.—Comparison of mineral assemblages in metamorphic rocks of New Zealand, southwestern Oregon, and California. Solid lines represent uniform and persistent development of a mineral, whereas dashed lines indicate sporadic occurrence.

recrystallization and foliation in the Colebrooke is comparable to that reported for the Chl 3 subzone and Type III blueschists; therefore, the metamorphic fabric does not give any clue to conditions characteristic of either facies. As noted earlier, mineral zonation or evidence of progressive metamorphism could not be established in the Colebrooke Schist (fig. 1). To the south, in California, a progressive mineral and textural zonation in Franciscan graywackes has been established (Blake and others, 1967). The graywackes grade upward from slightly reconstituted pumpellyite-bearing rocks into the lawsonite-bearing South Fork Mountain Schist and are considered to belong to the blueschist facies. The Colebrooke and South Fork Mountain Schists are similar in lithology and in metamorphic mineral assemblage. However, there is no field evidence to show a regional metamorphic gradation from the Dothan Formation (here considered to be coextensive with the Franciscan Formation of northern California) into the Colebrooke.

In the metasedimentary rocks, lawsonite coexists with epidote (fig. 8A); in the metabasalt, pumpellyite with epidote. Where these minerals coexist without evidence of replacement reaction, it is concluded that the metamorphic conditions represent a transition between blueschist and greenschist facies.

CHEMICAL COMPOSITION

In order more completely to understand the possible protoliths that may have given rise to the Colebrooke Schist, the author had chemical analyses made of a representative suite of metasedimentary rocks (table 6) and metabasalts (table 7). Graywackes characteristic of the Galice, Otter Point, and Dothan Formations were also analyzed, for comparison, as these three formations have been considered as possible protoliths of the Colebrooke Schist (tables 1–3).

It is readily apparent that metasedimentary rocks in the Colebrooke are similar to metasedimentary rocks in the Galice, whereas graywackes of both the Dothan and Otter Point seem to be quite different from the Colebrooke. Plots of normative and Niggli values illustrate their differences (figs. 13, 14). The Otter Point and Dothan graywackes from the western part of the geosyncline contain a higher volcanogenic component than do the Dothan graywackes from the axial part of the geosyncline. There seems to be a chemical overlapping of the Colebrooke Schist and the graywackes from the axial part of the geosyncline.

TABLE 6.—*Chemical and spectrographic analyses of metasedimentary rocks from the Colebrooke Schist*

[Rapid rock analyses by Paul Elmore, G. W. Chloe, James Kelsey, J. L. Glenn, S. D. Botts, Hezekiah Smith, Lowell Artis; spectrographic analyses by Chris Heropoulos]

	217-BLW-65	250-BLW-65	76-RGC-65-1	26-RGC-67-A	41-RGC-67-B	53-RGC-67-A	105-RGC-67	114-RGC-67	37-RGC-67	40-RGC-65
Chemical analyses (weight percent)										
SiO_2	70.4	67.5	68.6	65.0	72.1	66.1	69.4	68.6	65.4	65.2
Al_2O_3	11.2	13.3	14.4	14.6	12.3	15.4	12.9	13.8	15.2	14.2
Fe_2O_3	.63	1.0	.48	1.1	.87	1.0	.00	.00	1.1	1.4
FeO	4.7	5.3	4.2	5.9	4.3	5.2	4.7	4.7	4.8	5.1
MgO	3.7	3.4	2.7	4.3	2.8	2.7	3.1	3.2	2.6	3.6
CaO	1.6	1.2	.80	.35	.27	.53	1.1	.70	.80	.8
Na_2O	2.6	2.7	2.4	2.2	2.3	1.7	2.6	2.7	2.1	2.0
K_2O	1.0	1.0	1.6	1.2	1.0	1.8	1.2	1.1	1.4	1.8
H_2O-	.07	.15	.34	.24	.17	.19	.10	.19	.30	.29
H_2O+	2.9	3.3	3.4	4.2	2.9	3.6	3.3	3.3	3.7	3.8
TiO_2	.63	.70	.78	.64	.64	.77	.59	.68	.80	.67
P_2O_5	.15	.16	.16	.18	.15	.22	1.1	.25	.84	.18
MnO	.08	.04	.04	.00	.04	.04	.00	.00	.08	.08
CO_2	.42	.08	.08	.15	.12	.18	$<.05$	.05	$<.05$	.11
Total	100	100	100	100	100	100	100	99	99	99
Sulfide sulfur as S	.05	0	0	0	0	0	0	0	0	0
Specific gravity, bulk	2.71	2.62	2.66	2.61	2.66	2.73	2.55	2.62	2.65	2.71
Specific gravity, powder	2.76	2.76	2.76	2.72	2.72	2.76	2.76	2.76	2.76	2.76

Semiquantitative spectrographic analyses (ppm)

B	30	50	100	50	70	150	70	100	150	100
Sr *	121	67.2	54.1	51.4	51.5	76.6	25.4	26.3	----------	34.1
Rb *	30.7	32.0	57.6	37.4	43.3	71.8	42.3	41.8	----------	61.4
Ba	700	200	500	500	500	500	500	500	500	500
Co	15	30	----------	20	10	20	10	10	7	15
Ni	70	70	70	150	100	100	100	100	100	200
Cu	70	100	50	70	70	100	70	50	70	50
Cr	200	100	100	200	100	100	150	150	100	150
Pb	----------	10	20	10	15	10	----------	10	15	7
V	150	150	200	300	200	200	200	200	200	300
Y	20	20	20	20	30	30	30	20	30	20
Yb	3	3	2	3	3	3	3	2	3	3
Sc	20	20	20	30	20	20	20	20	20	20
Nb	----------	----------	7	7	10	15	10	15	15	7
Ga	10	10	15	15	15	15	15	15	15	15
Zr	150	150	200	100	200	200	150	150	300	150

* Determined by isotope dilution and X-ray flourescence. Analyst, Zell Peterman.

Sample	*Description and location*
217–BLW–65	Medium-dark-gray pelitic schist; quartz, albite, chlorite, white mica, carbonate; Deadline Creek.
250–BLW–65	Medium-gray pelitic schist; quartz, albite, white mica, chlorite, sphene; near Copper Canyon, Rogue River.
76–RGC–65–1	Medium-gray pelitic schist; quartz, albite, white mica, chlorite; Copper Canyon, Rogue River.
26–RGC–67–A	Light-olive-gray pelitic schist; quartz, albite, chlorite, white mica, epidote; Brushy Bald Mountain.
41–RGC–67–B	Medium-light-gray pelitic schist; quartz, albite, white mica, chlorite; Silver Creek.
53–RGC–67–A	Dark-gray phyllite; quartz, albite, white mica, graphite; Lobster Creek.
105–RGC–67	Light-gray pelitic schist; quartz, albite, mica, chlorite, epidote, lawsonite; Fall Mountain.
114–RGC–67	Medium-light-gray pelitic schist; quartz, albite, mica, chlorite; Fall Mountain.
37–RGC–67	Dark-gray to medium gray banded phyllite; quartz, albite, mica, chlorite, graphite; Silver Creek.
40–RGC–65	Medium-gray phyllite; quartz, albite, chlorite, muscovite, lawsonite, graphite; Sawtooth Mountain.

TABLE 7.—*Chemical and spectrographic analyses of metabasalts from the Colebrooke Schist*

[Rapid rock analyses by Paul Elmore, G. W. Chloe, James Kelsey, J. L. Glenn, S. D. Botts, Hezekiah Smith, Lowell Artis; spectrographic analyses by Chris Heropoulos within the limit of detectability the following elements were looked for but not found: B, Pb, Nb.]

	16-RGC-64-2	21-RGC-64-2	39-RGC-64-A	51-RGC-64	41-RGC-65	52-RGC-65	53-RGC-67-C	98-RGC-67 Rim	98-RGC-67 Core	104-RGC-67-B	133-RGC-67-A
Chemical analyses (weight percent)											
SiO_2	51.8	55.8	48.6	48.5	51.8	49.0	45.5	45.4	47.0	39.5	50.9
Al_2O_3	14.0	16.0	13.7	13.0	15.5	13.0	14.8	14.4	12.5	15.7	14.5
Fe_2O_3	1.1	.71	1.4	1.1	1.7	4.4	4.3	1.3	13.2	8.9	4.6
FeO	9.5	6.9	10.4	10.4	9.2	7.9	10.2	12.9	1.3	8.4	5.7
MgO	6.0	3.9	5.1	6.3	5.1	5.2	6.2	5.8	6.1	6.2	6.1
CaO	7.8	4.7	8.3	10.6	6.4	10.2	10.8	9.0	9.8	14.4	10.0
Na_2O	4.3	7.0	3.6	3.2	5.0	2.5	1.2	3.0	2.8	.40	3.2
K_2O	.10	.10	.60	.10	.10	1.6	.10	.10	.20	.06	.06
H_2O^-	.09	.08	.08	.63	.03	.16	.13	.29	.43	.15	.08
H_2O^+	3.1	2.3	4.6	3.7	3.2	2.6	3.8	4.7	3.7	3.9	2.4
TiO_2	1.4	1.4	2.5	2.0	1.4	2.2	2.4	2.3	2.2	1.6	1.4
P_2O_5	.10	.37	.20	.18	.11	.21	.22	.27	.25	.18	.38
MnO	.19	.17	.20	.17	.13	.12	.25	.13	.12	.17	.12
CO_2	.10	.45	.25	.16	.16	1.0	.12	.08	.11	.05	<.05
Total	100	100	100	100	100	100	100	100	100	100	99
Sulfide sulfur as S	0	0	0	0	0	0	0	0	.07	.16	----------
Specific gravity, bulk	2.93	2.79	3.00	3.00	2.89	3.01	3.09	3.00	2.96	3.23	2.97
Specific gravity, powder	2.92	2.78	2.92	3.04	2.92	3.08	3.08	3.04	3.08	3.32	3.08

Semiquantitative spectrographic analyses (ppm)

Sr*	72.9				237			98.8	117.4		
Rb*	.60				2.36			1.92	7.5		
Ba	30	20	1500	15	70	50	100	100	500	30	30
Co	50	20	50	50	50	50	50	50	50	50	50
Ni	50	20	50	70	50	70	70	50	50	70	70
Cu	20	100	100	100	100	100	150	150	150	100	70
Cr	50	50	50	100	70	100	150	70	50	150	150
V	300	200	700	300	300	500	500	500	500	200	300
Y	50	50	70	50	30	70	70	70	70	50	50
Yb	5	5	7	7	5	7	7	7	7	7	7
Sc	50	30	70	50	50	70	70	70	70	70	70
Ga	15	15	20	15	15	15	20	20	20	20	15
Zr	100	70	200	150	70	200	150	150	150	100	100

*Determined by isotope dilution and X-ray fluorescence. Analyst, Zell Peterman.

Sample	*Description and location*
16–RGC–64–2	Dusky-yellow-green massive metabasalt breccia; actinolite, albite, chlorite, sphene; Wild Horse Lookout.
21–RGC–64–2	Grayish-olive-green metakeratophyre; albite, actinolite, chlorite, sphene; Wild Horse Prairie.
39–RGC–64–A	Massive grayish-olive-green metabasalt; actinolite, albite, chlorite, carbonate, stilpnomelane; Skookumhouse Butte.
51–RGC–64	Massive grayish-olive-green metabasalt; actinolite, albite, chlorite, pumpellyite; Quosatana Butte.
41–RGC–65	Massive breccia, grayish-olive-green; albite, actinolite, epidote, pumpellyite, carbonate, chlorite; Sawtooth Mountain.
52–RGC–65	Massive grayish-olive-green metabasalt; albite, epidote, actinolite, chlorite stilpnomelane, carbonate; Coffee Butte.
53–RGC–67–C	Foliated grayish-olive-green metabasalt tuff; epidote, albite, chlorite, actinolite; Lobster Creek Boy's Camp.
98–RGC–67 Rim	Massive dusky-yellow-green pillow rim of metabasalt; Quosatana Butte.
98–RGC–67 Core	Massive grayish-olive-green pillow core of metabasalt; Quosatana Butte.
104–RGC–67–B	Massive grayish-olive-green metabasalt tuff; chlorite, actinolite, epidote, pumpellyite, albite, calcite; Rogue River.
133–RGC–67–A	Foliated dusky-yellow-green metabasalt tuff; albite, epidote, actinolite, chlorite, sphene; Lobster Creek Bridge.

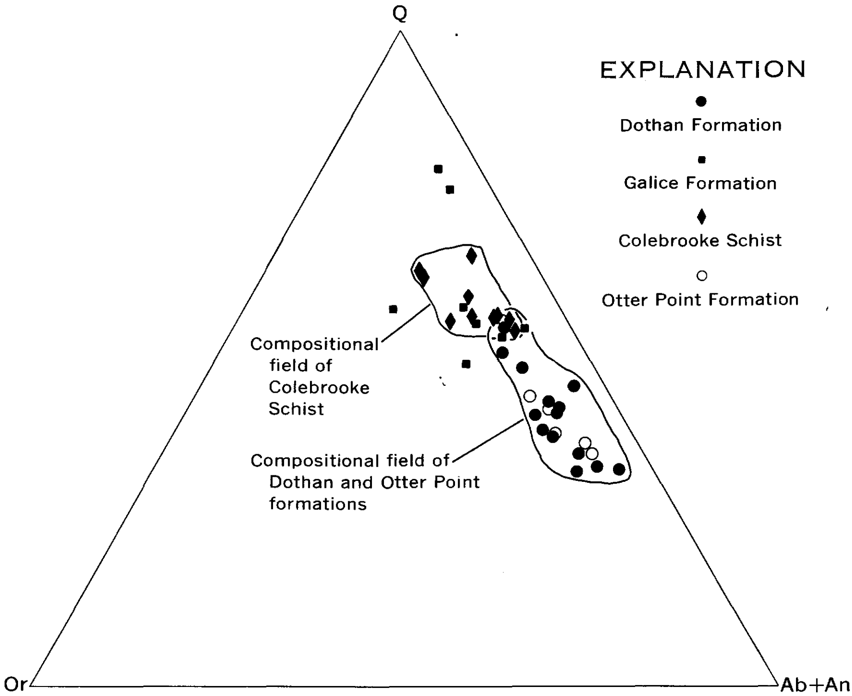


FIGURE 12.—Triangular plot of the normative values for quartz (Q), plagioclase (Ab+An), and orthoclase (Or) of analyzed sedimetary and mestasedimentary rocks from the Colebrooke, Dothan, Otter Point, and Galice Formations.

The Colebrooke appears to be chemically distinct compared with the Franciscan and Dothan graywackes; this must reflect either a source area of a different type or changes that have occurred during metamorphism.

The abundance of quartz veins (fig. 9) in the Colebrooke Schist suggests that solutions during metamorphism caused their formation. Whether such solutions were responsible for changes in bulk composition cannot now be established. The similarity between bulk compositions of the Galice and Colebrooke metasedimentary rocks and their differences in superimposed metamorphism suggest that the derived bulk compositions fairly closely parallel the composition of the original sediments.

The compositions of the metabasalts from the Colebrooke are most closely associated with oceanic tholeiites (Engel and others, 1965) because of the very low values for K, Ba, Sr, and because of their similarity in bulk composition as shown on the AFM plot (fig. 14).

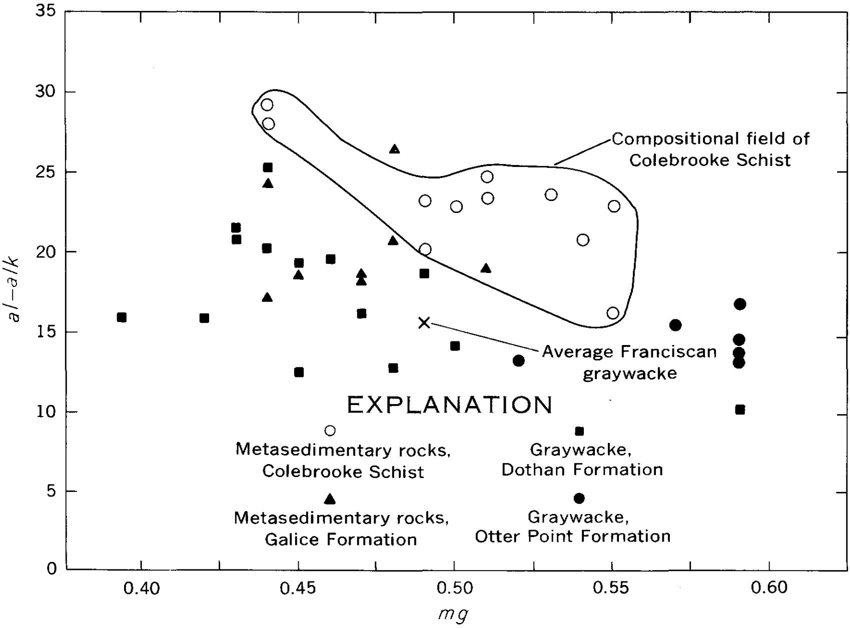


FIGURE 13.—Niggli values, *mg* versus *al-alk*, of analyzed sedimentary and metasedimentary rocks in the Galice, Dothan, Colebrooke, and Otter Point Formations, compared with average Franciscan graywacke.

The scarcity of analytical data on metabasalts associated with eugeosynclinal deposits makes difficult a comparison of metabasalts from other areas with the Colebrooke. Enough data are available on the basalts from the Franciscan Formation to show that they and the Colebrooke metabasalts have many chemical features in common. Certainly it would seem that these basalts formed from similar magmas. These eugeosynclinal basalts were emplaced as submarine extrusions and may have undergone some deuteric alteration before metamorphism. The rather broad range in composition from tholeiite basalt through keratophyre suggests that the original magmatic compositions varied or that postvolcanic alterations were responsible for variations in bulk composition. A previous study of basalts and equivalent metabasalts from the Franciscan has shown that there is little or no bulk chemical change in basalts metamorphosed to blueschists (Coleman and Lee, 1963). Larger submarine volcanic piles emplaced in the Colebrooke sediments may have undergone considerable deuteric alteration as they slowly cooled in the presence of seawater; however, Moore (1965) reported that exposure to seawater had not produced gross chemical changes in the submarine lavas in Hawaii.

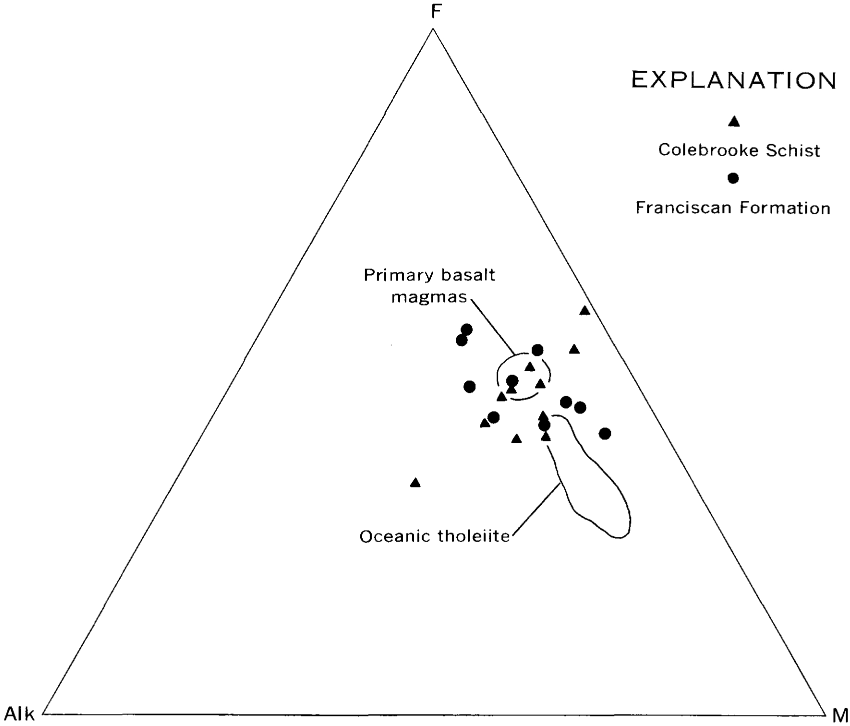


FIGURE 14.—AFM plot of metabasalts from the Colebrooke Schist as compared with oceanic tholeiites, primary magmas, and Franciscan submarine lavas.

MINOR ELEMENTS AND STRONTIUM ISOTOPES

The minor-element content of sedimentary rocks in the Colebrooke Schist, when it is compared with the Galice, Dothan, and Otter Point Formations, gives further evidence of the similarity between the Colebrooke and Galice.

The average strontium content (52.1 ppm) of the Colebrooke is much lower than that found in the other sedimentary units and reflects the extremely low calcium content. Boron shows a higher concentration in the Colebrooke than in the other sedimentary rocks; this may indicate higher concentration during deposition or possibly concentration that occurred during metamorphism. The elements Co, Ni, Cu, Cr, and Pb show a fairly wide range in content in the various sedimentary units but are generally similar, with Ni>Co. The presence of chromium may reflect both mafic and ultramafic components. Uranium and thorium are lower in the Colebrooke and Galice than in the Dothan and Otter Point. The Th/U and U/K ratios are lower in the Colebrooke and Galice than in the Dothan. A pattern of similarity between metasedimentary rocks of the Colebrooke and Galice Formations clearly emerges from the data in table 8. The Dothan and Otter Point graywackes, on the other hand, clearly show similarity to the Franciscan and Great Valley graywackes.

To further this comparison, the author had Sr^{87}/Sr^{86} values determined on all these units. When corrected to their initial values, all these sedimentary rocks have remarkably low initial ratios, and there does not seem to be any significant difference between them. Values as low as these were interpreted (Peterman and others, 1967) as indicating a strong volcanogenic clastic component in graywackes. Further comparison between these Oregon graywackes and Californian and New Zealand graywackes shows that all are characterized by low initial Sr^{87}/Sr^{86} ratios. The Colebrooke metasedimentary rocks have a significantly higher initial Sr^{87}/Sr^{86} ratio than the other graywackes, but this is not an adequate basis to infer that the Colebrooke detritus emanated from a different source. The overall low initial ratios suggest that these sediments did not have a continental source.

The metabasalts of the Colebrooke Formation clearly have low initial Sr^{87}/Sr^{86} ratios and this, together with their low barium, zirconium, and potassium contents, suggests that their chemical affinities are with oceanic tholeiites rather than continental basalts. The common presence of pyroclastic beds of basaltic composition within the Colebrooke indicates that the unit's sedimentary rocks may contain a large component of volcanic debris which effectively lowers the intial Sr^{87}/Sr^{86} ratio. Metamorphic recrystallization has been so complete that it is now difficult to establish the presence of volcanic clasts in the metasedimentary rocks. Colebrooke metabasalts are compared with other basalts in table 9.

The analytical data clearly distinguish the Colebrooke and Galice metasedimentary rocks from the Dothan and Otter Point eugeosynclinal graywackes. Although the source and depositional environment for the Galice and Colebrooke are not known, the thin-bedded turbidites characteristic of both these units and the presence of oceanic tholeiites strongly suggest that these sediments were deposited directly on oceanic crust.

CONDITIONS OF METAMORPHISM

The metamorphic age of the Colebrooke Schist was considered by Diller (1903) to be pre-Devonian. Louderback (1905) suggested that the Colebrooke was equivalent in age to the Mariposa Formation. More recently Dott (1965) and Koch (1966) presented radiometric whole-rock K–Ar ages on the Colebrooke Schist of 125 and 138 m.y. The

TABLE 8.—*Values of Rb, Sr, Rb^{87}/Sr^{86}, Sr^{87}/Sr^{86}, U, Th, and K on the Colebrooke, Galice, Dothan, and Otter Point Formations*

[Analyses for U, Th, K by gamma spectrometry by Carl Bunker; analyses for Rb, Sr, Sr isotopes by Zell Peterman. Sample numbers are the same as listed in tables 1, 2, 3, and 7]

Sample	U (ppm)	Th (ppm)	K (weight percent)	Th/U	U/K $\times 10^{-4}$	K/Rb	Rb/Sr	Rb (ppm)	Sr (ppm)	Rb^{87}/Sr^{86}	$(Sr^{87}/Sr^{86})_n$	(Sr^{87}/Sr^{86}) initial
Metasedimentary rocks from the Colebrooke Schist												
26-RGC-67A	1.13	2.86	1.12	2.52	1.0	299	0.728	37.4	51.7	2.095	0.7102	0.7065
41-RGC-67B	1.59	4.17	1.11	2.62	1.4	256	.841	43.3	51.5	2.437	.7115	.7072
53-RGC-67A	2.29	6.91	1.75	3.02	1.3	243	.937	71.8	76.6	2.718	.7123	.7075
76-RGC-65-1	1.84	4.57	1.52	2.49	1.2	264	1.064	57.6	54.1	3.087	.7108	.7053
105-RGC-67	1.34	3.49	1.20	2.60	1.1	284	1.665	42.3	25.4	4.829	.7128	.7042
114-RGC-67	1.53	4.16	1.06	2.72	1.4	254	1.589	41.8	26.3	4.610	.7150	.7068
217-BLW-65	1.26	2.90	.814	2.30	1.5	265	.254	30.7	121	.733	.7066	.7053
250-BLW-65	1.36	3.81	.810	2.80	1.7	253	.476	32.0	67.2	1.379	.7093	.7068
9-AG-63-6							2.014	73.7	36.6	5.83	.7173	.7069
22-RGC-64-2							2.186	97.7	44.7	6.35	.7176	.7063
38-RGC-64							.799	48.2	60.3			
40-RGC-65							1.800	61.4	34.1	5.22	.7174	.7081
45-RGC-64							1.437	59.2	41.2	4.17	.7148	.7074
50-RGC-65							.364	14.1	38.6			
Metasedimentary rocks from the Galice Formation												
52-RGC-67A	1.84	4.63	1.34	2.50	1.4	278	0.228	48.1	211	0.661	0.7080	0.7066
52-RGC-67B	1.1	2.4	.90	2.19	1.2	281	.193	32.0	166	.559	.7065	.7054
55-RGC-67A	1.6	3.7	1.62	2.51	1.0	299	.441	54.2	123	1.275	.7083	.7057
55-RGC-67B	2.19	5.35	2.52	2.44	.87	291	.887	86.7	97.8	2.566	.7102	.7050
134-RGC-67	1.94	4.56	.85	2.35	2.3	260	.140	32.7	233	.407	.7067	.7059
135-RGC-67	1.04	2.69	.85	2.58	1.2	225	.387	37.7	97.4	1.121	.7053	.7030
139-RGC-67A	2.48	6.77	1.97	3.00	1.3	278	.427	70.8	166	1.235	.7072	.7047
139-RGC-67B	2.05	4.3	1.36	2.09	1.5	336	.191	40.5	212	.554	.7057	.7046

Graywackes from the Dothan Formation

58-RGC-67	2.23	7.69	1.09	3.44	2.0	251	0.253	43.5	172	.0731	0.7057	0.7043
65-RGC-67	1.71	4.74	1.10	2.77	1.6	256	.296	42.9	145	.858	.7058	.7041
67-RGC-67	2.38	5.93	1.31	2.49	1.8	236	.185	55.6	300	.537	.7060	.7050
68-RGC-67	1.72	5.00	1.11	2.90	1.5	300	.330	37.0	112	.956	.7063	.7044
69-RGC-67	2.46	9.07	.83	3.68	3.0	229	.176	36.3	206	.510	.7043	.7033
78-RGC-67	2.12	5.66	1.05	2.68	2.0	281	.084	37.4	445	.243	.7064	.7059
89-RGC-67	2.02	6.17	1.36	3.05	1.5	240	.510	56.6	111	1.473	.7090	.7061
90-RGC-67	1.64	4.86	.52	2.98	3.2	186	.192	27.9	145	.558	.7068	.7057
93-RGC-67	2.64	7.63	.55	2.89	4.8	213	.122	25.8	211	.353	.7064	.7057
53-RGC-68	1.86	5.34	1.12	2.87	1.7	272	.138	41.1	298	.400	.7061	.7053
54-RGC-68	1.73	4.99	1.18	2.89	1.5	256	.147	46.0	313	.426	.7061	.7053
55-RGC-68	1.79	5.07	1.09	2.83	1.6	244	.130	44.7	344	.376	.7059	.7052
56-RGC-68	2.34	7.43	1.20	3.18	1.9	282	.147	42.6	290	.426	.7061	.7053
58-RGC-68	2.06	6.06	1.31	2.94	1.6	253	.310	51.8	167	.898	.7073	.7056

Graywackes from the Otter Point Formation

52-RGC-68	1.14	2.89	1.11	2.54	1.0	332	0.068	33.4	491	0.197	0.7047	0.7043
86-RGC-68	1.21	3.02	.61	2.50	2.0	409	.046	14.9	323	.133	.7050	.7047
87-RGC-68	2.18	6.20	.70	2.84	3.1	242	.163	28.9	177	.472	.7069	.7060
89-RGC-68	1.54	3.83	.96	2.48	1.6	289	.148	33.2	224	.429	.7055	.7047
90-RGC-68	1.42	3.47	.98	2.44	1.4	268	.154	36.5	237	.446	.7054	.7045
93-RGC-68	1.18	2.98	.84	2.52	1.4	259	.269	32.5	121	.779	.7073	.7058

TABLE 9.—*Comparison of trace elements in parts per million, in metabasalts from the Colebrooke Schist*

Sample	K	Ba	Rb	Sr	K/Rb	Rb/Sr	Sr^{87}/Sr^{86} (initial)
16-RGC-64-3	500	30	0.60	72.9	830	0.0082	0.7036
41-RGC-65	1,200	70	2.36	237	490	.010	.7044
98-A-RGC-67 (rim)	700	100	1.92	98.8	370	.019	.7040
98-A-RGC-67 (core)	2,200	500	7.50	117.4	290	.064	.7044
Average continental [1] tholeiite	5,000	200	10	230	500	.04	.705
Average oceanic [1] tholeiite	1,400	14	1.2	115	1,166	.01	.702–0.703

[1] Data from Armstrong (1968) and U.S. Geol. Survey unpublished data.

Colebrooke Schist was considered (Blake and others, 1967) to be correlative with the South Fork Mountain Schist, the metamorphic equivalent of lower grade Franciscan metagraywackes that contain the pelecypod *Buchia*, of latest Jurassic and Early Cretaceous age. A Rb–Sr isochron of 112 m.y. is reported (Peterman and others, 1967) on these same *Buchia*-bearing graywackes of the Yollo Bolly area. Using the textural classification (Blake and others, 1967) as a basis for further radiometric dating, Suppe (1969) reported that the *Buchia*-bearing metagraywackes of textural zone 2 have an average whole-rock age of 107 m.y. This age is similar to that reported (Peterman and others, 1967) on the basis of Rb–Sr; however, textural zone 3, or South Fork Mountain Schist, has an average whole-rock K–Ar age of 125 m.y. (Suppe, 1969). The two K–Ar ages, 125 and 138 m.y., reported by Dott (1966) seem to coincide with the dates derived by Suppe for textural zone 3.

To further establish the possible age of metamorphism, eight samples of Colebrooke Schist from widely separated areas were used for whole-rock Rb-Sr radiometric determinations, and the results are shown in table 8 and figure 15.

On the strontium evolution diagram (fig. 15) an isochron that includes all 12 Colebrooke Schist samples gives an age of 130 ± 29 m.y. (not shown); if three samples representing coarse-grained graywackes are eliminated, however, an isochron of 28 ± 18 m.y. results. This age of metamorphism falls near the Jurassic-Cretaceous boundary, but plus-or-minus ranges this large prevent assignment to one period or the other.

The large plus-or-minus ranges may reflect different sedimentary source areas with markedly different initial Sr^{87}/Sr^{86} values and concomitant development of parallel isochron lines, as suggested by Bofinger and Compston (1967), or they may result from only partial reaction of the clastic fragments during metamorphism. All the samples studied are completely recrystallized; therefore, it is difficult to demonstrate isochron slope variation resulting from unmetamorphosed

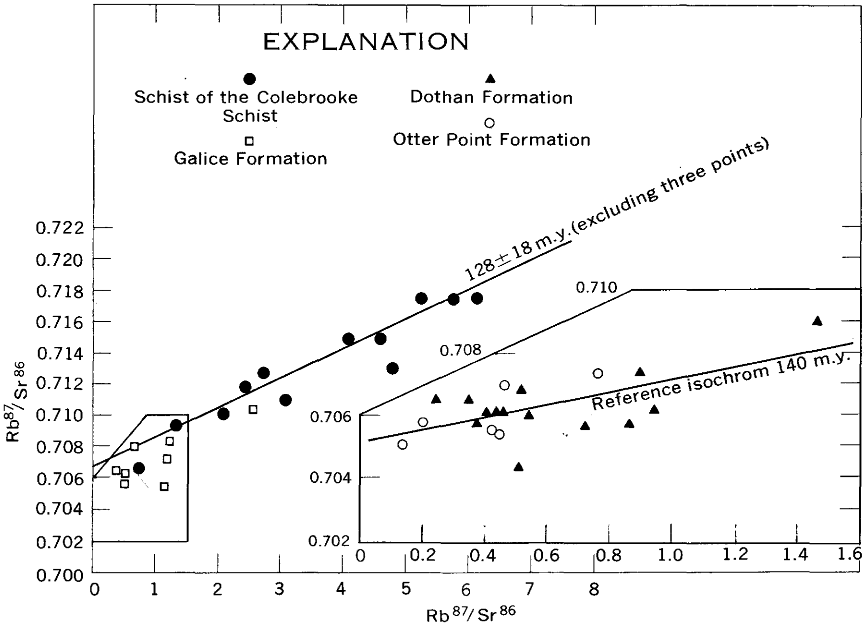


FIGURE 15.—Strontium evolution diagram showing isochron developed from samples of the Colebrooke Schist. Expanded inset shows data from the Dothan and Otter Point Formations with a 140 m.y. reference isochron. Data from Zell Peterman, U.S. Geological Survey.

clastic grains. Since the whole-rock samples represent widespread areal distribution throughout the Colebrooke Schist, it seems more likely that the large uncertainty is due to sedimentation from different source terranes that originally had divergent initial Sr^{87}/Sr^{86} ratios.

A 128 m.y. value for the time for metamorphism of the Colebrooke Schist compares favorably with the 125 m.y. average age reported for the South Fork Mountain Schist in the Black Butte area by Suppe (1969). If, however, the ages of metamorphism of the Colebrooke and South Fork Mountain Schist are similar, then the progressive time-related upside-down metamorphism previously described (Blake and others, 1967) must be revised. Furthermore, metamorphism of the Colebrooke would have to occur during at least part of the Franciscan-Otter Point sedimentation, and after Nevadan plutonic activity at 136 to 150 m.y. The Colebrooke protolith is similar to the Galice and must represent a sedimentary unit deposited during Galice time, but unlike the Galice it was not invaded by Nevadan intrusive rocks (fig. 2). The Colebrooke metamorphic facies is intermediate between blueschist and greenschist and shows evidence of two deformational events: the first contemporaneous with metamorphism, the second related to thrusting of the Colebrooke on top of the Dothan, Galice, and Otter Point. The direction of thrusting was inferred to be from west to east, which suggests that the Colebrooke represents trench sediments at the extreme edge of the continental shelf. Metamorphism began during Valanginian time (Early Cretaceous), after the Nevadan plutons had invaded the Galice farther east. The intimate relation between the Colebrooke Schist and underlying serpentinite sheets suggests that during metamorphism, eastward movement of the ensimatic Colebrooke metasedimentary deposits, perhaps by ocean-floor spreading, brought mantle peridotites along with the deformed Colebrooke into juxtaposition against the continent. This impingement of the thin ensimatic unit against the continental edge provided conditions necessary to metamorphose the Colebrooke Schist. Continued eastward movement placed at least part of the Colebrooke Schist and serpentinized periodotites on top of the Dothan-Otter Point-Galice terrane sometime during the Late Cretaceous.

As noted above, the mineral assemblages of the Colebrooke metasedimentary rocks and metabasalts are intermediate between those of the blueschist and greenschist facies. The presence of lawsonite in the pelitic schists and pumpellyite-epidote in the metabasalts indicates a low-temperature environment. According to Taylor and Coleman's (1968, fig. 15) schematic representation of pressure-temperature relationships, the Colebrooke Schist was probably recrystallized at temperatures between 200° and 250° C and pressures between 5 and 6 kilobars. The conditions needed to produce high pressures and low temperatures have provoked considerable controversy but still remain enigmatic. At least 60,000 feet of overburden with an average density of 2.8 would be required to obtain such pressures. At a depth of 60,000 feet, temperatures calculated on the basis of a normal thermal gradient would be too high (about 300° C), but with a depressed gradient, temperatures of 200°–250° C could obtain. However, the estimated thickness for the Galice here considered as a possible protolith for the Colebrooke is 3,000 to 15,000 feet. If the Colebrooke sediments had attained similar thicknesses, the maximum pressure attainable would be about 4 kidobars. There may have been some thickening during metamorphism as a result of plate tectonics, but the estimated maximum structural thickness of the Colebrooke is approximately 3,000 feet.

If the metamorphism began during deformation of the ensimatic Colebrooke sedimentary rocks by thrusting toward the continent, then some tectonic overpressures may have developed. Evidence of such pressure is lacking, but the deformation accompanying metamorphism suggests lateral compression. There is no clear answer to the problem of blueschist metamorphic conditions; however, it seems clear that the Colebrooke Schist was metamorphosed in a narrow zone associated with orogenic activity of fairly thin ensimatic sediments impinging on the continental edge. There was no accompanying intrusive or volcanic activity in the area where the Colebrooke was being metamorphosed. There are no Mesozoic or older rock units on top of the presently exposed Colebrooke Schist; therefore, the thickness of overburden present during metamorphism cannot be determined. The unconformity between the Otter Point and Myrtle Group may have developed during the orogenic phase that produced the Colebrooke Schist.

The additional radiometric evidence from California and Oregon blueschist terranes has revealed that there may be at least three separate periods of blueschist metamorphism. The oldest is 150 m.y. and pre-Nevadan. This period of metamorphism is represented by relatively high temperature blueschists, eclogites, and amphibolites later structurally displaced after metamorphism. The occurrence of large tectonic blocks and klippe such as Big Craggies and smaller blueschist masses demonstrates that this terrane is a cryptic one, only detached parts of which can now be studied. Most of these tectonic fragments have been transported upward into the crust imbedded in serpentinite or mélanges related to plate tectonics. The Big Craggies may, however, represent an outlier of the Klamath Mountains amphibolites.

The next blueschist event appears to have occurred 125–130 m.y. ago in the Colebrooke Schist and, in California, in the South Fork Mountain Schist, Nacimiento block, and Angel Island. These metamorphic areas are larger in size and extent than the pre-Nevadan tectonic blocks; however, there is evidence that at least the Colebrooke and South Fork Mountain Schists may represent plates that were tectonically transported eastward.

The third period of blueschist metamorphism, recognized within the autochthonous Lower Cretaceous Franciscan of northern California, appears to have occurred 110 m.y. ago (Suppe, 1969). Blueschists of this period appear to have been metamorphosed in place and may have formed during the emplacement of the Colebrooke and South Fork Mountain Schist plates.

Alternatively, it is possible that blueschist metamorphism was continuous from Late Jurassic to Late Cretaceous. However, it is difficult to explain the juxtaposition of high- and low-temperature blueschists of different ages. There is abundant evidence that the 150 m.y. high-temperature blueschists were retrograded to low-temperature blueschists during tectonic transport. If ocean-floor spreading has been intermittent, and the impingement of trench sediments against the continental edge can produce both blueschist metamorphism and emplacement of mantle fragments into the continental crust, then the position of the blueschist and ultramafic belts must mark former sutures that developed during impingement of the oceanic plate against the continental plate.

On the basis of this geologic evidence of imbricate thrusting, we can say that the Pacific Ocean plate was actively spreading under the coast of southern Oregon and northern California from Middle Jurassic to at least Late Cretaceous time.

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