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BASIC REGIONAL METAMORPHIC ROCKS IN PART OF THE KLAMATH MOUNTAINS, NORTHERN CALIFORNIA

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ABSTRACT

Regional metamorphic rocks of basic composition in parts of Coffee Creek and Cecilville quadrangles in tectonic sequence from bottom to top are: Stuart Fork greenstone, Salmon Hornblende Schist, Grouse Ridge hornblende schist and gneiss. Probable westward thrusting has placed early medium-grade rocks over more recent low-grade rocks.

Mineralogic differences between the three units reflect differences in history, composition, and origin. Stuart Fork plagioclase is albite, whereas that of the other units is albite to sodic andesine. The medium-grade rocks show a plagioclase composition gap in the peristerite range. Stuart Fork epidotes cluster near the ideal composition 33 mol per cent $Fe^{3+}/Al+Fe^{3+}$, but some clinozoisite occurs, and there is evidence for a clinozoisite-epidote immiscibility. Higher grade rocks contain low-iron epidote. Amphibole is actinolite, locally crossite to ferric glaucophane in Stuart Fork rocks, and hornblende in Salmon and Grouse Ridge rocks. Chlorite shows an increase in Mg content in medium-grade rocks.

The mineralogic evidence suggests that the earlier, medium-grade metamorphism was of the kyanite-sillimanite type (Barrovian), and the later low-grade metamorphism was of the high-pressure intermediate type in Miyashiro's (1961) classification of facies series.

INTRODUCTION

The purpose of this paper is to describe the detailed petrology of three adjacent basic metamorphic units in the Klamath Mountains; to explain, in terms of composition and metamorphic history, why the three units are distinct; and to discuss the nature of the metamorphism. These units, described in the regional study of Davis *et al.* (ms.), and in a doctoral thesis by the writer (Univ. Calif. Berkeley, 1962) are the greenstone member of the Stuart Fork Formation, the Salmon Hornblende Schist, and the hornblende schists and gneisses of the Grouse Ridge Formation. All three comprise what was originally named Salmon hornblende schist by Hershey (1901).

The area of this report is that mapped by the author (Fig. 1; Davis *et al.*, ms., Pl. 1), and it includes northwestern Coffee Creek and northeastern Cecilville quadrangles. The area, one of regionally metamorphosed rocks intruded first by peridotites and then by Late Jurassic (140 to 125 m.y.) trondhjemites and quartz diorites (Davis *et al.*, ms.), is located 65 miles northwest of Redding, California in the central metamorphic belt of the Klamath Mountains (Irwin, 1960, p. 10, 15). Only the basic regional metamorphic rocks will be considered in detail. The pattern of metamorphism is complex as a result of (1) a rather uniform metamorphic grade within the rocks of a given formation, (2) differences in metamorphic grade and metamorphic history between formations,

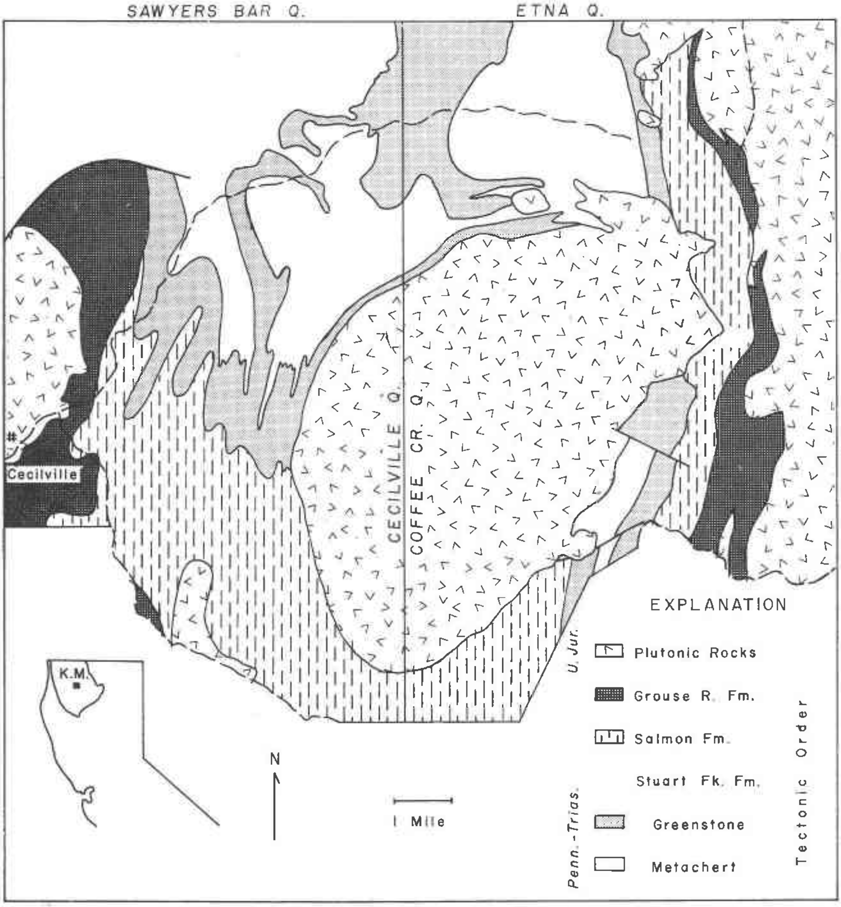

FIG. 1. Generalized geologic map of the area discussed in this report. The location of the report area and the California Klamath Mountains is shown on the index map of northern California at lower left.

and (3) retrogressive metamorphism in some units. Accordingly, there is no simple series of progressive metamorphic zones.

On the largest scale, the metamorphic units comprise an antiform; the complete structural sequence from bottom to top is: Stuart Fork metacherts followed by Stuart Fork greenstone, Salmon Hornblende Schist, Grouse Ridge hornblende schist, and finally Grouse Ridge micaceous and calcareous metasediments. During Pennsylvanian (?) time (Lanphere and Irwin, 1965), the structurally highest Grouse Ridge Formation was metamorphosed largely to the staurolite[1] zone, while the

[1] The metamorphic facies and subfacies classification used in this report is essentially

underlying Salmon formation was metamorphosed to the garnet zone and in part the staurolite zone. Metamorphism largely in the chlorite zone. affected all units. It is possible that the Salmon and Grouse Ridge formations were metamorphosed to medium grade, and later thrust over the Stuart Fork Formation. Low-grade progressive metamorphism of the Stuart Fork rocks and retrogressive metamorphism of the allochthonous (?) units pre-dated and, in part, post-dated thrusting. G. A. Davis (writt, comm., 1963) believes a thrust-fault relationship between the Grouse Ridge and Salmon formations may exist, although evidence for such thrust-faulting is not conclusive. A tectonic relationship between the two formations could explain apparent higher grade of metamorphism exhibited in several areas by the structurally highest Grouse Ridge rocks.

Basic Metamorphic Units

The sequence: Stuart Fork greenstone, Salmon hornblende schist, Grouse Ridge hornblende schist, comprises a continuous series of basic metamorphic rocks which at first sight appear indivisible. However, each unit is distinct, and differences between the units have considerable bearing on the geologic history of the area. The Stuart Fork greenstones are commonly fine-grained, unlineated rocks, which only show a foliation when near plutons. In abrupt contact with these rocks are the Salmon hornblende schists, which are coarser and show preferred orientation of hornblende prisms producing both planar schistosity and lineation. These rocks are in many places separated from the overlying Grouse Ridge rocks by a thin zone of Salmon Hornblende Schist (a shear zone?) containing numerous thin feldspathic lenses, many of which have become rootless isoclinal folds. Finally, the Grouse Ridge hornblende schists may be distinguished by coarse grain size, local gneissic banding, poorly developed planar schistosity and lineation, and presence of micaceous or calcareous layers and periodotite-serpentine intrusions. The mineral content and variability of rocks of the three units are summarized in Table 1. A brief petrographic description of each unit is given below.

Stuart Fork greenstone. Most of the Stuart Fork greenstones exhibit little or no preferred orientation of minerals, but some show primary igneous

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that of Turner in Turner and Verhoogen (1960) and Fyfe *et al.* (1958) modified from Eskola (1939). For brevity subfacies are referred to by their zone names as shown below. Thus the use of a zone name does not necessarily imply the presence of that mineral.

Chlorite z.	Greenschist fac., quartz-albite-muscovite-chlorite subf.
Biotite z.	Greenschist fac., quartz-albite-epidote-biotite subf.
Garnet z.	Greenschist fac., quartz-albite-epidote-almandine subf.
Staurolite z.	Amphibolite fac., staurolite-almandine subf.

textures (Davis *et al.*, ms.). The principal mineral assemblage is actinolite-epidote (and/or clinozoisite)-chlorite-albite-quartz-leucoxene. Calcite, hematite and ore are possible minor constituents. Crossite or ferric glaucophane occurs with epidote in a few specimens from northeastern Cecilville quadrangle on the contact between greenstones and siliceous rocks. The blue amphibole commonly fills veinlike areas in greenstones but locally occurs as the dominant mineral in schists. In blue amphibole rocks actinolite is absent or is largely replaced by chlorite and green biotite.

Salmon Hornblende Schist. The mineral assemblage of the Salmon schists is hornblende-albite (locally oligoclase)-epidote-chlorite-quartz-sphene. The rocks are reasonably restricted in composition in that clinopyroxene and calcite are rare and garnet is absent. The occurrence of clear albite with no indication of more calcic plagioclase suggests that most Salmon rocks were metamorphosed only to the garnet zone, but metamorphic grade reached the staurolite zone in the few oligoclase-bearing rocks in the eastern part of the area.

Most Salmon rocks contain well defined veins of actinolite, albite, and quartz, but some rocks, near the Stuart Fork greenstones in Cecilville quadrangle, contain calcite or chlorite which formed retrogressively during deformation after the main metamorphism, possibly during thrust

TABLE 1. AVERAGES AND RANGES OF MINERAL COMPOSITION FOR BASIC ROCKS OF THE THREE FORMATIONS. VOLUME PER CENT BASED ON VISUAL ESTIMATES

	1	2	3	4	5	6
Hornblende			70	35–87	65	34–76
Actinolite	43	16–78	tr	0–1	tr	0–2
Plagioclase	2	0–5	7	1–15	16	0–29
Epidote-Clinozoisite	40	8–64	15	0–50	10	0–30
Chlorite	5	0–20	1	0–10	2	0–8
Quartz	2	0–10	3	0–15	2	0–8
Others	8	0–23	4	0–6	5	2–20

1. Average of twelve typical Stuart Fork greenstones. Others, in order of abundance are: igneous augite, leucoxene, glaucophane, green biotite, ore, clacite, hematite.
2. Compositional range in the Stuart Fork greenstones.
3. Average of sixteen Salmon hornblende schists. Others in order of abundance are: ore, sphene, hematite, clinopyroxene, calcite, rutile.
4. Compositional range in the Salmon hornblende schists.
5. Average of fourteen Grouse Ridge hornblende schists. Others, in order of abundance are: biotite, calcite, ore, diopside, garnet, sphene, muscovite, rutile, hematite, tourmaline.
6. Compositional range in the Grouse Ridge hornblende schists.

faulting. In some rocks of the formation rutile is rimmed by an opaque mineral (ilmenite?) and in others the opaque mineral is rimmed by sphene. The sphene rims may not be retrogressive as was the case for the Bessi district (Banno and Kanehira, 1961), because the occurrence of sphene rims apparently does not correlate with known retrogressive minerals. Retrogressive effects in Salmon rocks can best be ascribed to conditions of the chlorite zone and/or biotite zone.

Grouse Ridge hornblende schist. The coarser Grouse Ridge rocks are similar in mineral content to the Salmon schists except for a greater degree of variability. Most rocks contain hornblende-albite, oligoclase, or andesine-epidote-chlorite-quartz-sphene-ore, although any mineral other than hornblende may be absent. Small amounts of light brown biotite, calcite, diopside, or almandine produce greater variety than is seen in Salmon schists. Of the minerals present only diopside and almandine are mutually exclusive, their place being taken by hornblende. However, in southwestern Coffee Creek quadrangle, Davis (writt. comm., 1965) reports coexistence of much garnet and diopside in two Grouse Ridge rocks. The garnet in one such specimen was identified as calcium-bearing almandine on the basis of refractive index, unit cell size and alteration to chlorite.

Retrogressive metamorphism is more extensive in Grouse Ridge rocks than in the other units. In most of them hornblende has been partly replaced along fractures and grain boundaries by pale actinolite. Plagioclase commonly contains saussuritic patches or coarser clinozoisite inclusions, suggesting alteration from a more calcic composition. Garnet, where present, is partly altered to chlorite and light brown biotite. Traces of biotite in other basic rocks are retrogressive, resulting from release of K_2O as hornblende (.36 to .73% K_2O, Table 3) is replaced by actinolite. Chlorite replaces some of the hornblende in a few rocks, but much chlorite appears to be the result of progressive metamorphism. The retrogressive metamorphism was in the chlorite and probably biotite zones (a few Grouse Ridge pelitic rocks contain fine-grained biotite which may be retrogressive).

Mineralogy and Chemistry

Optical and chemical data have been obtained for a number of minerals in the basic metamorphic rocks with a view to showing differences and similarities within the three formations and between these rocks and other metamorphic terranes. The data from which the diagrams in this section were prepared are presented in table form in the appendix.

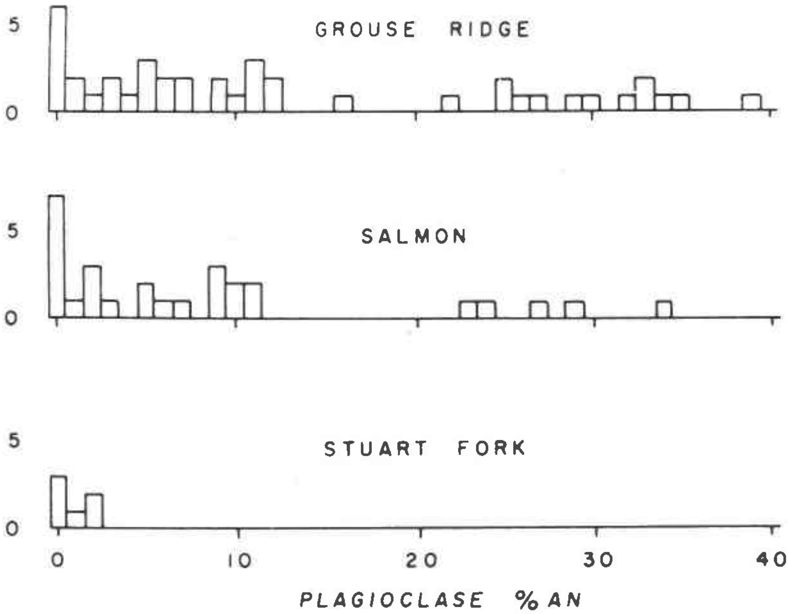

FIG. 2. Frequency diagram of plagioclase composition in basic metamorphic rocks described. Each square represents a single measurement. Between one and three measurements were made for most specimens with suitable plagioclase.

Plagioclase. Plagioclase compositions for rocks in the three formations were determined by the Federow method using the curves of Slemmons (1962) and are considered to be accurate to two or three mol per cent (Fig. 2). Plagioclase of the Stuart Fork greenstones is entirely albite An_0 to An_2, which in every case coexists with epidote or clinozoisite. The other formations contain oligoclase and sodic andesine as well as albite.

The average composition of the Grouse Ridge plagioclase is more calcic than that of the Salmon rocks. For Grouse Ridge rocks, 32% of the measurements yielded plagioclase more calcic than An_{20}, while only 18% of the measurements in Salmon rocks were above An_{20}. As noted above, the Grouse Ridge plagioclase also shows greater evidence of retrogression from calcic compositions than the Salmon plagioclase. Because plagioclase in both formations coexists with epidote, the above evidence suggests that progressive metamorphism of the Grouse Ridge rocks reached a higher grade on the average (largely staurolite zone) than the Salmon rocks (largely garnet zone). An alternative explanation is discussed in the section on epidote minerals.

The compositional gap in plagioclase commonly seen in regional metamorphic rocks (*e.g.* deWaard, 1959) is exemplified by the frequency diagrams for plagioclase composition in Salmon and Grouse Ridge rocks. Only one determination gave a value between An_{12} and An_{22}. Nevertheless, the compositional gap is much less than would be expected from the compositions of the exsolved phases in peristerites, An_0 to An_3 and An_{25} to An_{30} (Laves, 1954). There are two possible explanations for this. (1) The plagioclase crystallization may have been at a high enough temperature that the composition gap was significantly narrower than that for

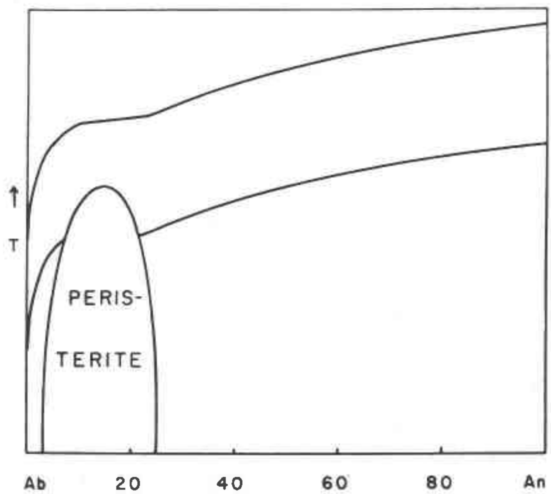

FIG. 3. Possible modifications of Ramberg's (1949) plagioclase-epidote equilibrium curve for constant P_{H_2O} and P_{tot} as influenced by peristerite unmixing. The upper curve would exist if the plagioclase-epidote equilibrium is always greater than the top of the peristerite solvus, while the lower curve would exist if unmixing occurred at the temperature of plagioclase-epidote crystallization.

unmixed peristerites (Fig. 3). The sodic plagioclases might now be peristerites in themselves as a result of slow cooling after initial crystallization. (2) Crystallization might have taken place at such temperatures that plagioclase of all compositions lay above the solvus. The scarcity of compositions between An_{12} and An_{22} would then result from a flattening of the epidote-plagioclase equilibrium curve as it passed over the solvus (Fig. 3). The existence of the peristerite immiscibility at low temperatures is due to positive heat of solution of An_3 and An_{25} which presumably exists in the more ordered plagioclases. This means that at low enough temperatures free energy of solution becomes positive according to the relation.

$$\Delta G_s = \Delta H_s - T\Delta S_s$$

despite the fact that entropy of solution (ΔS_s) is always a positive quantity. This positive heat of solution would still exist in relatively ordered feldspars above the solvus. Its effect would be to reduce the free energy of solution of albite in anorthite for the peristerite range. This reduction in turn would tend to flatten the epidote-plagioclase equilibrium curve but not make it strictly horizontal. In the peristerite range, a small temperature change would produce a large composition change, and sodic oligoclase would be less common but not altogether absent. This explains the existence of rare metamorphic plagioclases within the gap (see also de-Waard, 1959) which must otherwise be explained by metastable crystallization. According to this explanation many of the plagioclases might now be peristerites due to unmixing during cooling.

Epidote minerals. Clinozoisite and epidote have been identified in the basic metamorphic rocks. The Stuart Fork greenstones contain strongly pleochroic epidote and large areas of colorless clinozoisite in minute grains with anomalous blue interference colors, identified on the basis of *x*-ray and refractive index. Salmon schists contain moderately pleochroic epidote, and Grouse Ridge rocks contain nearly colorless epidote. Both Salmon and Grouse Ridge epidotes are weakly zoned and have more aluminous rims.

Approximate compositions of epidote minerals from the three formations, based on 2V or refractive index measurements, are presented in Figure 4. The approximate nature of these determinations is emphasized; any composition may be off by as much as 5 mol per cent. The Stuart Fork epidote minerals are in the ranges Ps_{29}[1] to Ps_{38} and Ps_7 to Ps_{16}, Salmon epidotes are Ps_{21} to Ps_{34}, and Grouse Ridge epidotes are Ps_{11} to Ps_{24}. Most samples show a range of composition, the mean of which is plotted in Figure 4.

In a general way, there is a decrease in iron content of the iron epidote with increasing grade of metamorphism. The effect of increasing grade to produce more aluminous epidotes is probably not the result of dehydration of the more iron-rich epidotes at lower temperatures. Indeed, work in progress by the author shows that the breakdown temperature of epidote and quartz to anorthite and grossularite *is* dependent on iron content, but the more iron-rich epidotes persist to higher temperatures. Earlier work by Winkler and Nitsch (1963) and by S. Merrin (1962, unpubl. Ph.D. Thesis, Pennsylvania State Univ.) indicated that iron content of the system has no effect on this reaction. The temperature depen-

[1] Ps_{29} indicates 29 mol per cent of the hypothetical molecule $Ca_2Fe_3Si_3O_{12}(OH)$, 71 mol per cent $Ca_2Al_3Si_3O_{12}(OH)$.

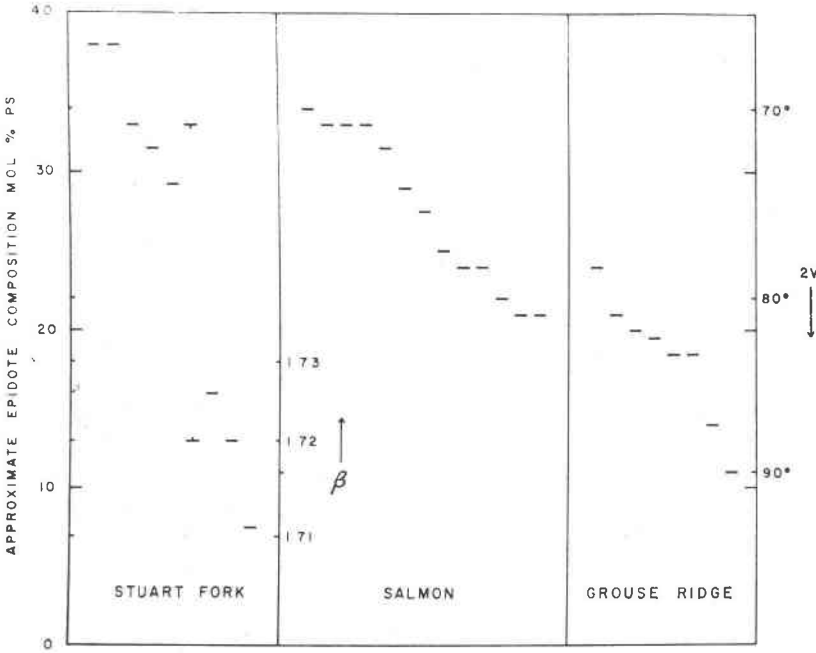

Fig. 4. Epidote composition in basic metamorphic rocks described, as estimated from 2V (Tröger, 1959) or from β (Deer *et al.*, 1962). The progression from left to right within rocks of a given unit is toward more aluminous compositions. A vertical line on the symbol indicates coexistence of epidote and clinozoisite.

dence on iron content of epidotes might well be the same when the reaction involves hornblende instead of grossularite.

At least three factors may be important in explaining the variation in iron content of the epidotes.

(1) In Stuart Fork rocks, which crystallized at lowest temperatures, the tendency for the iron epidote to have a composition near Ps_{33} is in agreement with the observations of Miyashiro and Seki (1958a) on low-grade rocks. There is also a composition gap between Ps_{16} and Ps_{29}. In two rocks clinozoisite and epidote crystallized together in apparent equilibrium. The scarcity of clinozoisite and two-epidote assemblages in these rocks is a reflection of the generally high ratio of $Fe^{3+}/Al+Fe^{3+}$. Strens (1963) has also observed such a gap (Ps_{13} to Ps_{24}) in very low grade rocks and explains it as a miscibility-gap between clinozoisite and epidote. The Salmon and Grouse Ridge epidotes, which crystallized at higher temperatures, fill in the gap, and presumably formed at temperatures above the solvus. (2) With increasing temperature one might expect a progressive reduction of the iron, unless the system was closed to oxygen allowing oxygen pressure to build up. (3) Differences in initial content of Fe_2O_3 are likely to be important, especially in Grouse Ridge rocks which show low Fe_2O_3 in the amphiboles as well (Table 3). Possibly, lower content of Fe_2O_3, producing more aluminous epidotes in the Grouse Ridge rocks, favored reaction of albite and epidote to oligoclase at slightly lower temperatures (see above), hence producing more

calcic plagioclase under the same conditions of metamorphism as those which affected the Salmon rocks.

In summary, the differences in epidote composition between Stuart Fork and Salmon basic rocks may be explained by an immiscibility at low temperatures and a greater variability in initial Fe_2O_3 content of Stuart Fork rocks. Differences between Salmon and Grouse Ridge epidotes reflect either initial differences in Fe_2O_3 content or conceivably progressive reduction of iron at higher temperatures if such higher temperatures existed.

The occurrence of iron-poor epidote minerals in the basic rocks of the Klamath Mountains has bearing on the use of clinozoisite as an indicator of metamorphic grade. Hamilton (1963) has mapped a clinozoisite isograd between the biotite and garnet isograds in basic contact-related metamorphic rocks near the Idaho batholith. It is the contention of the present writer that there is no reason for the instability of clinozoisite in chlorite-zone rocks of any metamorphic terrane. Clinozoisite is certainly present in chlorite-zone rocks of the Klamath Mountains. Two factors may have played a role in the observation of a clinozoisite isograd in the Idaho area.

(1) The clinozoisite which did appear (identified by its lack of color) may have been iron-poor epidote like that of the Grouse Ridge Formation, in which case it would not have appeared until temperatures were high enough to insure stable compositions in the miscibility gap. In this case two epidote minerals might have appeared at lower grades, the one strongly colored and Fe-rich, and the other true clinozoisite, which could have gone unobserved. (2) Rock compositions in the lower grades could have been rich enough in iron so that only epidote without true clinozoisite appeared.

The present study suggests that one can use iron-poor epidote (Ps_{15} to Ps_{25}) as a zone indicator dependent on an epidote immiscibility at low temperature. In the Klamath Mountains iron-poor epidote is apparently not stable in the chlorite zone but is stable throughout the garnet and staurolite zones. Hence its first appearance would occur between the biotite and garnet isograds.

The more aluminous rims seen on epidotes of many Grouse Ridge and Salmon rocks pose a problem. Banno and Kanehira (1961) show that *iron*-rich rims in epidote of basic schists result from retrogressive metamorphism concurrently with chloritization and armoring of rutile by sphene. In the Klamath Mountain rocks the effect on epidote is opposite even in retrogressed rocks, suggesting that either the epidote rims are the result of progressive metamorphism, or preferably that they are retrogressive, resulting from a mechanism not operative in the Japanese rocks (*e.g.*, introduction of solutions poor in Fe_2O_3).

Amphibole. Actinolite, hornblende and crossite have been studied optically and chemically. Measurements of β and 2V have been made to aid in showing differences between amphiboles of the three units and to relate optical properties to composition.

1. Calciferous Amphibole. All the calciferous amphiboles are similar in appearance, but those of the Stuart Fork greenstone are fibrous to varying degrees and locally occur as glomeroblastic replacement of former augite phenocrysts. The optical properties of amphiboles in the three units are summarized in Table 2. Grouse Ridge and Stuart Fork amphiboles have similar pleochroism while Salmon amphiboles are darker. A 2V–β plot (Fig. 5) of the type used by Shido and Miyashiro (1959, p. 86) for calciferous amphiboles of basic regional metamorphic rocks indicates that the amphiboles of the three units are optically distinct from each other and that Stuart Fork amphiboles are actinolite while those of the Grouse Ridge and Salmon rocks are hornblende.

TABLE 2. OPTICAL PROPERTIES OF CALCIFEROUS AMPHIBOLE

	Stuart Fork	Salmon	Grouse Ridge
β	1.638–1.657	1.662–1.675	1.647–1.668
$2V_\alpha$	66°–72°	59°–81°	73°–85°
$Z\wedge c$	15°–16°	15°–18°	14°–18°
X	Colorless	Lt. Yellow	Nearly colorless
Y	Lt. green	Green	Lt. green
Z	Lt. blue-green	Blue-green	Lt. bluish green

Chemical analyses (Table 3) were made for the nine calciferous amphiboles numbered in Fig. 5. The amphiboles were separated from coexisting minerals by fine grinding and repeated separations with the isodynamic separator and heavy liquids. Impurities, chiefly in the form of minute epidote inclusions, were estimated to be less than one per cent in all but three of the samples; 4657B contained about one per cent of impurity, C-57 contained about two per cent of epidote, and C-165 contained about four per cent of clinozoisite. The latter two samples, from the Stuart Fork greenstone, were among the best materials available and even grinding to less than 325 mesh per inch did not effect the removal of all the inclusions. The analyses of these two rocks were corrected for the impurity using appropriate epidote analyses. The changes are small, except for Al_2O_3 in sample C-165, which is reduced by 1.1%. Structural formulae are given for both the corrected and uncorrected analyses.

Structural formulae, calculated on the basis of 24 (O, OH) are in reasonable agreement with those of other hornblende and actinolite anlayses.

The maximum tetrahedral aluminum in the corrected Stuart Fork actinolites is 0.66, which is high for actinolite according to Deer *et al.* (1963); however, the most aluminous actinolite cited by Compton (1958) contains 0.53 Al^{IV}, and the least aluminous metamorphic true hornblende contains 0.84 Al^{IV}. Furthermore the actinolites fall in or very near the

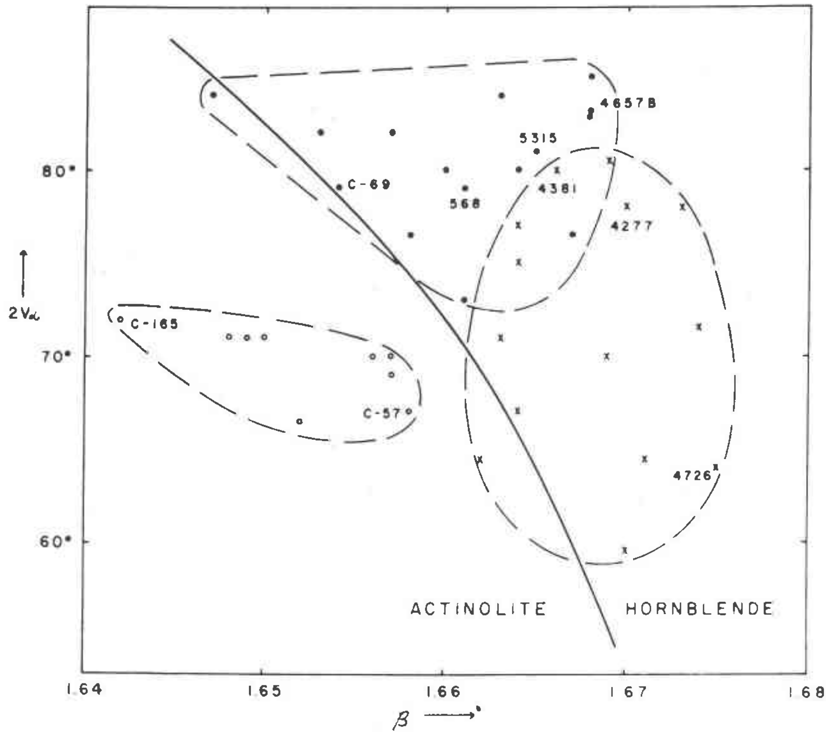

FIG. 5. β-2V diagram for calciferous amphiboles in basic metamorphic rocks described. Circles—Stuart Fork actinolite, dots—Grouse Ridge hornblende, *x*'s—Salmon hornblende. The heavy line approximately divides the diagram into fields of actinolite and hornblende for basic regional metamorphic rocks of the cental Abukuma Plateau (Shido and Miyashiro, 1959).

actinolite field in a Mg$-Al^{IV}$ diagram (Fig. 6; Shido and Miyashiro, 1959). All the other calciferous amphiboles fall in the hornblende field. Non-garnetiferous Grouse Ridge rocks contain hornblende with 1.14 to 1.54 Al^{IV}, Salmon hornblendes contain 1.32 to 1.60, and hornblende from a garnet-bearing Grouse Ridge schist contains 1.79. Thus the miscibility gap between low-grade actinolite and hornblende suggested by Shido and Miyashiro is not disproven by available analyses of Klamath Mountain amphiboles.

TABLE 3. AMPHIBOLE ANALYSES

	Stuart Fork Crossite and Actinolite					Salmon Hornblende			Grouse Ridge Hornblende			
	121	C-165	C-165c	C-57	C-57c	4381	4277	4726	C-69	5315	568	4657B
SiO_2	56.52	52.90	53.51	49.86	50.12	45.19	44.32	42.81	46.28	43.93	45.99	41.59
Al_2O_3	4.18	4.00	2.86	4.79	4.44	10.41	10.80	12.06	11.99	12.18	8.36	13.86
Fe_2O_3	8.35	1.27	1.13	2.95	2.71	4.18	4.68	5.55	2.23	3.56	3.13	3.99
TiO_2	0.30	0.74	0.77	0.89	0.91	0.58	0.71	0.60	0.58	0.73	0.59	0.69
FeO	10.61	10.88	11.32	14.32	14.49	12.93	13.12	14.10	10.45	12.14	13.79	14.57
MgO	8.27	15.18	15.80	12.02	12.26	11.28	10.65	9.62	12.96	11.92	11.55	9.03
MnO	0.16	0.24	0.25	0.32	0.32	0.25	0.26	0.31	0.26	0.25	0.28	0.22
CaO	3.03	12.17	11.69	11.75	11.52	11.50	11.27	10.68	10.36	11.04	12.22	10.94
Na_2O	4.18	0.51	0.53	0.84	0.86	1.58	1.62	1.82	2.04	1.52	1.43	1.58
K_2O	0.81	0.10	0.10	0.20	0.20	0.16	0.46	0.11	0.73	0.61	0.36	0.61
H_2O^+	2.17	1.64	1.63	2.10	2.10	1.75	2.02	1.92	1.85	1.98	1.70	2.22
H_2O^-	0.98	0.10		0.12		0.06	0.12	0.20	0.10	0.22	0.08	0.16
P_2O_5	0.19	0.20		0.22		0.21	0.17	0.25	0.20	0.21	0.22	0.29
Total	99.75	99.93		100.28		100.08	100.20	100.03	100.03	100.29	99.70	99.75
Number of Ions on the Basis of 24(O, OH)												
Si	8.104 } 8.10	7.618 } 8.00	7.713 } 8.00	7.305 } 8.00	7.342 } 8.00	6.679 } 8.00	6.556 } 8.00	6.396 } 8.00	6.710 } 8.00	6.456 } 8.00	6.860 } 8.00	6.214 } 8.00
Al^{IV}		0.382	0.287	0.695	0.658	1.321	1.444	1.604	1.290	1.544	1.140	1.786
Al^{VI}	0.706	0.297	0.199	0.132	0.109	0.491	0.438	0.519	0.758	0.565	0.329	0.655
Fe^3	0.900 } 1.63	0.138 } 0.49	0.123 } 0.37	0.326 } 0.52	0.298 } 0.47	0.465 } 1.00	0.521 } 1.01	0.625 } 1.19	0.244 } 1.04	0.394 } 1.00	0.352 } 0.72	0.448 } 1.15
Ti	0.020	0.050	0.052	0.062	0.062	0.040	0.050	0.042	0.039	0.050	0.041	0.048
Fe^2	1.271	1.310	1.364	1.741	1.775	1.598	1.622	1.761	1.266	1.491	1.719	1.820
Mg	1.765 } 3.06	3.256 } 4.60	3.392 } 4.79	2.623 } 4.40	2.675 } 4.49	2.484 } 4.11	2.347 } 4.00	2.141 } 3.94	2.799 } 4.10	2.609 } 4.13	2.567 } 4.32	2.010 } 3.86
Mn	0.019	0.030	0.030	0.040	0.040	0.031	0.033	0.039	0.032	0.031	0.035	0.028
Ca	0.465	1.877 1.88	1.804 1.80	1.843 1.84	1.808 1.81	1.821 1.82	1.786 1.79	1.709 1.71	1.608 1.61	1.738 1.74	1.953 1.95	1.751 1.75
Na	1.160 } 1.77	0.142 } 0.16	0.148 } 0.17	0.238 } 0.28	0.243 } 0.28	0.453 } 0.48	0.464 } 0.55	0.528 } 0.55	0.573 } 0.71	0.432 } 0.55	0.413 } 0.48	0.458 } 0.58
K	0.148	0.018	0.018	0.037	0.037	0.030	0.087	0.022	0.134	0.115	0.068	0.117
OH	2.332 2.33	1.771 1.77	1.762 1.76	2.307 2.31	2.311 2.31	1.939 1.94	2.241 2.24	2.152 2.15	2.011 2.01	2.172 2.17	1.901 1.90	2.488 2.49
Fe^2/Fe^2+Mg	.42	.29	.29	.40	.40	.39	.41	.45	.31	.36	.40	.48
Optical Properties[2]												
α	≈1.645[1]	1.625		1.640		1.654	1.657	1.661	1.641	1.654	1.649	1.659
β	≈1.664	1.642		1.658		1.666	1.670	1.675	1.654	1.665	1.661	1.668
γ	≈1.665	1.652		1.667		1.676	1.679	1.682	1.662	1.674	1.671	1.678
γ−α		0.027		0.027		0.022	0.022	0.021	0.021	0.020	0.022	0.019
$2V_\alpha$	≈0°−60°	72°		67°		80°	78°	64°	79°	81°	79°	83°
Z∧c		15°		15°		16°	18°	15°	19°	18°	17°	17°
D	3.069	3.090		3.164		3.196	3.231	3.271	3.156	3.153	3.197	3.216

121. Crossite, crossite-chlorite-epidote-quartz schist (road cut west of Sixmile Cr. S½ sec. 21, T. 39 N., R. 10 W., 3970 ft.).
C-165. Actinolite, actinolite-epidote-clinozoisite-chlorite greenstone (7.15 mi. S. 21½° W. of NE corner Cecilville quad., 4250 ft.).
C-165c. Corrected analysis.
C-57. Actinolite, actinolite-epidote-chlorite-albite greenstone (SE¼SE¼ sec. 12, T. 38 N., R. 11 W., 3450 ft.).
C-57c. Corrected analysis.
4381. Hornblende, hornblende-albite-epidote-chlorite schist (SW¼SE¼ sec. 28, T. 39 N., R. 9 W., 6860 ft.).
4277. Hornblende, hornblende-albite-epidote schist (NE¼NE¼ sec. 28, T. 39 N., R. 9 W., 6610 ft.).
4726. Hornblende, hornblende-epidote-quartz schist (S. of road, SE¼NE¼ sec. 29, T. 38 N., R., 9 W., 4490 ft.).
C-69. Hornblende, hornblende-epidote-muscovite-quartz-albite schist (7.35 mi. S. 42½° W. of NE corner Cecilville quad., 3190 ft.).
5315. Hornblende, hornblende-albite-calcite-quartz schist (S½NW¼ sec. 27, T. 39 N., R. 9 W., 5800 ft.).
568. Hornblende, hornblende-plagioclase-epidote-clinopyroxene schist (ridge in S½ sec. 15, T. 38 N., R. 9 W., 6670 ft.).
4657B. Hornblende, hornblende-plagioclase-epidote-almandine schist (S½NE¼ sec. 21, T. 38 N., R. 9 W., W. of Hickory Cr., 5080 ft.).

[1] See also Table 4. [2] Error, including actual and observed variation: Indices ±.002 Birefringence ±.002 Z∧c±1° 2V see appendix (±2° or more) Density ±.010

Analyses by Japan Analytical Chemistry Research Institute.

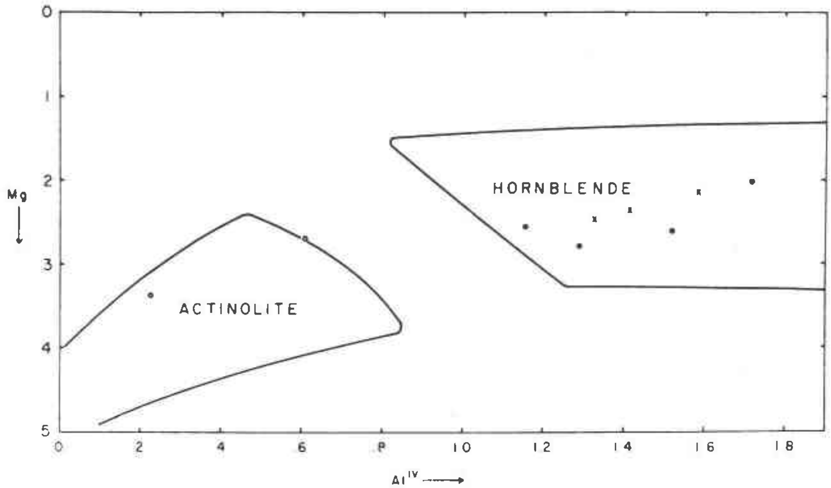

FIG. 6. Mg-Al^{IV} diagram for calciferous amphiboles of basic metamorphic rocks. The composition fields of actinolite and common hornblende are after Shido and Miyashiro (1959). Symbols as in Fig. 5. The positions of symbols are recalculated on the basis of $0=23$ to be consistent with the composition fields of Miyashiro's diagram.

Calcium content is normal; all samples contain between 1.61 and 1.95 Ca. The sum of atoms in the Y sites varies from 4.96 to 5.16. The content of the vacant site ($Na+K+Ca-2$) is less than 0.09 in the actinolites and 0.26 to 0.43 in the hornblendes. The unbalanced tetrahedral charge (Al^{IV} less octahedral trivalent ions), which should be balanced by $Na+K$ in the vacant site, is in each case within 0.25 of the content of the vacant site. This indicates only approximate agreement with the accepted solid solution substitutions Al(Al, Fe^{3+}) for Si(Mg, Fe^{2+}) and Al(Na, K) for Si.

Several samples contain slightly more than the requisite two OH^-, but only one (4657B with 2.39) is considered to be unusually high. This may be due to an error in analysis or the replacement of some oxygen in the lattice by OH^- (Nicholls and Zussman, 1955).

Due to the large number of variables, no attempt will be made to correlate optical and chemical variation in detail. However, the grouping of optical data for amphiboles of each formation (Fig. 5) should be explained. The Stuart Fork actinolites presumably owe their low 2V and refractive indices to low content of Al_2O_3 compared with that of the hornblendes. Reduction in alkalis might contribute to the lowering of 2V in magnesian actinolites (Winchell and Winchell, 1951, p. 434–435). In part the low FeO contributes to low refractive indices. The optical differences between Grouse Ridge and Salmon hornblendes cannot be explained by variation in Al_2O_3, FeO, MgO, or alkalis because hornblendes of each unit include approximately the same ranges of each of these. The single chemical characteristic which distinguishes Grouse Ridge from Salmon hornblendes is content of ferric iron; Grouse Ridge hornblendes contain between 0.24 and 0.45 Fe^{3+}, whereas Salmon hornblendes contain 0.47 to 0.63. Apparently the higher ferric iron increases refractive index and reduces 2V. The differences in other elements, which are not characteristic of a given formation, then superimpose their effects on the positions for the minerals on the diagram. The suggested control by ferric iron of the differences between properties of Grouse Ridge and Salmon hornblendes is in good agreement with the darker color of hornblende and epidote in the Salmon Hornblende Schist.

Most of the analyzed hornblendes coexist with sodic plagioclase and epidote with or without chlorite; but two specimens are unusual with respect to coexisting minerals (Table 3). Hornblende from specimen C-69 is in apparent equilibrium with coarse-grained muscovite. The presence of muscovite in the rock has little effect on the potassium content of the hornblende, although K is higher in this hornblende than in any other analyzed. Specimen 4657B is a garnet amphibolite whose hornblende contains more FeO and Al_2O_3 than any other specimen analyzed. This implies that both elements act together as controls on the formation of almandine-rich garnet in amphibolites. Possibly FeO is the more important, because magnesian compositions would favor a magnesian chlorite at this grade. Apparently Grouse Ridge hornblendes with the highest refractive index and 2V are those which occur with garnet (Fig. 5).

Shido and Miyashiro (1959) have differentiated basic metamorphic rocks of the central Abukuma plateau in terms of three zones of progressive metamorphism: A, characterized by actinolite; B, characterized by bluish green common hornblende; and C, characterized by green to brown common hornblende. The actinolites of zone A differ from the hornblendes of zone B in having more Mg and less Al, while the hornblendes of zone B commonly differ from those of zone C in having less alkalis and less titanium. The Salmon and Grouse Ridge hornblendes are optically and chemically similar to those of zone B, which crystallized at approximately the same grade. However, the Klamath Mountain hornblendes differ from other hornblendes in rocks of the same grade in that they contain slightly more alkalis. The Klamath specimens average 0.56 Na+K, Dalradian hornblendes average 0.51, and central Abukuma hornblendes average 0.46 (Shido and Miyashiro, 1959).

In summary calciferous amphiboles of the Stuart Fork Formation are established as actinolites, and those of the Salmon and Grouse Ridge formations are hornblende. Grouse Ridge and Salmon hornblendes differ in that the Grouse Ridge hornblendes contain less ferric iorn. Grouse

Ridge hornblendes richest in ferrous iron and aluminum commonly occur with garnet. The hornblendes are similar to those of comparable grade from other metamorphic terranes, except for slightly higher alkali content.

2. Blue Amphibole. In northeastern Cecilville quadrangle, blue amphibole occurs locally in the Stuart Fork greenstones at the contact with metacherts of the same formation. One blue schist (specimen 121) is composed largely of highly fibrous blue amphibole showing variable optical properties. Only approximate and incomplete optical properties were obtainable due to the fibrous and variable nature of the amphibole. Most abundant is fibrous material with anomalous brown to blue interference colors and other optical properties as given in Table 4. Less common is non-fibrous crossite with normal interference colors. There appears to be

TABLE 4. OPTICAL PROPERTIES OF BLUE AMPHIBOLE, SPECIMEN 121. INDICES ARE ±.005, $2V_\alpha$ IS ESTIMATED

	Increasing Fe→		
Texture	Fibrous	Fibrous	Non-Fibrous
Mineral	Fe-Glaucophane	Crossite	Crossite
Interference color	Brown	Blue	Normal
Dispersion	$r>v$, st.	$r<v$, st.	$r<v$, mod.
Orientation	$Z\approx c$	$Y\approx c$	$Y\approx c$
α	1.642	1.645	1.651
β	1.661	1.664	1.668
γ	1.662	1.665	1.671
$2V_\alpha$	0°–25°	0°–35°	40°–60°

complete variation between the types: intergrowths of anomalous brown and anomalous blue, and of anomalous blue and normal amphibole are common in the rock. The anomalous brown mineral, ferric glaucophane, has the pleochroic scheme: X = light yellow, Y = violet-blue, Z = greenish blue. The anomalous blue and normal mineral, both crossite, have X = light yellow, Y = greenish blue, Z = violet-blue. The extinction angle in all the blue amphibole is 3° ± 3°. A trace of green amphibole in the specimen ($\alpha = 1.640$, $Z\wedge c = 15°$, moderate birefringence) is either actinolite or abnormal glaucophane (Winchell and Winchell, 1951, p. 443). Iron-rich chlorite and epidote also coexist with the crossite-ferric glaucophane intergrowth.

The blue amphibole (specimen 121) was chemically analyzed (Table 3). Impurities of epidote and green amphibole comprised less than one per cent of the analyzed sample. The analysis represents the average composition of the blue amphibole consisting of both ferric glaucophane and crossite. Minor abnormalities in the composition may be related to the fibrous nature of the mineral. Both the X and Y positions are incompletely filled; there are insufficient trivalent ions and Na, whereas Ca is high. The analysis actually represents a solid solution of 83% crossite, 17% actinolite. The content of water is high and specific gravity is low. Most of the individual chemical abnormalities may be seen in other crossites and ferric glaucophanes, but the overall deficiency in the X and Y sites is unusual (Deer *et al.*, 1963).

Unlike the blue amphibole from collected samples in the area of this study, glaucophane or crossite where seen elsewhere in the Klamath Mountains coexists with lawsonite in some samples from each locality. Glaucophane schist has been found in southern Cecilville quadrangle by G. A. Davis (writt. comm., 1964), and in southwestern Helena quadrangle by D. P. Cox (1956, unpubl. Ph.D. Thesis, Stanford Univ.). In these two areas it is believed to represent local high-pressure conditions in the glaucophane schist facies, while in northeastern Cecilville quadrangle blue amphibole and epidote without lawsonite or jadeite imply lower pressure conditions equivalent to the glaucophane-schist facies, crossite subfacies of Misch (1959) or the epidote-glaucophane subfacies of Miyashiro and Seki (1958b). According to Turner and Verhoogen (1960, p. 543) such rocks represent conditions transitional to the greenschist facies.

Chlorite. Chlorite occurs in many basic rocks from all three units, and its optical properties vary as does its genesis. Progressive metamorphic chlorite is present in most Stuart Fork greenstones. In Salmon and Grouse Ridge basic rocks the mineral is prograde, retrograde (replacing hornblende or garnet), or absent.

The chlorites of the actinolite- and hornblende-bearing rocks fall into three groups according to optical properties: (1) light green chlorite with anomalous brown interference colors, small positive 2V, and $\beta = 1.612$ to 1.625; (2) green chlorite, with anomalous brown interference colors and small positive 2V or anomalous blue colors and small negative 2V, and $\beta = 1.627$ to 1.628; (3) green chlorite with anomalous blue interference colors, small negative 2V, and $\beta = 1.630$ to 1.636. The transition from optically positive to optically negative (at 1.627 to 1.628), which occurs as iron content of the chlorite increases, was also observed by Wiseman (1934, p. 361) in Dalradian basic metamorphic rocks. He found the transition occurred at $\beta = 1.631$. According to the classification scheme of Hey (1954) the present chlorites are aluminous iron pycnochlorite and aluminous magnesian brunsvigite; their major compositional variation is in iron content rather than Si/Al ratio. For the purpose of this discussion chlorites with $\beta > 1.628$ will be termed Fe-chlorites, while those with

$\beta < 1.628$ will be termed Mg-chlorites. No chlorite with $\beta > 1.636$ coexists with actinolite or hornblende in Klamath Mountain rocks as Wiseman observed in Dalradian rocks. A dark green magnesian daphnite ($\beta = 1.655$) coexists with crossite, but probably not with actinolite in Stuart Fork specimen 121.

Figure 7 shows plots of chlorite β against amphibole β for the three metamorphic units. The Stuart Fork chlorites are both Mg- and Fe-chlorites. Their indices show a reasonable straight line relationship with the amphibole indices, suggesting that FeO/FeO+MgO varies together

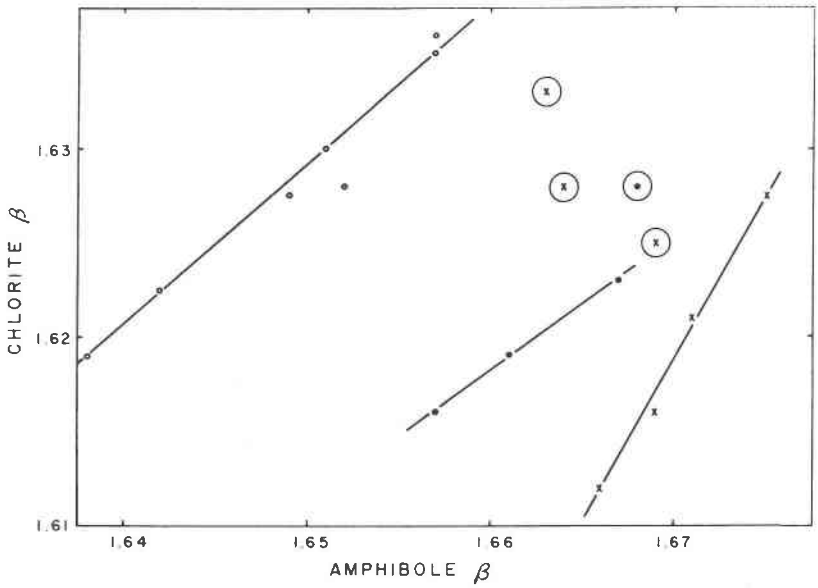

FIG. 7. Diagram showing refractive indices of coexisting chlorite and amphibole in the basic regional-metamorphic rocks described. Symbols as in Fig. 5. A large circle surrounding the symbol indicates that the chlorite is retrogressive.

in the chlorite and actinolite. The position of the line is about the same as that of Wiseman's (1934) curve. Progressive metamorphic chlorites of the Salmon and Grouse Ridge basic schists when present are consistently Mg-chlorites as would be expected under garnet- and staurolite-zone metamorphism (Turner and Verhoogen, 1960). The lack of coincidence of the Grouse Ridge and Salmon curves is principally a function of the amphibole refractive indices, which in these units are dependent on several factors besides FeO/FeO+MgO. The linear relations seen for the chlorite *vs.* amphibole indices are based on scanty data and may be in part fortuitous.

Retrogressive metamorphism of the medium-grade rocks produced largely Fe-chlorites whose indices do not fall in line with the prograde chlorite indices. During retrogression of some of the Salmon rocks it is possible that the amphibole indices changed also, tending to produce mineral compositions more like those of Stuart Fork greenstones. The conditions of retrogressive metamorphism of the Salmon and Grouse Ridge rocks may well have been those extant during the Stuart Fork progressive metamorphism.

In summary, Stuart Fork chlorites show a wide range of iron content, progressive metamorphic chlorites of the higher-grade rocks are restricted to the more magnesian compositions, and retrogressive chlorites of the higher-grade rocks are Fe-rich, like many of the Stuart Fork chlorites. Prograde chlorites of any given formation show systematic compositional relationships with coexisting amphiboles.

Comparison of Lithologies

The following points serve to compare the lithologies of the three basic units:

(1) Plagioclase coexisting with epidote varies from albite in Stuart Fork rocks to albite and oligoclase in Salmon rocks, and becomes a little more calcic on the average in Grouse Ridge rocks. (2) Epidote shows a low-temperature composition gap in Stuart Fork rocks, but shows no gap in the higher grade rocks. The most aluminous epidotes occur in Grouse Ridge rocks. (3) Amphibole is actinolite (some blue amphibole) in Stuart Fork greenstones, hornblende in Salmon rocks, and hornblende with low ferric iron in Grouse Ridge rocks. (4) Progressive metamorphic chlorites may be iron rich in the Stuart Fork Formation, but must be magnesian in the other units. (5) Rock composition is most homogeneous in the Salmon Hornblende Schist, least homogeneous, with metasedimentary interbeds, in the Grouse Ridge Formation. (6) Some primary volcanic textures are preserved in the fine-grained Stuart Fork greenstones, but such textures are obliterated by more complete metamorphism and deformation in the overlying units. Grouse Ridge basic rocks are more coarse-grained and show less preferred orientation than Salmon schists.

Differences between the three units may be explained in terms of the composition and history of the rocks. Contrast in metamorphic grade explains the textural and mineralogical differences between the Stuart Fork and Salmon basic rocks, both of which were probably derived from volcanics. A small change in grade might also explain the apparent difference between Salmon and Grouse Ridge plagioclase. However, most of the contrast between Salmon and Grouse Ridge basic rocks is best explained by differences in initial bulk composition and pre-metamorphic origin. The composition and homogeneity of the Salmon rocks attest to their origin as basic igneous rocks, probably volcanic. The Grouse Ridge rocks, with less ferric iron, probably came from a more reducing premetamorphic environment (alternatively iron was reduced to a greater extent during metamorphism at a slightly higher grade). Presence of calcite in some rocks and almandine in others suggests respectively calcareous and possibly pelitic contamination of original basic igneous material. Occurrence of metasedimentary interbeds indicates that the depositional environment was at least partly sedimentary. The most plausible origin of Grouse Ridge basic rocks is as water-laid or reworked tuff or volcanic detritus contaminated by varying amounts of carbonate or shale. A sedimentary origin might also explain the coarser metamorphic texture of the Grouse Ridge basic rocks, because transmission of fluids and recrytallization probably proceed differently in a sediment than in a volcanic rock. Alternatively, a higher metamorphic grade in the Grouse Ridge rocks may favor a coarser, less foliated texture.

In conclusion, basic rocks of the three Klamath Mountain metamorphic units are, in fact, distinct from each other in the area studied, thus justifying their status as parts of three different formations. Differences between the units were produced by differences in metamorphic grade, bulk composition, and pre-metamorphic history.

Age of Metamorphism

Petrologic evidence has established the existence of a medium-grade metamorphic event and a low-grade metamorphic event in the Klamath Mountains. Recent work may indicate that these metamorphic events are significantly separated in time.

Lanphere and Irwin (1965; personal communication from Lanphere) have dated hornblende from Salmon (or Grouse Ridge) hornblende schist exposed at the western edge of the metamorphic belt in Weaverville and Helena quadrangles. Potassium-argon ages of hornblende unaffected by Late Jurassic events are 270, 272, and 286 m.y. suggesting that medium-grade metamorphism was probably Pennsylvanian in age.[1] Ages as young as 135 m.y. on "Abrams" metasediments considered to be equivalent to Grouse Ridge (see also Davis and Lipman, 1962) may have resulted from Late Jurassic retrogressive metamorphism or contact metamorphism associated with Jurassic plutonics.

West and north of the area of this report rocks as young as Late Jurassic age have been metamorphosed to low grade (Irwin, 1960). Davis (1964) has correlated the rocks of the Stuart Fork Formation with slightly less metamorphosed rocks of the western belt of the Klamath Mountains which yield fossils of Pennsylvanian to Triassic (?) age. The oldest dated pluton of the Klamath Mountains, the Russian Peak, batho-

[1] Additional confirmation of the existence of Paleozoic metamorphism in the Sierra Nevada-Klamath Mountain system is given by a 307 ± 30 m.y. age on tremolite in serpentinite in the Sierra Nevada foothills near Visalia, California (Putman and Alfors, 1965).

lith, is unaffected by metamorphism and has a potassium-argon age of 140 m.y. on biotite (Davis *et al.*, ms.). Thus the age of low-grade metamorphism of the Stuart Fork Formation and probably of retrogressive metamorphism of the Salmon and Grouse Ridge formations may be Jurassic.

Nature of Klamath Mountain Regional Metamorphism

In this discussion, evidence from all regional metamorphic rocks will be used, including some from outside the report area.

The available petrologic data are consistent with the preferred structural interpretation for the area. During late Paleozoic time, the Salmon and Grouse Ridge formations were deformed by shearing and metamorphosed to the garnet and staurolite zones. Later, during Jurassic (?) time the Stuart Fork rocks, which were at that time widely separated from the middle-grade rocks, underwent chlorite-zone and local glaucophane-schist metamorphism. Toward the close of metamorphism the Salmon-Grouse Ridge sequence was thrust over the Stuart Fork Formation and retrogressively metamorphosed during the closing stages of regional metamorphism. To this must be added the possibility of another thrust separating the Grouse Ridge Formation from the underlying units. (G. A. Davis, writt. comm., 1963). The root zone of the thrust or thrusts is not definitely known. Stuart Fork rocks continue westward with reduction in the degree of metamorphic recrystallization, whereas the eastern boundary of the central metamorphic belt is more abrupt and is probably a high-angle fault or thrust fault which brings slightly metamorphosed Ordovician and Silurian rocks into view on the east. It appears likely, then, that the root zone is under the lower Paleozoic rocks to the east and that the sense of the thrust or thrusts is east over west.

There is incomplete evidence to the effect that metamorphic grade increased from west to east in both the Paleozoic and Jurassic (?) metamorphic events and that isograds had trends between N. 15° E. and north. Consider first the autochthonous (?) rocks, the Stuart Fork and western Paleozoic and Triassic rocks, which were affected by the low-grade event. West of the central metamorphic belt these rocks are incipiently metamorphosed probably to the chlorite zone (D. P. Cox, 1956, unpubl. Ph.D. Thesis, Stanford Univ.). Proceeding eastward, one encounters an increase in degree of recrystallization and finally local development of glaucophane schists, all of which are located near a 34-mile line trending N 15° E. between the northeast corner of Cecilville quadrangle and the southern edge of Helena quadrangle to the south. East of this line, most Stuart Fork rocks are completely recrystallized in the chlorite zone, but pre-metamorphic textures are locally preserved. The metamorphic grade of Stuart Fork rocks in the area of this study never rises above the chlorite zone, and all Stuart Fork rocks not affected by contact metamorphism are not more than four miles east of the zone of local glaucophanitic metamorphism. However, south of the eastern part of the area, in the Minersville quadrangle Stuart Fork rocks were metamorphosed to the biotite zone (Lipman *in* Davis *et al.* ms.). These rocks might have suffered from a local increase in regional metamorphism associated with a cluster of plutons, but Lipman feels that, since the biotite-bearing siliceous rocks are several miles from plutons, they have a purely regional metamorphic origin. These Stuart Fork rocks are nine miles from the line of local glaucophanitic metamorphism and could well be in a regional biotite zone. Thus, there is evidence, albeit somewhat meager, that Stuart Fork rocks show progressive increase in grade through the following steps as one proceeds S. 75° E.: incipient metamorphism→(glaucophane schist)→chlorite zone→biotite zone.

The evidence for increasing grade toward the east is even less certain in the allochthonous (?) units metamorphosed during the Paleozoic era. All the regionally metamorphosed Salmon rocks in the area (and probably most such rocks in the central metamorphic belt) are albite-bearing save a few at the eastern edge which contain oligoclase. Hence their grade is primarily in the garnet zone, increasing locally to the staurolite zone at the eastern edge. Western exposures of the Grouse Ridge Formation in the area of this report (Fig. 1) are rocks of the garnet zone, whereas many of the eastern Grouse Ridge rocks, east of the Salmon outcrop area, have been metamorphosed to the staurolite zone. The suggestion of eastward increase in grade is weakened by the recent recognition of staurolite-zone western Grouse Ridge rocks south of Cecilville (G. A. Davis, writt. comm., 1964). These conclusions are tentative and it remains to be seen whether future work will substantiate, modify or refute them.

Each metamorphic episode in the Klamath Mountains may be assigned to a facies series (Miyashiro, 1961). The facies series classification is based principally on differences in rock pressure for various metamorphic terranes. By comparison with several standard facies series, one can relate the metamorphism for a given time and area to one of the five facies series: (from high to low pressure) jadeite-glaucophane type, high pressure intermediate type, kyanite-sillimanite type (normal Barrovian), low-pressure intermediate type (Buchan), and andalusite-sillimanite type (central Abukuma).

Evidence bearing on a facies series for the Salmon-Grouse Ridge sequence is as follows:

(1) Hornblendes have a slightly higher average alkali content than those of Dalradian epi-

diorites or central Abukuma basic schists. Shido and Miyashiro (1959) interpret an increase of alkalis in amphiboles which crystallized at a given grade as related to increased load pressure, because alkalis would otherwise cause the formation of more feldspar with lower density than the amphibole. Other factors which increase alkali content in amphiboles (*e.g.* increased metamorphic grade or greater alkalis in the rock) can probably be ruled out for the Kalamath Mountain rocks when comparing them with the Dalradian or central Abukuma rocks. (2) No kyanite or staurolite appear in the pelitic rocks, but neither do sillimanite, andalusite, or cordierite. The rocks were simply not aluminous enough for these minerals to form. (Cordierite and andalusite do occur in Stuart Fork contact metamorphic rocks whose genesis followed the lower greenschist retrogressive metamorphism). (3) Almandine-rich garnets occur in both basic and pelitic Grouse Ridge rocks. Their absence in Salmon rocks is dependent on composition, not grade. The characteristics of the Salmon-Grouse Ridge terrane are similar to those of the kyanite-sillimanite facies series with pressures perhaps on the high side as indicated by the alkali content of the hornblendes.

Evidence bearing on the facies series of the Stuart Fork rocks affected by Jurassic (?) metamorphism is as follows.

(1) Crossite, glucophane, and lawsonite are locally developed. (2) Most of the rocks are restricted to the chlorite zone and possibly the biotite zone.

The scarcity of glaucophanitic rocks and the abundance of greenschists indicate that the facies series here was high-pressure intermediate rather than glaucophane-jadeite series. There is a good possibility that the glaucophane schists resulted from localized tectonic over-pressure or increase in fluid pressure, and that their occurrence along a N. 15° E. line is because this zone underwent metamorphism at conditions closest to those of the glaucophane-schist facies.

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Appendix. Mineral Data for Selected Klamath Mountain Basic Metamorphic Rocks

Number	Amphibole $2V_\alpha$[4]	Amphibole β	Epidote $2V_\alpha$ or β	Plagioclase % An	Chlorite β Sign	Others, in order of decreasing abundance[1]
Stuart Fork Greenstones[2]						
2317A	71°	1.650	x	ab.	x	le. bi. q.
C-38	69°	1.657	71°	ab.	1.635−	q. he.
C-165	72°	1.642	71° 1.721	ab.	1.623+	le. q.
2137	71°	1.648	1.727	2	x	le.
C-57	67°	1.658	74°	ab.	1.636−	le. q. he.
C-40	67°	1.652	68°	0	1.628±	q. op.
221B	70°	1.656	X	ab.		gb. le. q. op.
2215	X	1.638	1.711	ab.	1.619+	an. le.
C-98	70°	1.657	72°	ab.	x	q.
122	71°	1.649	1.720	ab.	X	gb. ca. cr.
221A	X	1.651	68°	0	1.630−	cr. le. gb. q. op.
Salmon Hornblende Schists						
5322	77°	1.664	81°	ab.		q. sp. op. ru. *ac.*
4342	72°	1.674	75°	0		q. op. sp. he.
5415	65°	1.671	79°	23–34		q. op. sp. he.
4277	78°	1.670	81°	3–8	1.621+	q. sp. *ac.* op. he. ga.
4726	64°	1.675	80°	0–2	1.627±	q. op. he. *ac.* sp.
4381	80°	1.666	78°	0–5	1.612+	op. *ac.* sp. ru. he.
C-231	75°	1.664	79°	ab.	x	q. sp. op.
C-58	71°	1.663	72°	9	1.633−	*ac.* sp.
4242	81°	1.669	75°	0	1.616+	q. op. *ac.* sp. ru.
C-99	70°	1.669	71°	1, 9	1.625+	q. op. *ac.* sp. he.
C-28	65°	1.662	70°	2, 9		*ca.* q. *ac.* op. sp.
C-284B	60°	1.670	X	ab.	x	*ca.* q. op.
422	78°	1.673	71°	0		q. *ac.* sp.
C-86	67°	1.664	71°	ab.	1.628±	q. *ac.* *ca.*
Grouse Ridge Hornblende Schists						
4572[3]	77°	1.658	x	11		q. op.
568	79°	1.661	84°	24–36		di.
5716	82°	1.653	90°	0–5		*ac.* sp. q. op. he.
5310	80°	1.660		0–2, 9–11	x	*ac.* op. bi. sp.
5640B	73°	1.661	x	6, 30–39	1.619+	ca. op. di. sp.
C-69	79°	1.654	88°	ab.	x	mu. g. op.
4244	82°	1.657	x	3–7	1.616+	q. ru. bi. *ac.* he.
5315	81°	1.665	79°	0–7		ca. q. bi. *ac.* op. ru.
C-218[3]	83°	1.668	X	ab.		q. sp.
548C	84°	1.663	83°		x	op. sp. to. *ac.*
542	84°	1.647		0, 9		di. sp. *ac.*
4651	80°	1.664	81°	12, 25–33		di. bi. op. ca. *ac.* sp. ru.
557	85°	1.668		8, 22–24	x	ga. di. sp. g. op.
577	77°	1.667	84°	0–4	1.623+	q. ca. bi. op. sp. he.
4657B	83°	1.668	83°	22–35	1.628−	ga. bi. q. to. op. ru.

Notes

[1] Abbreviations: le.—leucoxene, bi.—biotite, gb.—green biotite, q.—quartz, he.—hematite, op.—opaque mineral, au.—igneous augite, ca.—calcite, cr.—crossite, sp.—sphene, ru.—rutile, ac.—actinolite, ga.—garnet, di—diopside, mu.—muscovite, to.—tourmaline. Italicized abbreviation—retrogressive mineral.

[2] Specimens listed in order of decreasing amphibole content.

[3] Grouse Ridge lithology exposed as thin layers in Salmon Hornblende Schist.

[4] Error in $\beta \pm .003$. Range in 2V measurements, attributable to measuring error and actual variation: Amphibole ± 2° most measurements; ± 3°–4° 5415, 4726, C-231, 4572, C-69, 542, 4651; ± 5°–6° 4277, 4381, 5716, 5310, 5640B, 4657B; ± 8°–9° C-99, 422. Epidote ± 2°–3° most measurements; ± 4° C-57, C-98, 4381, 5716, 5314; ± 6°–8° 5322, 5415, 4726, C-231, C-28, 4651, 577.

X Mineral present, 10%–50%.

x Mineral present, <3%.