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AN EXAMINATION OF METAMORPHISM AND SCAPOLITE IN THE SKALKAHO
REGION, SOUTHERN SAPPHIRE RANGE, MONTANA

by

Timothy E. La Tour

B.S., Louisiana State University, 1967


Presented in partial fulfillment of the
requirements for the degree of

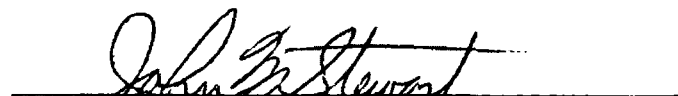
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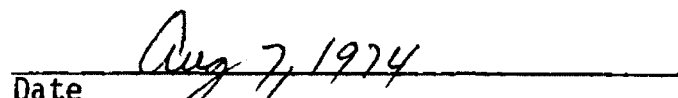
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CHAPTER I

INTRODUCTION

Purpose and Scope

The purpose of this paper is to report the results of an examination of metamorphism in the Skalkaho region, Sapphire Range, Montana, and the relationship between the metamorphism and scapolite compositions in the area. In order to establish relevance of this relationship to the overall geology of the area, in addition to the main study, several smaller related projects were undertaken. All aspects of the study are listed below:

- (a) A cursory examination of the igneous rocks in the area,
- (b) Reconnaissance geologic mapping of the area
to provide a basis for areal interpretation of the data,
- (c) A cursory examination of the gross structure to
provide a basis for structural interpretation of the data,
- (d) A detailed examination of the metamorphic rocks in the
area including determination of isograds,
- (e) A detailed examination of the scapolite, including
contouring points of equal composition.

Previous Work

Little detailed work concerning any aspects of geology has been accomplished in the Sapphire Mountains, that which has been done being

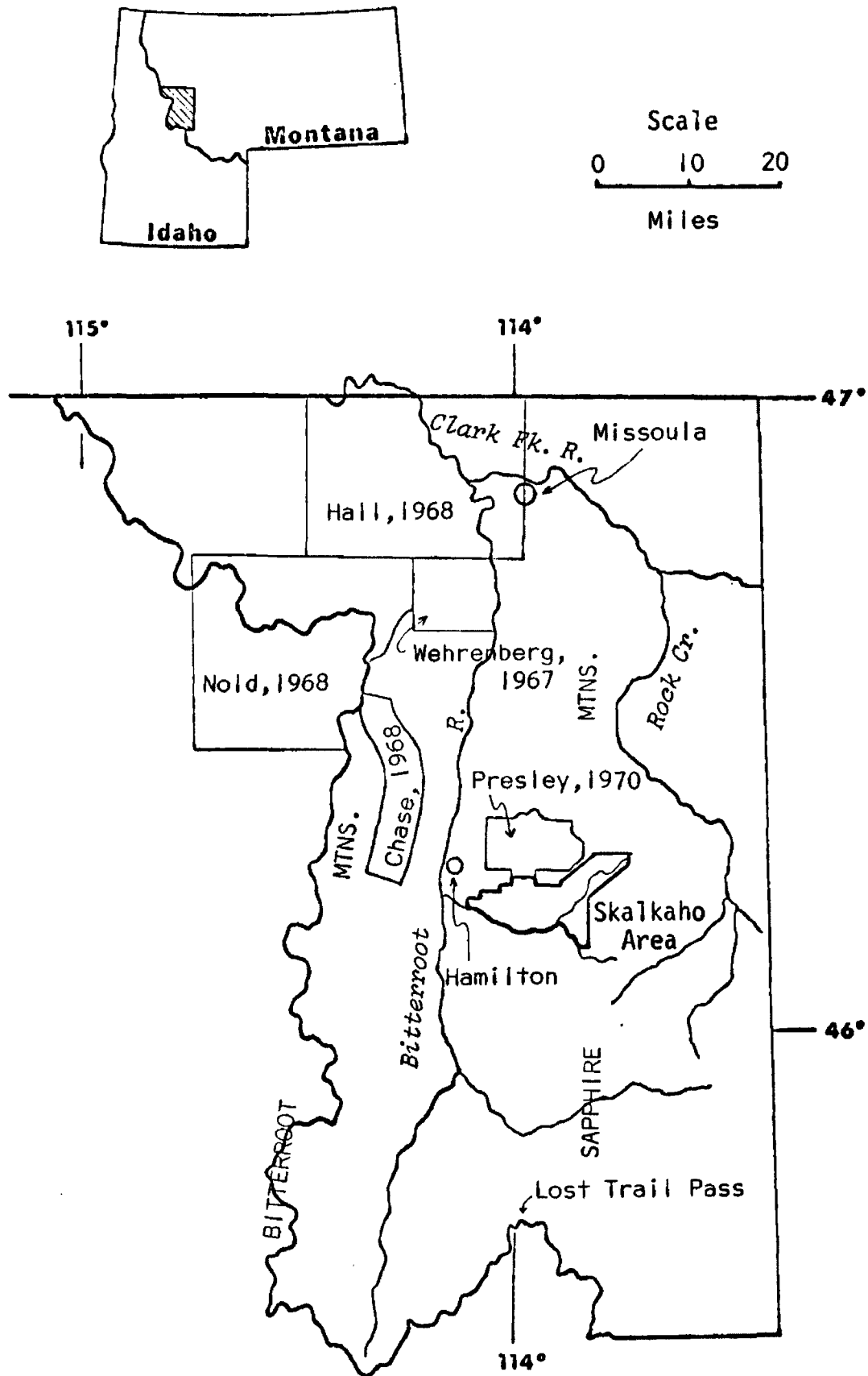


Fig. 1.1. Index and previous-work map of Bitterroot Valley and Sapphire Range, western Montana. Study areas are indicated by author and date, and the Skalkaho area is boldly outlined (modified from Presley, 1970).

generally concentrated in the northern one-half of the range. Considerably more study has been devoted to the Bitterroot Range to the west, primarily work related in some way to the Idaho batholith (see Fig. 1.1). Presley's (1970) work in the Willow Creek drainage basin and the present work in the Skalkaho area represent the first attempts at detailed study of metamorphism in the Sapphire Range.

CHAPTER II
GENERAL GEOLOGY

Location and Topography

The Skalkaho region is located in the southern Sapphire Range east-southeast of Hamilton, Montana. The area studied lies west of the drainage divide and comprises approximately sixty square miles¹ (Fig. 2.1). The Bitterroot Range which consists predominantly of the Idaho batholith is across the Bitterroot valley immediately west of the Sapphire Range.

Fairly rugged, forest-covered topography near the divide grades into rolling, grass-covered hills near the valley. Soil cover is great throughout the area, and outcrops are locally confined to road cuts.

Stratigraphy

The generalized stratigraphic sequence of the Belt Supergroup rocks in the area is below:

youngest	Missoula Group
	Wallace Formation
	Ravalli Group
oldest	Prichard Formation

Exposed in the Skalkaho area are rocks of the Ravalli Group, Wallace Formation, and probably the Missoula Group. The Wallace comprises the

¹The portion of the study dealing with scapolite (Chapter IV) also includes the Willow Creek area to the north of the Skalkaho region.

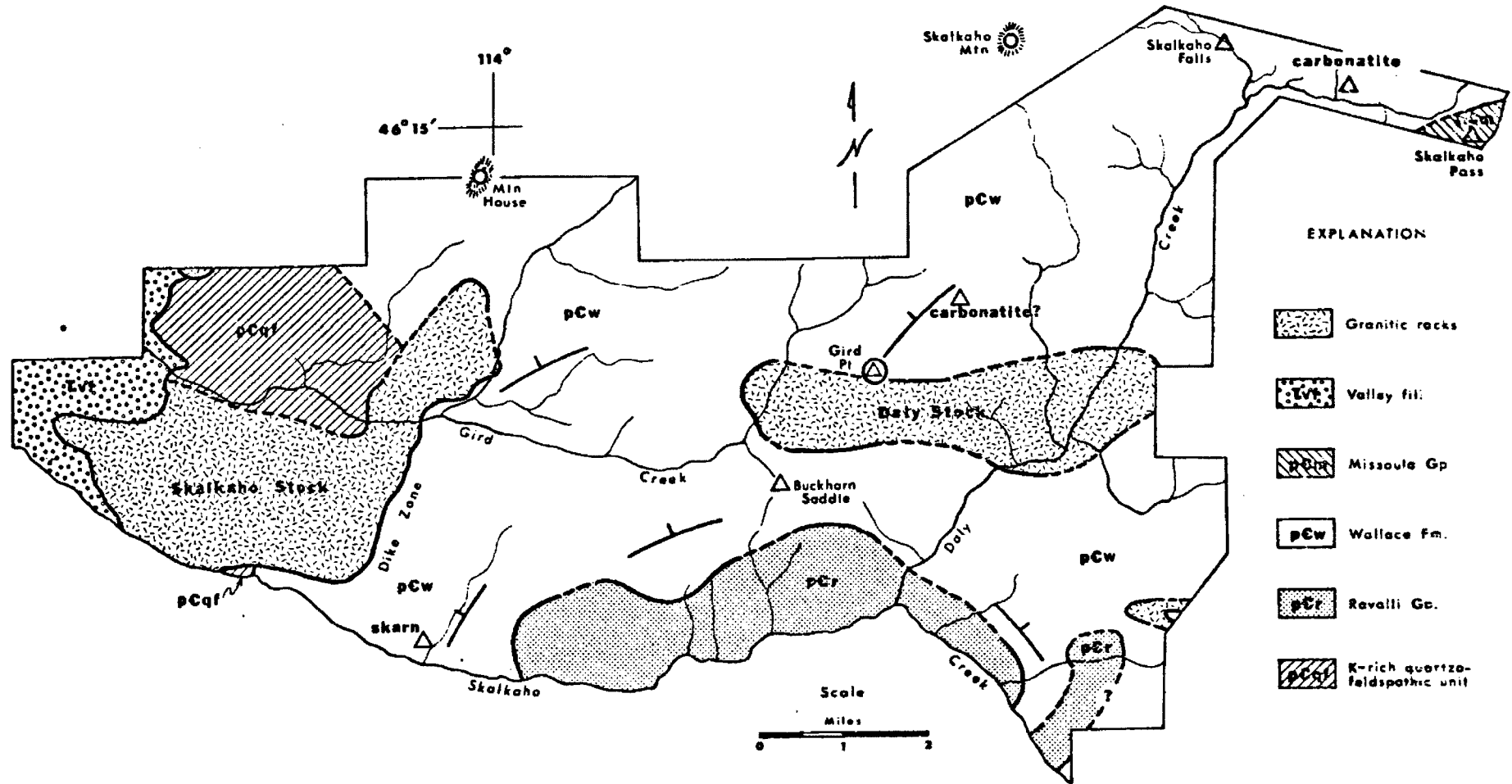


Fig. 2.1. Reconnaissance geologic map of the Skalkaho area, southern Sapphire Mountains, Montana. General stratigraphic strikes and dips are shown, and major topographic features are labeled.

largest part of the rocks, accounting for well over three-fourths of the area. Rocks of the Ravalli Group crop out along the southern boundary of the study area, and appear to be conformably overlain by rocks of the Wallace Formation. Cropping out in a very small area near the divide is a unit identified as part of the Missoula Group.

In the southeastern corner of the study area, a small, highly cross-bedded quartzofeldspathic unit crops out separated from the Ravalli Group by a thin sliver of Wallace. It is considered to be Ravalli also, although it appears to have been deposited under a different sedimentary environment from that of the bulk of the Ravalli rocks. Because of the abrupt change in sedimentary character, the crossbedded unit may have been faulted into place.

Some evidence of overturned beds was observed by this author and by J. L. Talbot (verbal comm., Feb., 1974); consequently, a measured section thickness without tectonic corrections would be useless and is not reported here.

Structure

Bedding attitudes were recorded wherever possible, but detailed structure such as cleavage was not investigated.

Plotted on an equal area net, most bedding attitudes appear randomly scattered, except for those in the south and southwest part of the area. The poles to bedding in that area are concentrated in the southeastern quadrant of the net. Whether or not density of poles describes a great circle or a small circle, the axis to the fold trends approximately 305° and plunges 45° N.W.

In the southeastern corner of the area, in addition to the possible faulting discussed above, local faulting and shearing of the rocks is common. Though faults were not seen in outcrop, local bedding attitudes change dramatically within a few meters of each other, and small sheared zones are common. These structures were not studied in any detail and cannot be elaborated on.

Cleavage in some areas was seen easily in the outcrop and varied from being parallel to the compositional bedding to cutting the bedding at moderate angles. J. L. Talbot (verbal comm., Feb., 1974) has mapped the cleavage and bedding attitudes in a small portion of the study area and has evidence of at least one large overturned fold. Minute isoclinal overturned folds observed in outcrop seem to substantiate Talbot's findings.

In thin section some samples exhibit structures such as preferred alignment of crystallographic or optic axes, or crenulation cleavage. Mineral orientations are discussed below where appropriate.

Gouge zones were observed in the northeastern corner of the area, along the road between Skalkaho Falls and the divide. On a topographic map these zones appear crudely aligned in an east-west direction. If the line represents a large fault, it may be coincident with a long lineament mapped through the area from ERTS photographs (D. Alt, verbal comm., July, 1973). The correlation was not investigated. Rocks on either side of the gouge line are not significantly different.

Igneous rocks

Intrusive rocks. Three different kinds of intrusive rocks were observed in the study area. They are two granitic plutons, at least one

but perhaps two small carbonatites, and several diabase intrusives. None were studied in detail, but three samples from the granitic plutons (Skalkaho and Daly stocks) were examined in thin section.

One sample from the Skalkaho stock (L-1-1) was examined and found to be a muscovite-bearing granodiorite¹. The sample is characterized by coarse, interlocking grains of plagioclase, microcline and quartz. The plagioclase is fairly well twinned, but not zoned. The microcline is poorly twinned. Muscovite occurs as coarse, blocky plates randomly scattered. Minor biotite is pleochroic with Z = golden brown, and X = yellowish gold.

Two samples from the Daly stock were examined, one from the margin of the stock and one from the interior. Both samples are hornblende-biotite quartz diorites, but differ in grain size and percentage of mafics. The sample taken near the margin (L-6-3) contains twice the percentage (30%) of mafic minerals as that taken in the interior (L-6-6) (14%). Sample L-6-3 also contains finer-grained plagioclase which are preferentially aligned. All plagioclase in both samples is strongly zoned.

Whereas the Skalkaho stock resembles in outcrop, mineralogy, and texture the Willow Creek stock (cf. Presley, 1970), the Daly stock does not. Additional work should be done with the Daly stock to determine its relationship to other granitic plutons in the region.

¹ Igneous rock names are based on the I.U.G.S. classification (Streckeisen, 1967).

Extrusive rocks. Many small felsic extrusives were seen in the vicinity of the numerous dikes associated with the Skalkaho stock. One "typical" felsite (L-1-9b) was examined. It is light to medium gray in outcrop, porphyritic, and somewhat vesicular. In thin section it was identified as a porphyritic quartz trachyte (groundmass K-feldspar was identified through use of sodium cobaltinitrite stain). Phenocrysts are plagioclase and sanidine, each five percent of the sample. Minor amounts of quartz and plagioclase were seen in the predominantly K-feldspar groundmass.

Other felsic extrusives are yellow to brown in outcrop, generally more vesicular than those which are gray. The yellow-brown color seems related to iron oxides.

CHAPTER III

REGIONAL METAMORPHISM

Regional metamorphism is related to tectonic activity in mountain belts, either presently active or once active in the past. Miyashiro (1973) has suggested the term "orogenic" as being more descriptive than the term "regional." In any case regional metamorphism is distinguished from "contact" metamorphism or "burial" metamorphism by the following considerations:

Contact metamorphism is a direct result of the country rocks being locally heated by an igneous intrusive. Burial metamorphism is caused by deep burial of the sedimentary pile, with little or no deformation. Heat for burial metamorphism is that of the geothermal gradient; pressure is that exerted by the overburden. In general, burial metamorphism is restricted to lower grades. Contact metamorphism is generally accepted to represent low-pressure conditions, though this is not always the case (Presley, 1970).

Since a rise in temperature is generally thought to be more significant than a rise in pressure in producing most regional metamorphic terranes, the present average geothermal gradient associated with areas which have undergone medium-pressure regional metamorphism of approximately twenty degrees Centigrade per kilometer (Miyashiro, 1973, p. 86) alone is probably inadequate to facilitate recrystallization to the observed

higher grades of metamorphism. Thus, an additional heat source is believed to exist which, along with elevated pressures, produces high-grade metamorphic assemblages. If heating is intense enough to reach the stability range of the granulite facies, partial melting can occur, producing a magma which rises through the more dense surrounding rocks and is emplaced below the crustal surface to cool and crystallize.

Regional metamorphism is very often spatially associated with igneous intrusives. The significance of this relationship is not completely understood; however, clearly one reason is that emplacement of an intrusive exposes previously deeply buried metamorphic rocks. Since the rocks buried deepest have been metamorphosed greatest, upon being exposed, they should be nearest the intrusive. Additionally, the lines connecting points of equal grade, (isograds) should be crudely concentric with the exposed margins of the intrusive. Complete discussion of regional metamorphism is in Hyndman (1972) from which most of the above was taken.

The regional metamorphism in western Montana (including that exposed in the Skalkaho area) appears to fit the classic picture described above. Under the direction of Professor Donald W. Hyndman, a research project involving several graduate students at the University of Montana has been initiated to study the distribution of reported and unreported metamorphism in the vicinity of the Idaho batholith. Information gathered to date has produced a map of isograds which are roughly concentric with the northern and northeastern margins of the batholith.

Ravalli Group

Exposed along the southern margin of the study area is a micaceous quartzofeldspathic unit which was mapped as Ravalli (Fig. 2.1). Although this unit appears to lie stratigraphically below the Wallace Formation as would be expected, (see Chap. II), final confirmation as Ravalli was based on the preponderance of plagioclase feldspar over potassium feldspar (Donald Winston, verbal comm., Apr., 1974). Rocks in this unit have been metamorphosed to sillimanite grade.

These rocks are generally massive, fine grained, quartzofeldspathic metasediments. Their color is variable, ranging from very light gray to dark gray. Bedding planes are commonly defined by very thin (one to six centimeters) intercalated layers of deeply weathered, fissile mica schist. Throughout quartzofeldspathic parts of the unit variable amounts of fine-grained biotite are present, accounting for the color variation. These biotite grains are commonly concentrated into slightly darker bands, but there is no tendency to break along the bands, and the overall texture is still massive. The banded appearance may represent either mild metamorphic differentiation or original compositional layering, probably some of both. Other bedding or sedimentary features are almost entirely absent, a notable exception being a heavily cross-bedded portion of the unit at its eastern extremity.¹ It is possible that this crossbedded unit has been faulted into place; this possibility is discussed in Chapter II.

¹J. L. Talbot (verbal comm., Apr., 1974) has observed a few crossbeds in other parts of the unit, but none were seen by this author.

In numerous places throughout this unit are relatively thick zones of biotite-rich schist several meters thick. Intercalated with the pelitic beds are thinner (up to twenty centimeters) beds of predominantly quartzofeldspathic rock. Although volumetrically miniscule when compared to the unit as a whole, the pelitic beds are useful in determining metamorphic grade.

Six thin sections from the Ravalli were examined in detail. The typical mineral assemblages are as follows:¹

- (a) plagioclase (approx. An₃₀) + K-feldspar + biotite + quartz + muscovite ± chlorite ± sillimanite
- (b) K-feldspar + biotite + muscovite + chlorite

ACFK equilibrium tetrahedra are shown in Figure 3.1, and tabular listing of mineralogy is in Table 3.1. Rocks of this unit are characterized by the preponderance of plagioclase over potassium feldspar, occurrence of biotite, and absence of calcium-rich phases. The percentage of mica in the rocks varies from ten to thirty percent, a reflection of the variation in the pelitic nature of the unit.

The grain size is generally medium to fine, but a small amount of coarse quartz is locally present. Feldspar and quartz form an interlocking matrix with the mica commonly aligned in a moderately- to well-defined schistosity (Fig. 3.2). In one sample a crenulation cleavage has developed, and the mica has recrystallized to polygonal arcs.

Plagioclase feldspar is present in all but one sample from this unit. In this specimen a small amount of K-feldspar is present, but

¹One sample contains cordierite and is discussed on page 58.

eighty percent of the specimen is quartz (see Fig. 3.1b). Such high percentages of quartz are uncommon in this part of the Ravalli Group.

Potassium-Rich Quartzofeldspathic Unit

In addition to the Ravalli Group, two other units of quartzofeldspathic rock were observed. Most of these rocks crop out at the west end of the study area and are in contact with the Skalkaho stock to the south. A smaller but lithologically similar suite occurs south of the Skalkaho stock along Skalkaho Creek; it is possibly a continuation of those rocks which lie to the north (see Fig. 2.1).

These rocks are everywhere separated from the Ravalli rocks by thick sections of calc-silicates of the Wallace Formation. However, there is reason to suspect that south of the study area, perhaps between Skalkaho Creek and Sleeping Child Creek, this unit and the Ravalli merge as one. Such an interpretation is consistent with the interpretation of scapolite data, discussed in a later section of this paper.

Rocks of this unit exposed along Skalkaho Creek are light to medium gray in color. They are generally banded gneisses with coarse grains of quartz and plagioclase comprising the light colored bands, and medium to fine quartz, plagioclase, orthoclase, and biotite making up the dark.

Stringers of granitic material, commonly as small as one half centimeter thick, have been injected into most of the rocks. Because of the recrystallization to a more massive texture the rocks tend to weather somewhat like the granite with which they are intimately related. Stopping of these rocks by the granite is very pronounced. Blocks floating in the granite range in size from four centimeters to three meters across.

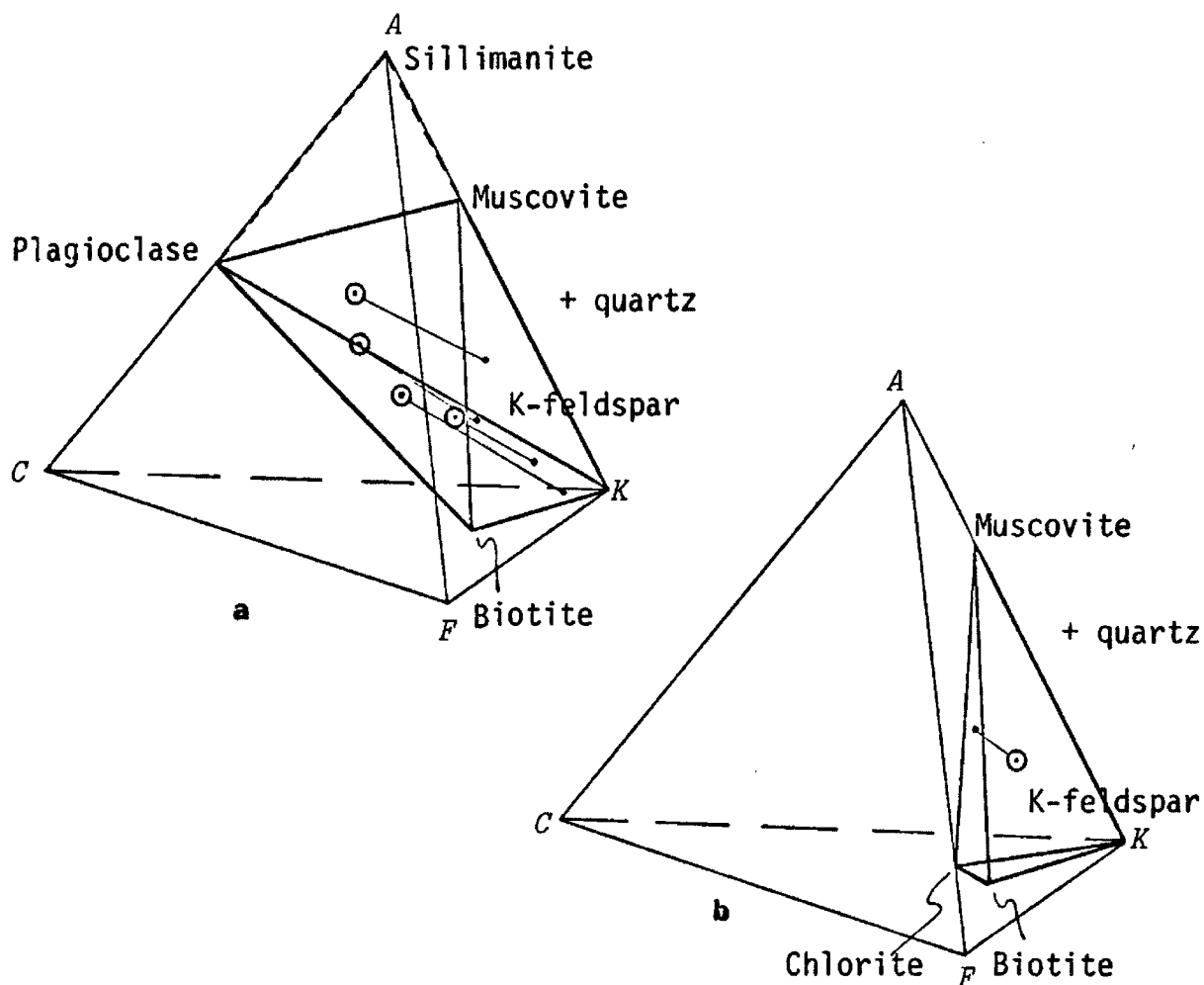


Fig. 3.1. Equilibrium assemblages of the Ravalli Group. = whole rock composition, and shows position of each whole rock composition projected on a single face of the subtetrahedron.

Table 3.1. Modal mineralogy of the Ravalli Group. Each lettered assemblage (e.g., b) corresponds to the appropriately lettered tetrahedron in Figure 3.1 and assemblage on page 11.

	Mineral %	plagioclase	K-feldspar	quartz	biotite	muscovite	sillimanite	chlorite	No. of thin sections
Assemblage	(a)	12-39	4-32	10-54	6-18	3-10	0-1	0-1	4
	(b)	-----	5	80	5	5	---	3	1

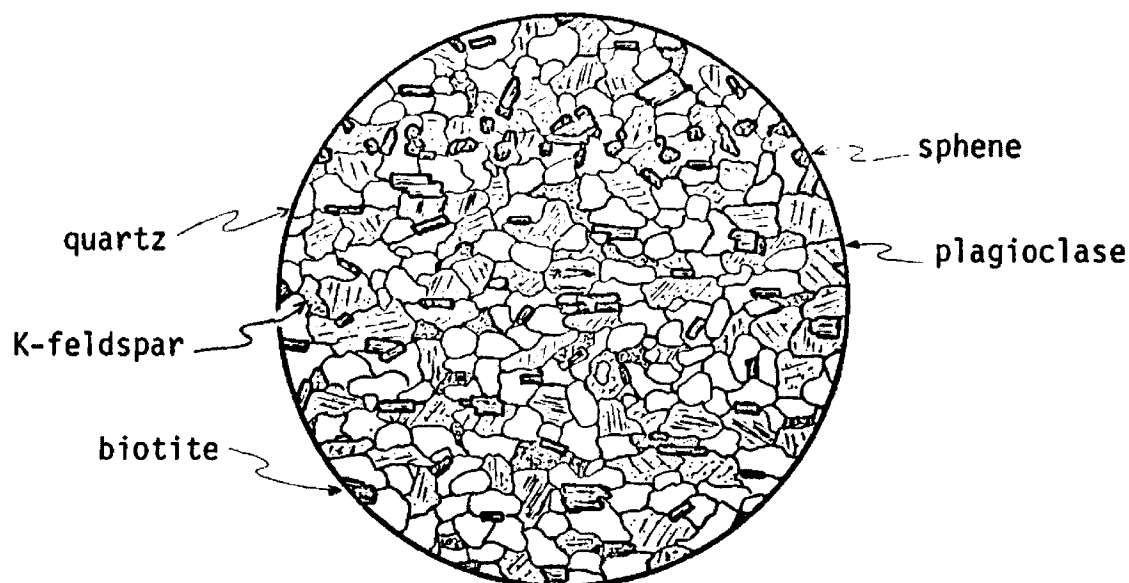


Fig. 3.2. (80X) Thin section sketch of a typical sample from a quartzofeldspathic portion of the Ravalli Group. Note the preponderance of plagioclase over K-feldspar and the crude alignment of mica. A concentration layer of sphene can be seen near the top of the sketch. Sample taken $2\frac{1}{2}$ miles southwest of Buckhorn Saddle.

The larger blocks have been shifted and adjusted to a minor degree by the intruding granite, whereas the smaller blocks exhibit all attitudes.

Exposures of the unit lying north and east of the Skalkaho stock are less gneissic in texture and range in color from light to medium gray. The most striking feature of these rocks is the large amount of sillimanite, occurring with quartz and muscovite as discrete pods aligned with the cleavage. These blue-gray pods are lenticular in cross section and circular when viewed at right angles to the cleavage (Fig. 3.3).

Five thin sections from this unit were examined. The typical mineral assemblage is quartz + potassium feldspar + biotite + muscovite + plagioclase + sillimanite. ACFK equilibrium tetrahedra are shown in Fig. 3.4, and tabular listing of mineralogy is in Table 3.2.

Three samples collected from the small outcrop along Skalkaho Creek are coarse-grained, banded gneisses whose texture under the microscope resembles that of granite. The potassium feldspar is microcline, biotite is only mildly aligned, and much of the plagioclase is well twinned (see Fig. 3.5). Evidently the metamorphic grade here is high.

Potassium feldspar makes up more than fifty percent of total feldspar in two of the three rocks and occurs with an equal amount of plagioclase in the third. Biotite is minor in all three and well aligned in only one which also contains sillimanite + muscovite as a stable assemblage.

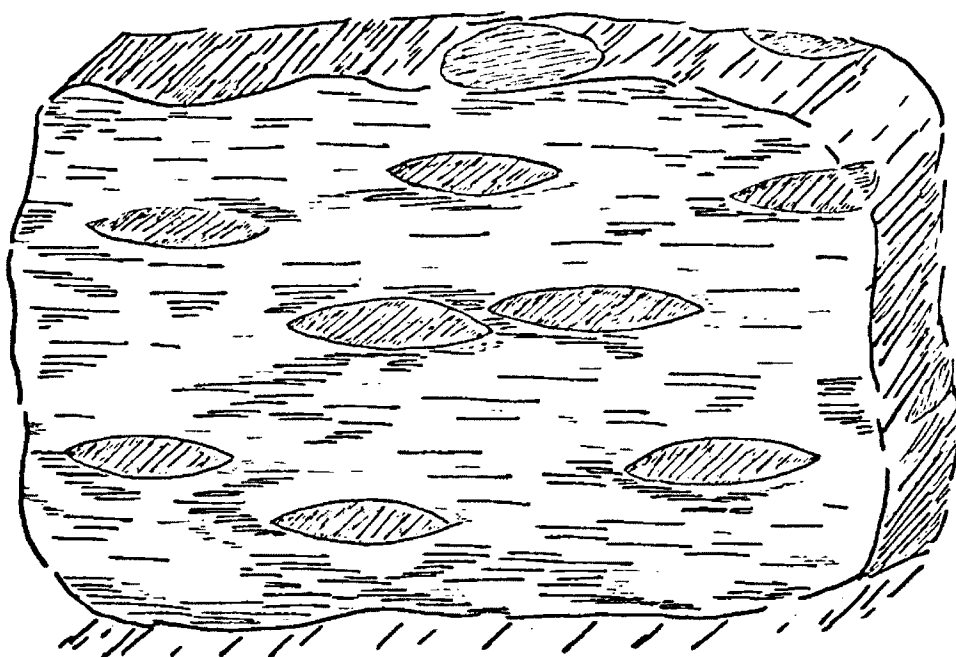


Fig. 3.3. (Actual size) Sketch of sillimanite-rich sample from K-rich quartzofeldspathic unit taken north of Skalkaho stock. Lenticular pods of sillimanite + muscovite + quartz are striking. See text for further discussion.

Examination of two thin sections from the large outcrop north and east of the Skalkaho stock indicates that these rocks are in the sillimanite-muscovite zone. Although orthoclase occurs in the same rocks, the sillimanite-muscovite assemblage is virtually isolated by quartz into discrete pods, and sillimanite-orthoclase stability is not established.

Potassium feldspar comprises over ninety percent of the total feldspar, causing the total rock composition to plot very near the K_2O corner of the ACFK tetrahedron (Fig. 3.4). This is at variance with most of the total rock compositions plotted for the rocks collected along Skalkaho Creek, and suggests that perhaps these outcrops are not actually two parts of the same unit. A more detailed study of these high-grade rocks is in order and will need to be accomplished before their petrogenesis can be established with certainty.

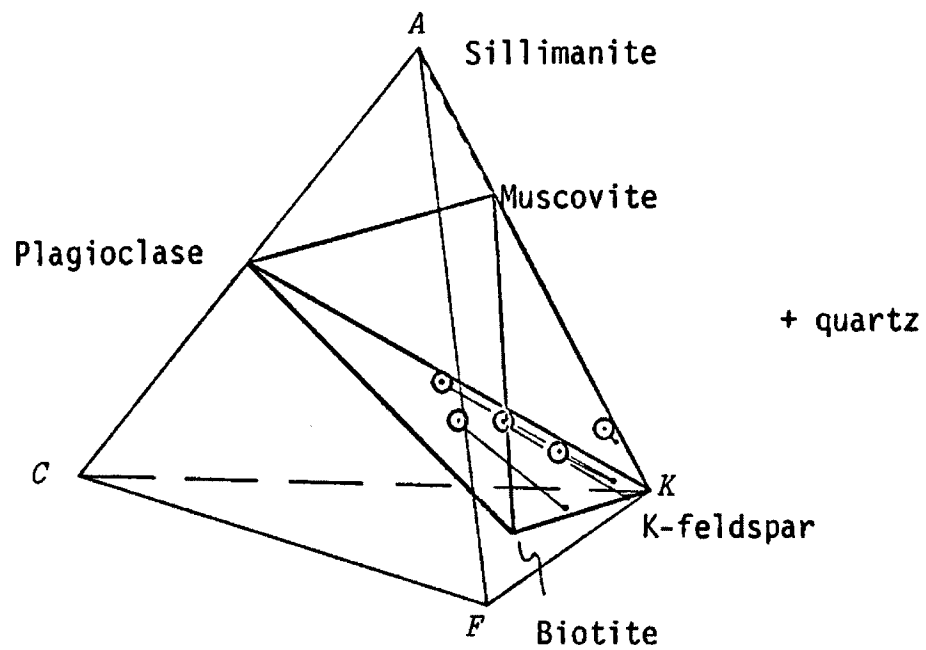


Fig. 3.4. Equilibrium assemblage of K-rich quartzofeldspathic unit. See Figure 3.1 for explanation of symbols.

Table 3.2. Modal mineralogy of K-rich quartzofeldspathic unit. The assemblage corresponds to the tetrahedron in Figure 3.4.

Mineral	Plagioclase	K-feldspar	quartz	biotite	muscovite	sillimanite	No. of thin sections
%	5-30	12-35	25-69	1-23	½-12	0-1	5

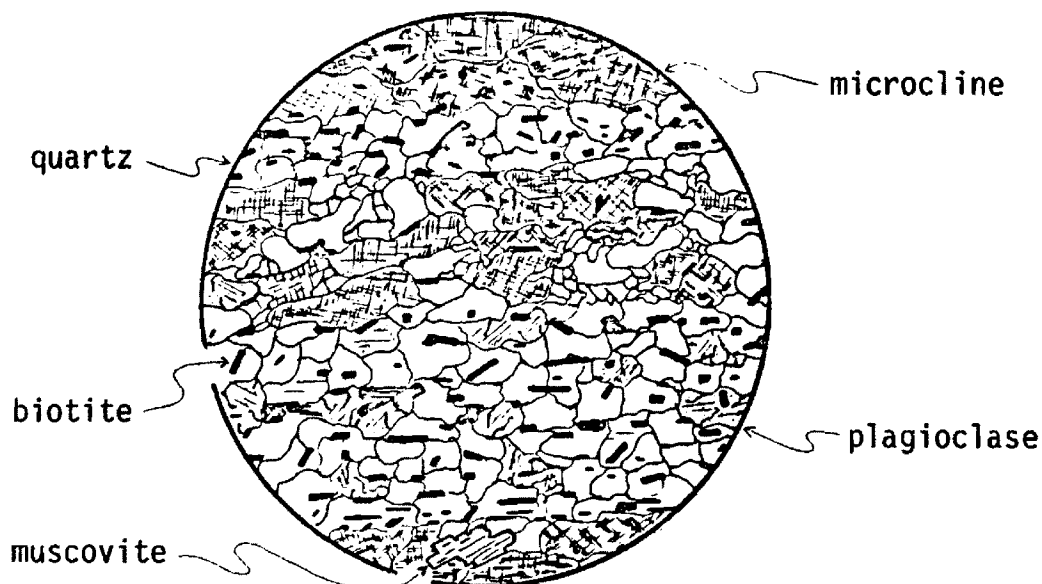


Fig. 3.5. (20X) Thin section sketch of a typical sample from the K-rich quartzofeldspathic unit taken near Skalkaho Creek. Note regular gneissic layering and coarse interlocking grains.

Wallace Formation

Greenschist facies. Rocks of the Wallace Formation metamorphosed to the greenschist facies lie generally in the eastern one-third of the study area (see Fig. 2.1). They are characterized primarily by the absence of diopside (where the composition is appropriate) and by the preservation of original sedimentary structures.

Three metamorphic zones within this facies are thought to be present. In order of increasing grade they are the dolomite-quartz zone, the talc zone, and the tremolite zone. Evidence relating to the dolomite-quartz zone is particularly sketchy, but its existence appears to be real.

Rocks in this facies exhibit a wide variety of appearances in outcrop. Their colors range from very light gray to very dark gray and from light brown to green. The color is due primarily to original

mineralogical composition. For example, the rocks containing high percentages of calcite tend to be lighter colored than those containing a high percentage of feldspar. Some color, however, is a result of the growth of metamorphic minerals, such as actinolite. As a result, some of the rocks in the tremolite zone are green.

Textures range from massive to thinly laminated to porphyroblastic to brecciated. Except for the breccia chips and some porphyroblasts the rocks are very fine grained. Rocks with massive texture are few and not even locally abundant.

As a result of soft-sediment deformation the laminae are commonly contorted and irregular in thickness. Thickness of the laminae is highly variable but generally ranges from paper thin to a few centimeters. The thin laminae are generally darker in color (e.g. dark gray), and the thicker laminae are light colored (e.g. tan).

Many of the rocks are metamorphosed equivalents of an original sedimentary breccia¹. Breccia fragments vary in size from one millimeter to one-half meter, but a modal size is approximately one centimeter in diameter. Fragments in the form of large blocks were observed in only one location, Skalkaho Falls (see Fig. 2.1), where they underly the cascading water.

Breccia chips are generally white to very light gray, and the shape varies from angular to sub-round. In some samples sedimentary laminae are preserved within the chips. The groundmass surrounding the chips is most frequently brown or tan and accounts for the overall color of the rock.

¹Metamorphosed breccia of the Wallace Formation was also described by Nold (1968, page 84).

One sample of the metamorphic breccia also exhibits subtle lamination which cuts across chip-groundmass boundaries. In this instance boundaries of the breccia chips appear to be less well defined and somewhat gradational into the groundmass. These laminae are interpreted to be a result of metamorphic differentiation. In another specimen white boudins of quartz and albite developed in a gray calcareous groundmass. More resistant to weathering than the rest of the rock, the boudins stand out high in relief. A few of the rocks contain scapolite and are discussed in Chapter IV.

Twenty-six thin sections of rocks in the greenschist facies were examined in detail. Generally the rocks are fine to very fine grained, but a few specimens contain medium to coarse grains of quartz, calcite, and dolomite. Talc and/or scapolite occur as porphyroblasts in a few samples.

The typical mineral assemblages of this facies are as follows:

Dolomite-quartz zone:

(a) dolomite + albite + quartz

Talc zone:

(b) talc + calcite + phlogopite + albite + quartz + scapolite

(c) talc + calcite + phlogopite + albite + quartz

(d) talc + dolomite + calcite + albite + quartz

(e) calcite + phlogopite + albite + quartz

(f) calcite + albite + quartz

Tremolite zone:

(g) actinolite + plagioclase (approx. an_{25}) + K-feldspar +
biotite + calcite + quartz \pm scapolite

- (h) tremolite + albite + calcite + quartz \pm phlogopite
- (i) tremolite + plagioclase (approx. An₂₀₋₄₀) + calcite + quartz
- (j) tremolite + scapolite + calcite + quartz + phlogopite \pm albite

The range of percentages of minerals present are calcite (0-81%), quartz (4-59%), plagioclase (0-70%), albite (0-69%), phlogopite (0-30%), dolomite (0-15%), talc (0-25%), scapolite (0-23%), tremolite (0-60%). ACFK and ACFNa equilibrium tetrahedra are shown in Figure 3.11, and tabular listing of mineralogy is in Table 3.3.

The wide range of calcite and plagioclase reflect original compositional variation. For example, the specimen which contains the highest percentage of plagioclase also contains the lowest percentage of calcite.

Occurrence of phlogopite and biotite represents availability of chemical components within the original sediments, but their presence or absence may be of some significance as related to formation and stability of talc (see p. 52). The phlogopite is pleochronic with Z = light orange tan, and X = colorless to extremely pale yellow. Biotite pleochroism is Z = brown olive, and X = light yellow.

Three metamorphic zones were identified petrographically. For clarity each is discussed separately below.

Only one thin section from the dolomite-quartz zone was obtained; consequently, acceptance of the existence of the zone should be guarded. Nevertheless, if the mineral assemblage and texture exhibited in this thin section is representative of other rocks in the area, the zone may indeed exist.

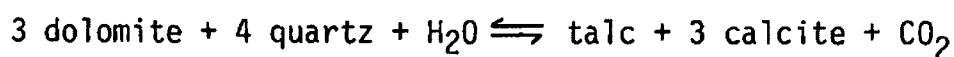
The equilibrium mineral assemblage is dolomite + quartz + albite (see (a) above). Thirty percent of the rock is composed of breccia chips

up to one-half centimeter in diameter, each of which is approximately ninety percent albite and ten percent quartz (see Fig. 3.6). Medium to coarse quartz grains occur outside the breccia chips. Dolomite occurs as coarse, subhedral to euhedral grains. The remainder of the rock is a very fine matrix of albite and quartz.

Identification of dolomite was made petrographically by determining optical and crystallographic directions with respect to twin lamellae present in a few of the grains. Many of the lamellae are bent and distorted, and undulose extinction is fairly common. The euhedral crystal habit is characteristic of dolomite and very uncommon in calcite (Kerr, 1959).

Some dolomite crystals are slightly zoned, but the zoning is simple and appears to be a result of a later addition of a "dirty" rim onto an earlier "clean", euhedral dolomite crystal. Twin lamellae in the core of the crystals do not persist into the rims. The rims contain small inclusions of feldspar, quartz, and minute graphite specks but do not appear to be reacting with quartz.

At moderate temperatures the first reaction in the progressive metamorphism of a siliceous dolomite should be to destroy dolomite and produce talc according to the following reaction:¹



¹This and other reactions are discussed in more detail beginning on page 49.

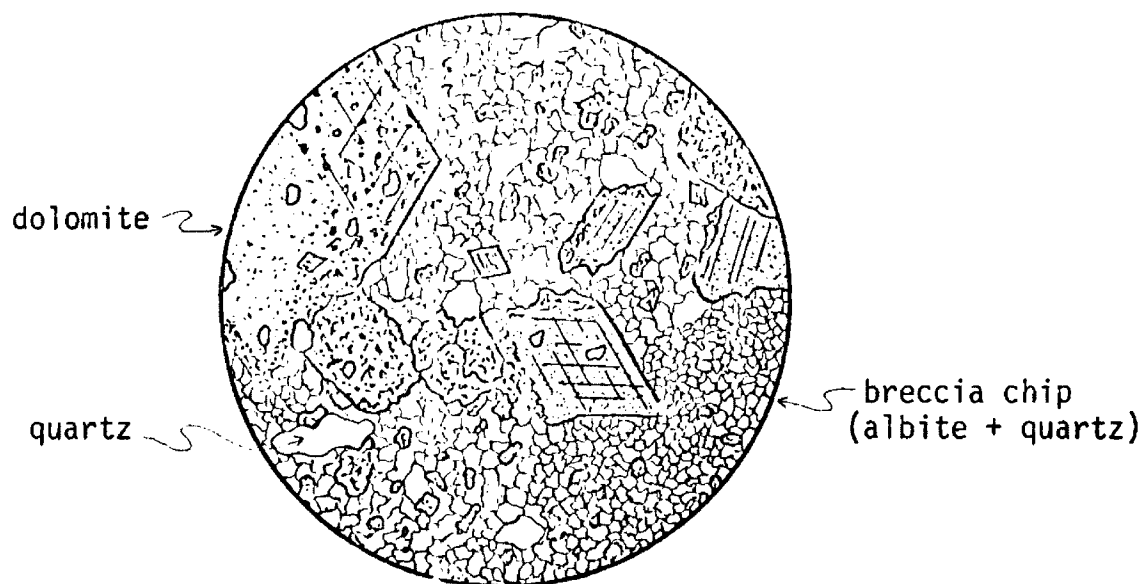


Fig. 3.6. (80X) Thin section sketch of the sample from the dolomite-quartz zone, Wallace Formation. Idioblastic dolomite shows "dirty" rims. Medium-sized quartz and dolomite share matrix with fine-grained albite and quartz. Sample taken near contact with Missoula group in vicinity of Skalkaho Pass. See text for further discussion.

Since the reaction has not occurred, the specimen must be below the talc zone. This occurrence of dolomite + quartz in an apparently stable configuration may represent the lowest grade of metamorphism in the Skalkaho region.

In the talc zone seven thin sections apparently containing talc were examined petrographically. Positive identification of talc was attempted by X-ray diffraction, but because of the small amount of the mineral present, talc peaks were not noticeable. No peaks for white mica (conceivably misidentified as talc) were seen either. Through association, the mineral is most likely talc. It has two modes of occurrence: (a) as poikiloblasts which are up to one millimeter in diameter; (b) as small spherulitic and fan-shaped aggregates along grain boundaries of quartz and dolomite.

The first mode of occurrence is the most common. The poikiloblasts are generally indistinct, appearing to be in the initial stages of growth. A few of the smaller poikiloblasts are better formed and are illustrated in Figure 3.7.

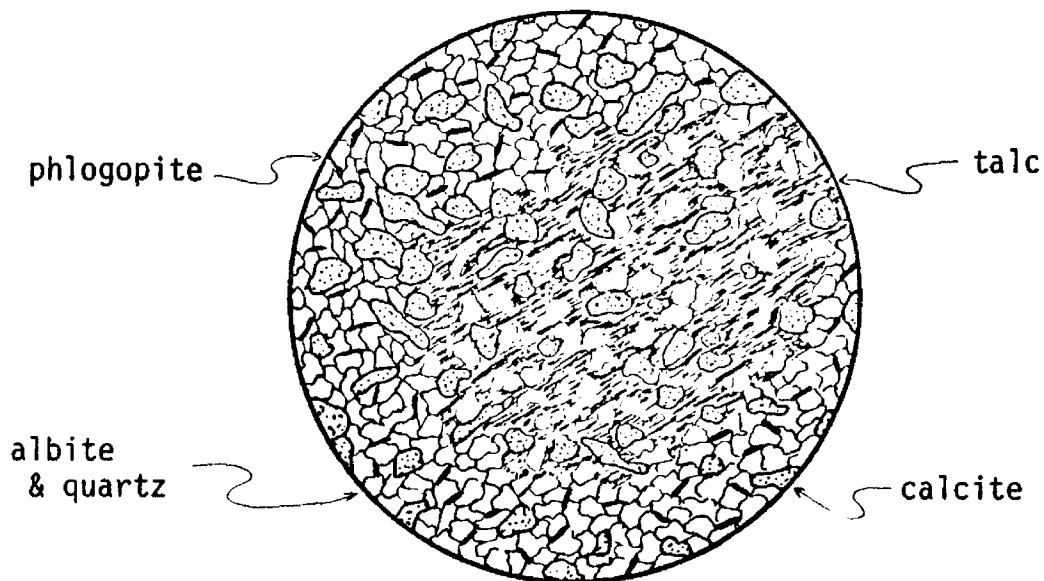


Fig. 3.7. (80X) Thin section sketch of a typical sample from the talc zone, Wallace Formation. Poikiloblasts of talc containing inclusions of quartz and calcite are in latter stages of growth. Sample taken along Skalkaho highway, midway between Skalkaho Pass and Skalkaho Falls. See text for discussion.

The latter mode of occurrence was observed in only one thin section. Since both reactants and products (in going from the dolomite-quartz zone to the talc zone according to the above reaction) are present in the same specimen, the sample is either barely within the talc zone or more likely lies along the dolomite-quartz-talc reaction boundary (see Fig. 3.19). For convenience it is considered here.

The mineral assemblage in this rock is dolomite + calcite + talc + quartz + albite + iron oxide (see Fig. 3.11d). Dolomite is euhedral to

subhedral but highly corroded, substantiating the suggestion that it is breaking down to form talc. Calcite occurs as small anhedral aggregates and single grains, primarily in the fine-grained matrix. This occurrence is similar to that of calcite in the remainder of this facies.

As can be seen in Fig. 3.8 the talc tends to be concentrated along grain boundaries of the dolomite, and in many instances forms an interstitial matrix between dolomite and quartz grains. It occurs as spherulitic and fan-shaped aggregates with wavy extinction. The aggregates are moderately birefringent, many showing second order interference colors.

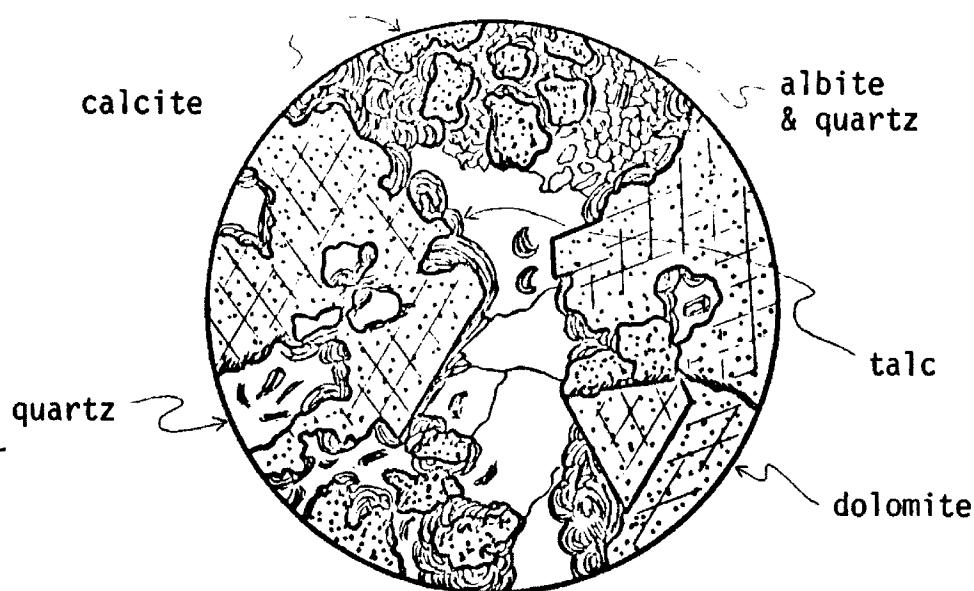


Fig. 3.8. (80X) Thin section sketch of the sample from the dolomite-quartz-talc reaction boundary (reaction 1, p. 49). Spherulitic talc occurs mostly along grain boundaries of quartz, corroded euhedral dolomite, and anhedral calcite. Albite (some twinned) occurs as a fine-grained sutured matrix near top of figure. Sample taken east of Daly Creek, 1 mile northeast of Daly stock.

Eleven thin sections from the tremolite zone containing tremolite/actinolite¹ were examined in detail. Each occurrence of the amphibole is more-or-less distinctive; however, it is possible to distinguish two modes of occurrence: (a) discrete blades or prisms, commonly as aggregates; (b) radiating or fan-shaped aggregates of fibrous or needle-like indistinct crystals. In a few instances both modes occur in the same section, but generally one mode is dominant. Three of the samples contain scapolite and are discussed in Chapter IV.

The first mode of occurrence, discrete grains of tremolite, is exhibited by eight samples. The typical mineral assemblage is tremolite + quartz + calcite \pm plagioclase (approx. An₁₀₋₂₅) \pm scapolite (Me₂₁₋₄₅) \pm biotite \pm K-feldspar. Accessories include opaques, apatite, sphene, zoisite, chlorite, and muscovite. All specimens contain tremolite with Z = very pale to extremely pale green, and X = colorless.

As seen in Figure 3.9 tremolite is strongly embayed, poorly terminated, and moderately poikilitic. Local post-crystallization deformation is revealed by broken amphibole blades which have not recrystallized. Alignment of amphibole prisms ranges from fair to nonexistent, suggesting that stress during growth was not great.

¹For purposes of this study, the name "actinolite" is given to calcium-ferromagnesian amphiboles whose pleochroic color in white light is light kelly green or darker when the Z optical direction is aligned with the vibration direction of the polarizer. Those which are extremely pale green to colorless when aligned in this manner are called "tremolite" (Deer, Howie, and Zussman, 1966, p. 163). Most workers do not assign pleochroic color schemes to a definite Mg / Mg + Fe" ratio, presumably because of the wide variety of substitution which occurs in the amphiboles, independent of the above ratio. Therefore, the names used here are arbitrary and are descriptive only.

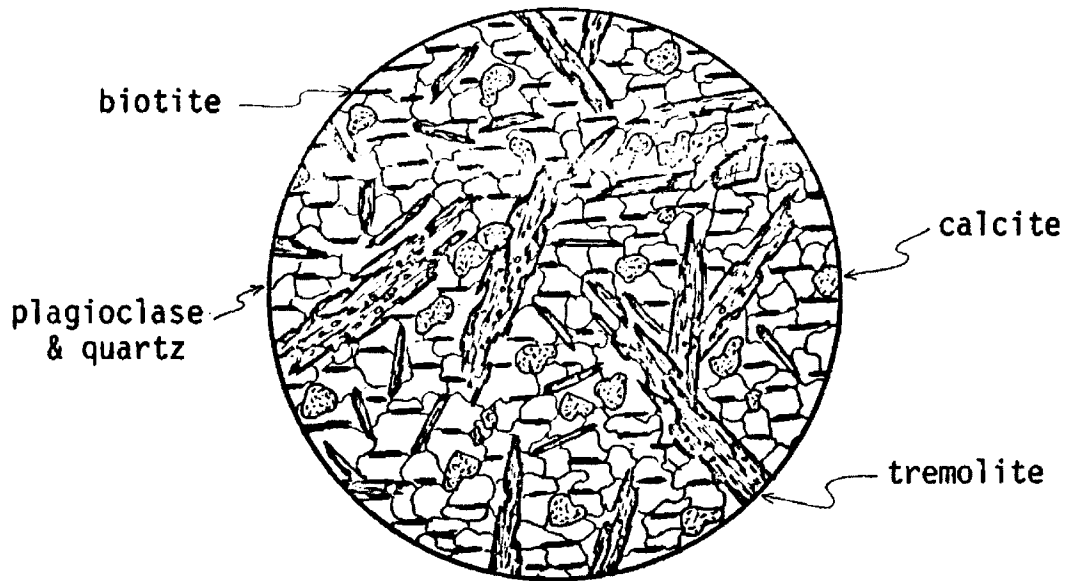


Fig. 3.9. (80X) Thin section sketch of a sample from the tremolite zone, Wallace Formation, showing tremolite as embayed prisms. Sample taken along Daly Creek, midway between Daly stock and Skalkaho Falls. See text for discussion.

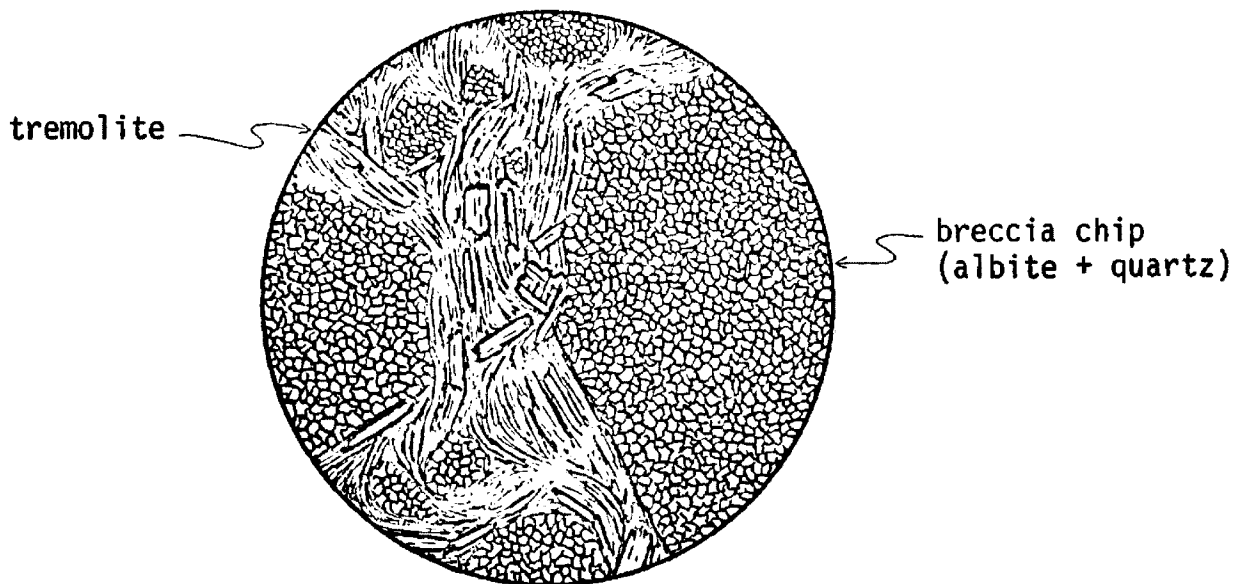


Fig. 3.10. (80X) Thin section sketch of a sample from the tremolite zone, Wallace Formation, showing tremolite as mostly fibrous aggregates. Tremolite wraps around breccia chips of albite and quartz. Sample taken 2 miles north-northeast of Gird Point. See text for discussion.

The second mode of occurrence, fibrous or needle-like aggregates, was seen in only three samples. Two of the three specimens are metamorphic breccia (Fig. 3.10). Tremolite occurs between the breccia chips, wrapped around them or radiating from nuclei on their margins. In the non-breccia sample the radiating aggregates tend to be concentrated into layers, producing a gneissic appearance.

No talc was found in the tremolite zone. Reactions involved in moving from the talc zone to the tremolite zone are discussed below. The tremolite zone represents the high-temperature end of the greenschist facies in the Skalkaho region.

Amphibolite facies. Rocks of the Wallace Formation which have been metamorphosed to the amphibolite facies comprise most of the study area. Pelitic rocks, intercalated with green calc-silicates, occur to a much greater extent than in the greenschist facies rocks which lie farther east. They are most common in an area of numerous dikes associated with the Skalkaho stock and are described below.

The calc-silicates are by far the most abundant rock type. Mineralogically, they are characterized by the presence of diopside, where the composition is appropriate. The first occurrence of diopside is considered to mark the lower boundary of the amphibolite facies. Diopside persists throughout the facies; consequently, it is useless in locating metamorphic grades within the facies. Additionally, because of the general scarcity of pelitic rocks, zonal boundaries within the facies were impossible to locate. For that reason in discussion of calc-silicates in this report, the terms "amphibolite facies" and "diopside zone" are used interchangeably.

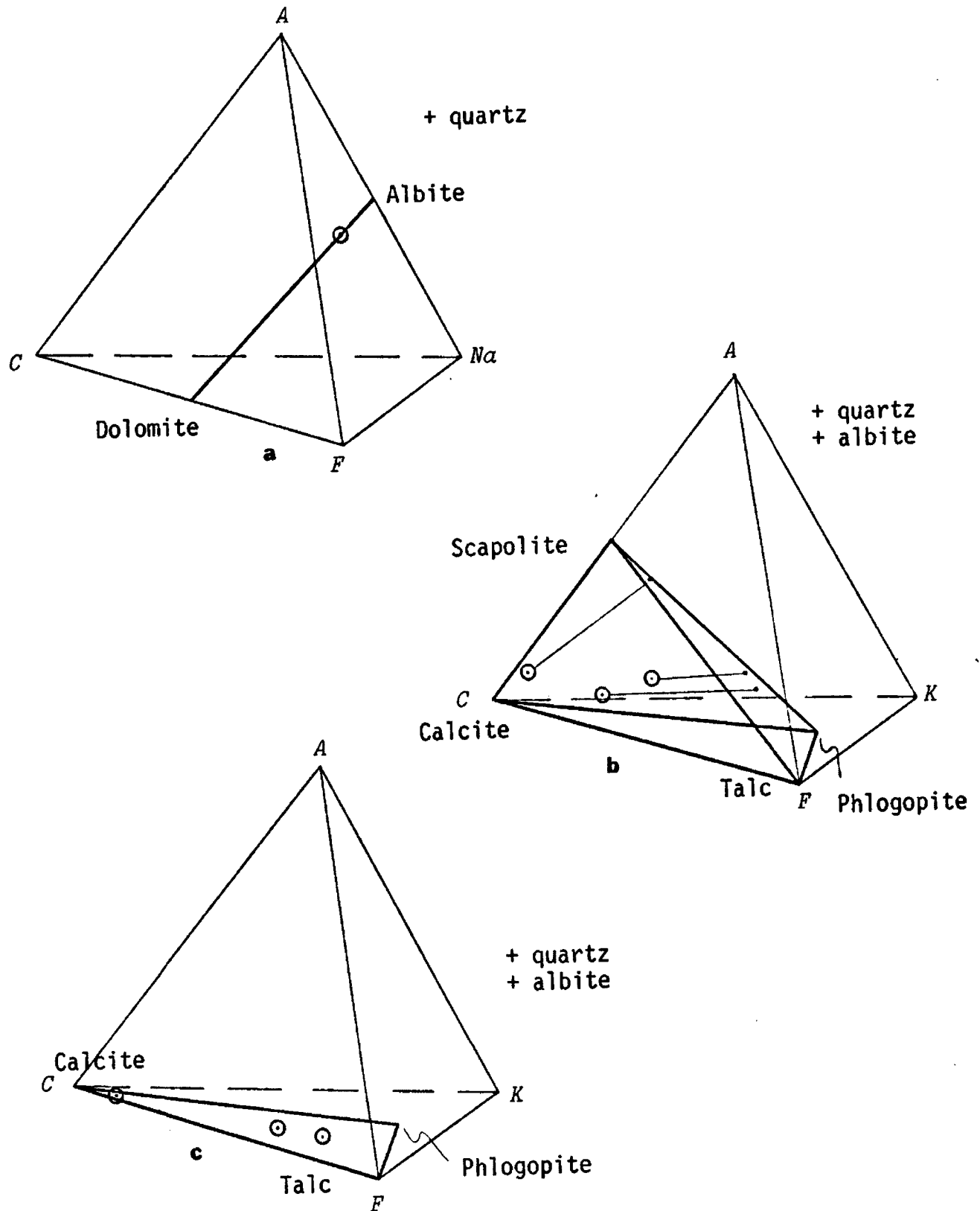


Fig. 3.11. Equilibrium assemblages of Wallace Formation in greenschist facies. See Figure 3.1 for explanation of symbols.

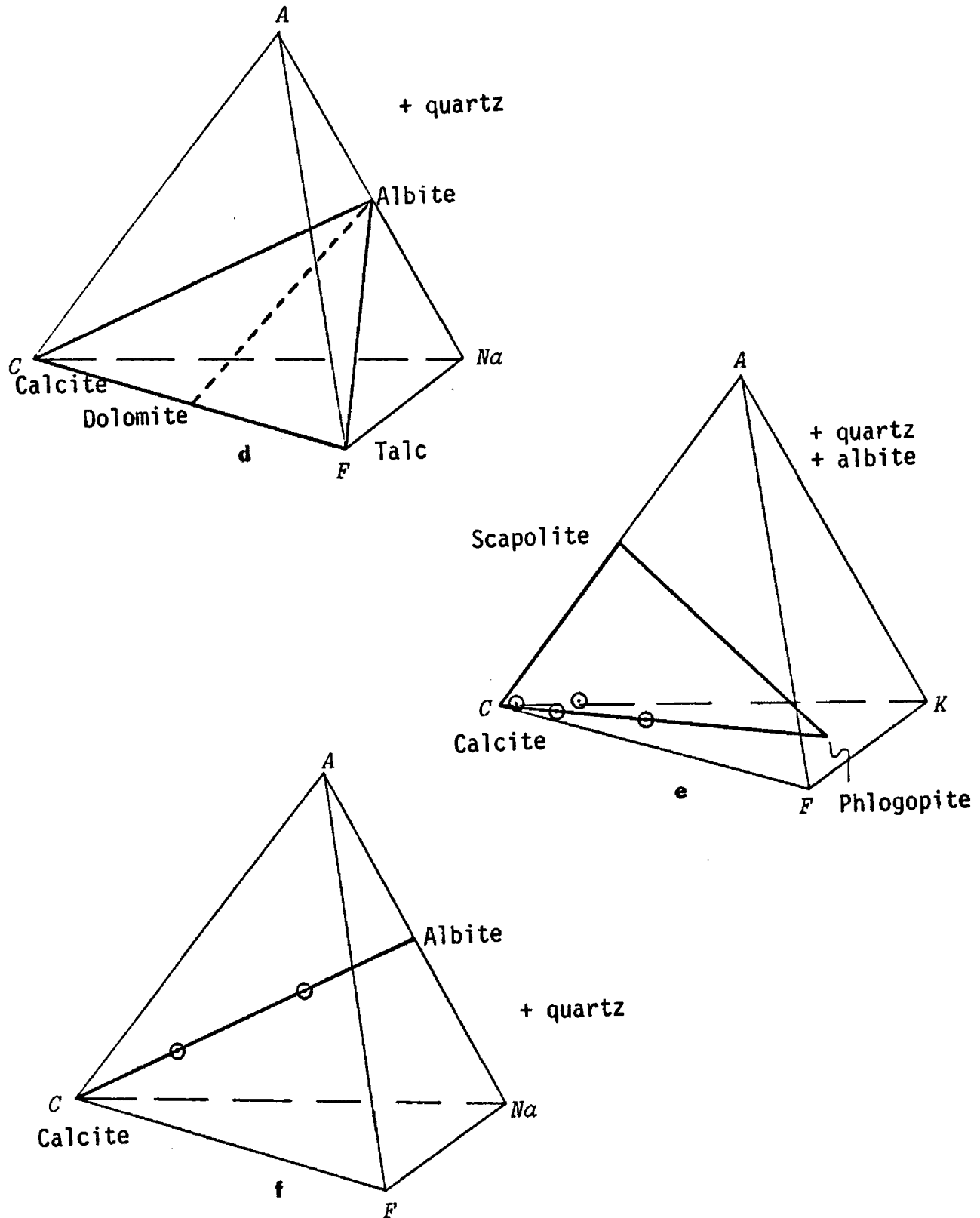


Fig. 3.11 (continued)

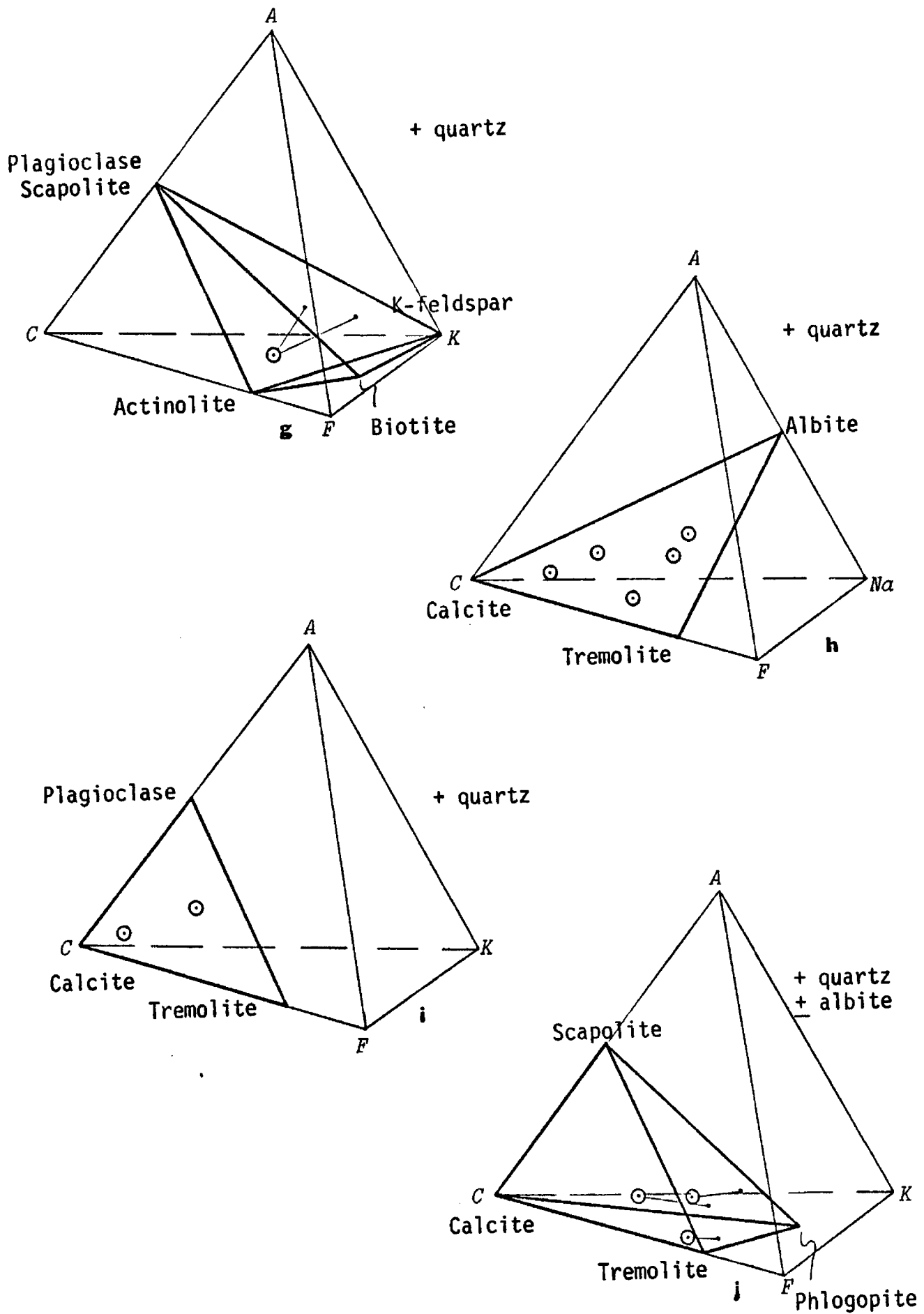


Fig. 3.11 (continued)

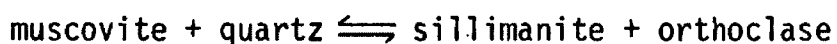
Table 3.3. Modal mineralogy of Wallace Formation in greenschist facies. Each lettered assemblage (e.g., f) corresponds to the appropriately lettered tetrahedron in Figure 3.11 and assemblage on page

Zone	Dolomite- Quartz	Talc					Tremolite			
Assemblage	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
Mineral %										
tremolite/ actinolite	--	----	----	--	----	----	55-57	15-60	10-35	11-58
talc	--	1-5	5-25	5	----	----	----	----	----	----
dolomite	15	----	----	30	----	----	----	----	----	----
calcite	--	26-50	8-65	5	40-81	25-65	1-7	8-53	20-45	12-20
albite	69	5-20	8-33	40	1-19	27-45	----	10-27	----	0-25
plagioclase	--	----	----	--	----	----	2-5	----	11-37	----
phlogopite	1	2-28	5-30	--	1-25	----	----	----	----	10-42
biotite	--	----	----	--	----	----	5-20	----	----	----
quartz	15	5-26	4-25	20	10-20	7-30	½-13	6-59	7-33	10-12
K-feldspar	--	0-tr	----	--	0-½	----	7-12	0-2	----	0-1
scapolite	--	8-23	----	--	0-10	----	0-14	----	----	5-14
Number of thin sections	1	3	3	1	4	2	2	5	2	3

Two samples from pelitic units within the dike zone which were examined in thin section possess sillimanite in a stable configuration with muscovite (Fig. 3.12). In one of the sections several grains of muscovite appear to be decaying and in two places are optically aligned with adjacent orthoclase. Additionally, a few needles of sillimanite penetrate orthoclase grains without apparent reaction. These textures suggest that the grade of metamorphism is likely on the reaction boundary between the sillimanite-muscovite zone and sillimanite-orthoclase zone.

Evans and Guiddoti (1966) located a zone ten kilometers wide in Maine in which sillimanite, muscovite, orthoclase, and quartz all appeared in the same rocks. The zonal isograd which is theoretically a plane in space, clearly does not exist in Maine and should not be expected elsewhere.

The above authors recorded a gradual decrease in the amount of muscovite with increasing grade. The present sample in question (L-5-24) contains the following mineral assemblage: Sillimanite (10%) + orthoclase (20%) + muscovite (1%) + quartz (29%) + plagioclase (approx. An_{30}) (10%) + biotite (30%). If all the orthoclase is genetically related to the reaction



then the percentage ratio of orthoclase to muscovite, 20:1, suggests that the assemblage is very near the high-temperature side of the reaction zone. The genesis of the orthoclase is of course not known; therefore, a conclusion as to the location of this assemblage within the reaction zone is speculative.

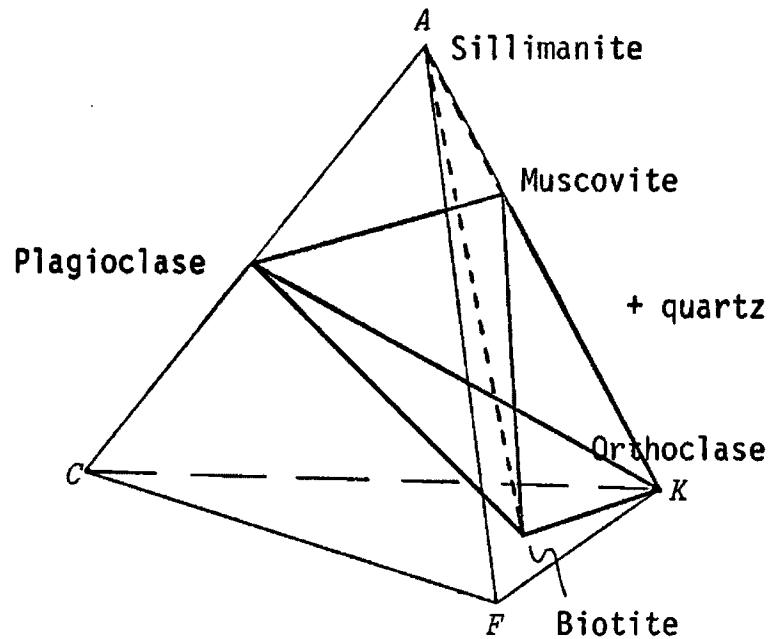


Fig. 3.12. Assemblage of a sillimanite-bearing sample from a pelitic unit of the Wallace Formation in amphibolite facies. Because equilibrium is not established, whole-rock composition is not plotted. Sample taken adjacent to skarn. See text for discussion.

Table 3.4. Modal mineralogy of a sillimanite-bearing sample from a pelitic unit of the Wallace Formation in amphibolite facies. The assemblage corresponds to the tetrahedron in Figure 3.12.

Mineral	plagio- clase	ortho- clase	quartz	biotite	musco- vite	silliman- ite	No. of thin sections
%	10	20	29	30	1	10	1

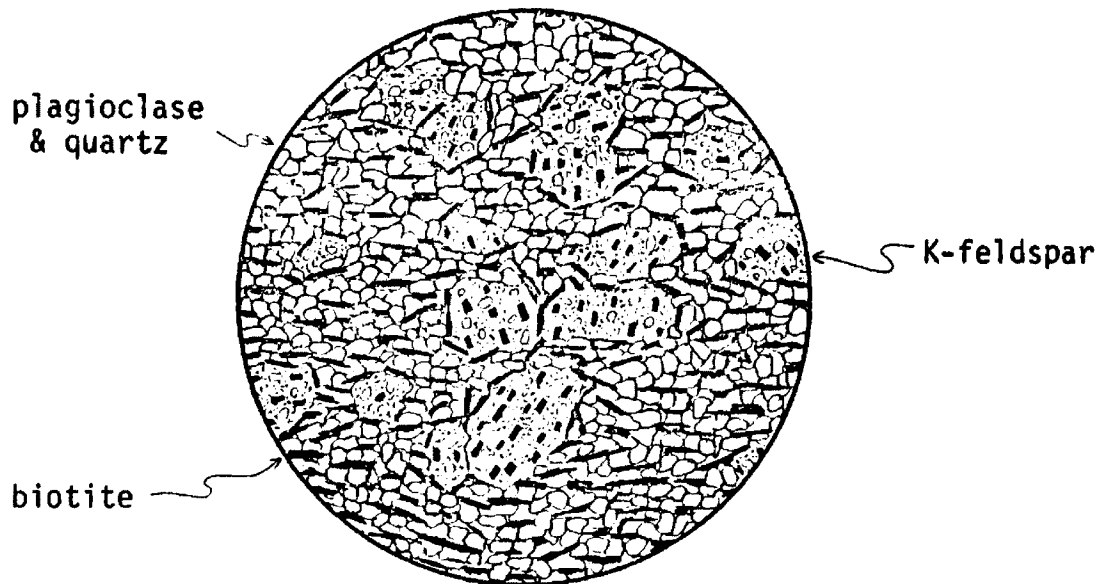


Fig. 3.13. (20X) Thin section sketch of a sample from a pelitic unit of the Wallace Formation (amphibolite facies). Schistosity bends around orthoclase porphyroblasts which exhibit hecilitic texture. Note difference in nature of biotite inclusions from biotite which defines the schistosity. Sample taken $1\frac{1}{2}$ miles east-northeast of skarn (see Fig. 2.1). See text for discussion.

In one specimen K-feldspar occurs in a hecilitic texture as coarse porphyroblasts in a matrix of plagioclase and quartz (Fig. 3.13). A schistosity defined by parallelism of biotite, bends around the porphyroblasts, suggesting that the K-feldspar was present prior to the development of the schistosity. The porphyroblasts contain inclusions of perfectly straight and aligned biotite grains which are commonly at high angles to the schistosity.

There is some distortion of the schistosity around the edges of the porphyroblasts, suggesting that they may have been rolled; however, there is no evidence of "S", "Z", or spiral inclusion patterns. Additionally, the enclosed biotite grains are short and "stubby," whereas the rest of the biotite is long and bladed. This suggests that perhaps the "stubby" biotite represents the early stages of a developing schistosity which

was overgrown by the orthoclase, thus chemically isolating the biotite and preventing its further development. Some of the porphyroblasts were then rolled but not before their growth had been completed. Otherwise, the porphyroblasts would have continued to overgrow the schistosity as they rolled, producing a more complex inclusion pattern. It is interesting to speculate how an easily deformable mineral such as orthoclase could withstand shear forces causing it to be rolled in a high stress environment during the development of the later stages of the schistosity without extensive recrystallization.

The calc-silicate rocks are generally light to dark green in outcrop, but some occur in various shades of gray and brown. Variation in color is due primarily to mineralogy and thus to original chemical composition. The more pelitic rocks tend to appear brown; the more quartzofeldspathic appear gray. Rocks rich in actinolite are dark to medium forest green, those rich in diopside are light green to grayish green, and those locally rich in epidote are yellowish green.

Three modal textures were identified, gneissic, spotted, and brecciated. Combinations of the three textures are common. Except for breccia fragments and porphyroblasts, the rocks are fine grained. Those rocks gneissic in texture commonly possess regular banding on the order of one millimeter to ten centimeters. It is believed that the banding is primarily a reflection of original compositional layering, though some metamorphic differentiation probably has occurred.

In some outcrops cleavage can be seen to cut the layering at moderate angles, clearing^{ing} eliminating the possibility that the same stress caused both the cleavage and layering. In most locations, however,

distinct cleavage (schistosity) is parallel to subparallel to the mineralogical layers, probably representing axial plane cleavage on the limbs of a large fold. In still other locations, pinched-out layers with mineralogically identical layers on either side suggest that isoclinal folding and transposition of bedding have occurred. Such structures are common in the western (highest grade) part of the study area, and are currently being examined as part of a larger project by J. L. Talbot of the University of Montana.

Spotted texture is somewhat rare. The spots are white scapolite in a dark green matrix of actinolite. Scapolite grains in diopside-rich rocks are not distinctive enough to impart a spotted appearance.

Green and white breccia is fairly common, but is generally concentrated such that in a given location only breccia is observed. The breccia observed here is probably correlative with that observed in the greenschist facies rocks to the east, probably representing a sedimentary horizon or horizons.

Breccia which has been metamorphosed to amphibolite grade is generally less distinct than that of the lower-grade rocks. The breccia chips are white and subangular to sheared out into linear fragments. Fragment boundaries are indistinct in many samples, but quite sharp in others. Fragment sizes range from one millimeter to fifteen centimeters, the full range being exhibited by almost all outcrops of breccia.

Twenty-seven thin sections of calc-silicate rocks of the amphibolite facies were examined in detail. The rocks are generally medium- to fine-grained, but coarse grains of diopside are locally common. Porphyroblasts

of scapolite are also locally abundant.

Typical mineral assemblages may be divided into two types: Predominantly pelitic and predominantly calcareous. The pelitic assemblages do not represent major rock units, but occur as very localized narrow bands or zones within the predominantly calcareous rocks. Characteristic mineral assemblages of the pelitic bands are as follows:

- (a) plagioclase + quartz + biotite + chlorite \pm K-feldspar
- (b) plagioclase + quartz + biotite + K-feldspar + actinolite

Characteristic mineral assemblages of the calc-silicate bands are as follows:

- (a) diopside + plagioclase + quartz \pm calcite \pm scapolite
- (b) diopside + plagioclase + quartz + K-feldspar \pm biotite
 \pm scapolite \pm epidote
- (c) diopside + actinolite + plagioclase + quartz \pm K-feldspar
 \pm scapolite \pm calcite \pm epidote
- (d) diopside + actinolite + plagioclase + quartz + calcite \pm
scapolite
- (e) actinolite + plagioclase + quartz + biotite + scapolite \pm
K-feldspar
- (f) actinolite + plagioclase + quartz + K-feldspar + scapolite +
chlorite

The range of percentages of minerals are diopside (0-60%), actinolite (0-78%), plagioclase (approx. An $_{30-70}$) (0-70%), quartz (2-52%), K-feldspar (0-64%), calcite (0-70%), scapolite (0-47%), chlorite (0-17%), epidote (0-9%), biotite (0-30%), garnet (0-2%). Accessories include apatite, sphene, zircon, and sericite. ACFK equilibrium tetrahedra are

shown in Figures 3.16 and 3.17, and tabular listing of mineralogy is in Tables 3.5 and 3.6.

Diopside occurs in most of the samples examined. Its absence in a few samples appears to be directly related to the inappropriate composition of the whole rock, i.e., no calcite was available to react with the actinolite to form diopside (e.g., Sample L-1-10). Diopside exhibits five general modes of occurrence:

- (a) Coarse, anhedral grains, often concentrated into bands of one millimeter or less.
- (b) Large poikiloblasts, locally so full of inclusions that the poikiloblasts initially appear to be a collection of optically aligned, medium-sized grains.
- (c) Aggregates of fine- to medium-sized grains which are locally crudely radiating from a point.
- (d) Scattered discrete fine- to medium-sized anhedral grains.
- (e) New mineral growth after actinolite, generally crystallographically aligned with the amphibole.

The diopside is colorless (rarely very pale green) and if fine-grained it is in some cases very difficult to distinguish from fine-grained very pale green tremolite. In the narrowly banded gneisses several modes of occurrence are commonly displayed in the same sample, but each is generally confined to a specific narrow band (Fig. 3.14).

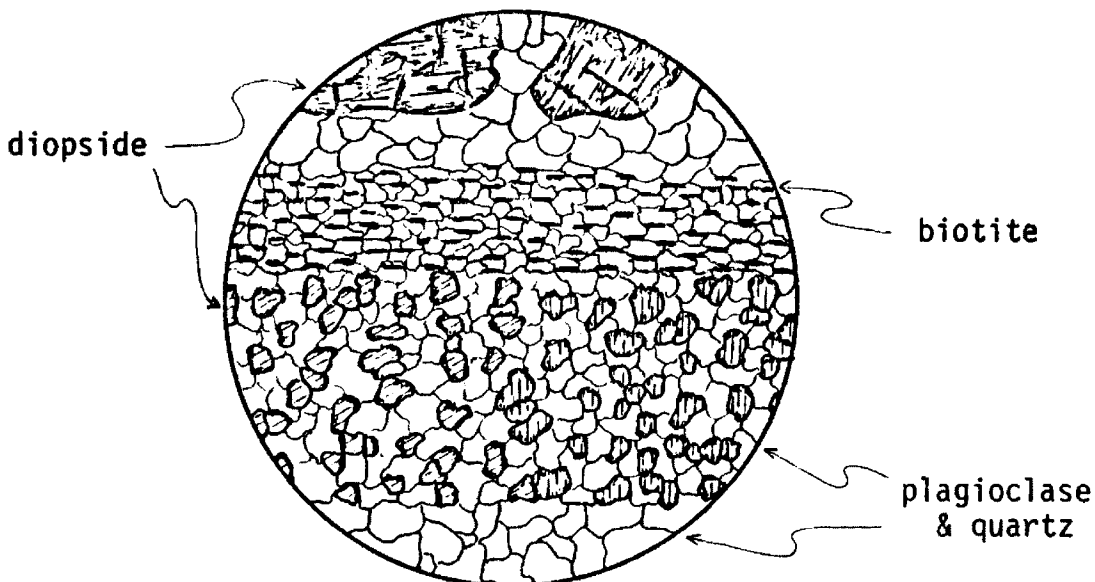


Fig. 3.14. (20X) Thin section sketch of a sample of calc-silicate gneiss, Wallace Formation (amphibolite facies). Note the occurrence of predominantly pelitic bands within the sample which is mostly calc-silicate. Two modes of occurrence of diopside is seen in a single sample. Sample taken 1 mile east-northeast of skarn.

None of the diopside was analyzed for composition, but the fact that it is almost exclusively colorless suggests that its composition is displaced near the composition of pure diopside (Deer, Howie, and Zussman, 1966).

Actinolite (and a little pale green tremolite) occurs in many of the samples. The following modes of occurrence were observed:

- (a) Radiating aggregates of bladed prisms.
- (b) Anhedral, irregular patches of fine to coarse grains.
- (c) Decayed fibrous or needle-like grains associated with calcite and diopside (Fig. 3.15).
- (d) Bladed prisms defining a lineation.

Presence of actinolite in the diopside zone is easily explained by the absence or extreme scarcity of calcite with which the actinolite needs to react to form diopside.

In many samples actinolite and diopside occur together. In several specimens actinolite can be seen to be reacting with calcite to form

diopside (Fig. 3.15). These rocks generally contain "clean" actinolite and calcite as well. It is likely that this mineral assemblage represents a reaction "boundary" or zone as described earlier with regard to sillimanite-muscovite-orthoclase equilibrium.



Fig. 3.15. (320X) Thin section sketch of a sample from the tremolite zone - diopside zone reaction boundary (reaction 5, p. 51). Diopside growing after actinolite as elongate prisms in presence of "clean" actinolite and calcite is seen under high power. Sample taken 1 mile northeast of northeast "tongue" of Skalkaho stock. Nature of this reaction and reaction boundary is discussed in text.

In other samples actinolite is observed to be highly decayed and indistinct. These rocks are possibly at a higher grade, but still within the reaction zone.

The third occurrence of actinolite with diopside is that in which both diopside and actinolite are well formed and "clean". In these rocks either no calcite or very little calcite was observed. That observed is not in grain-to-grain contact with actinolite. It is conceivable that at the higher grades most of the water has been driven off and diffusion of potential reactants is essentially absent, thus allowing the persistence of an unstable assemblage.

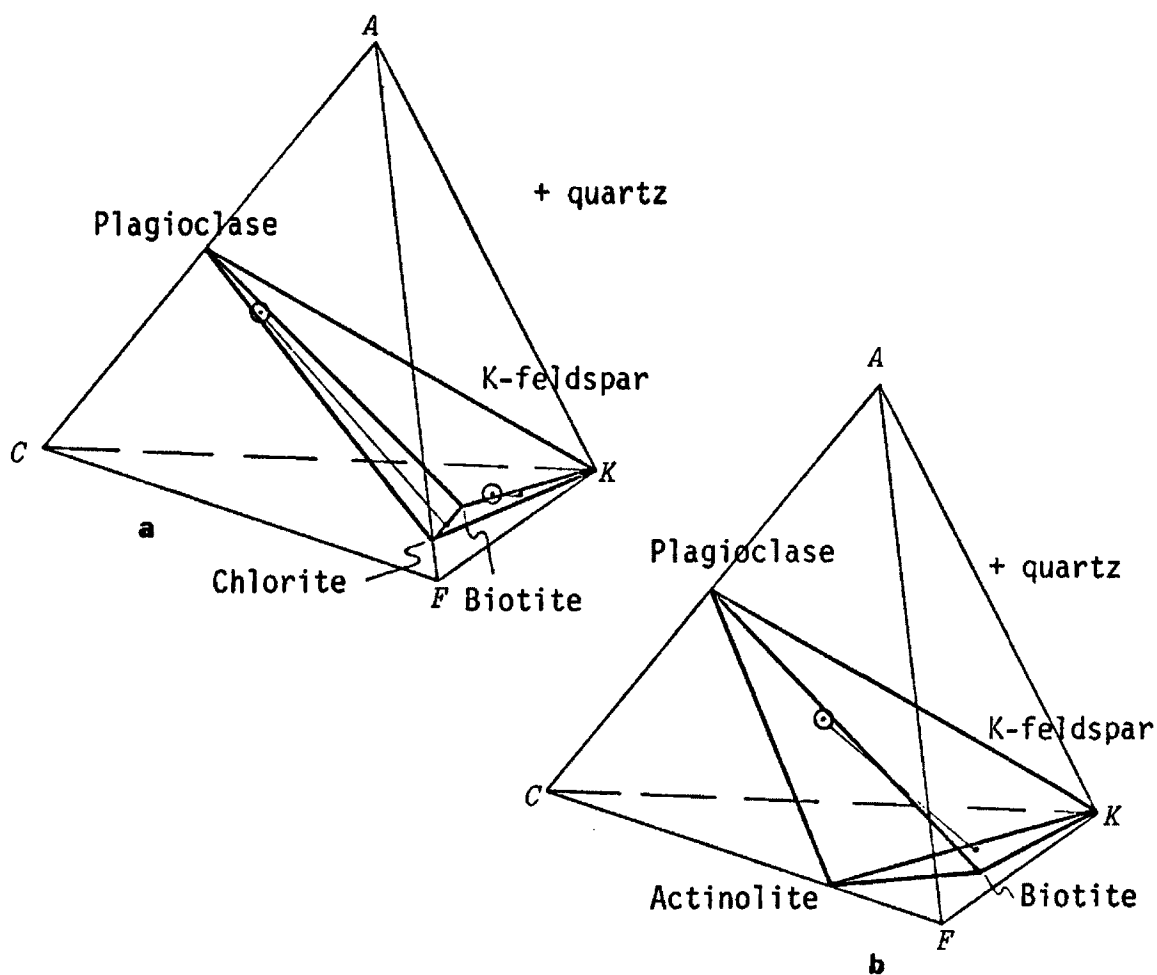


Fig. 3.16. Equilibrium assemblages of pelitic bands within predominantly calc-silicate rock of Wallace Formation of amphibolite facies. Positions of biotite and chlorite within their respective fields chosen for ease of projection. See Figure 3.1 for explanation of symbols.

Table 3.5. Modal mineralogy of pelitic bands with predominantly calc-silicate rock of Wallace Formation of amphibolite facies. Each lettered assemblage (e.g., b) corresponds to the appropriately lettered tetrahedron in Figure 3.16 and assemblage on page 38.

Se	Mineral %	plagioclase	K-feldspar	quartz	biotite	actinolite	chlorite
			0-25	38-40	5-25	---	5-7
			5	25	9	17	---

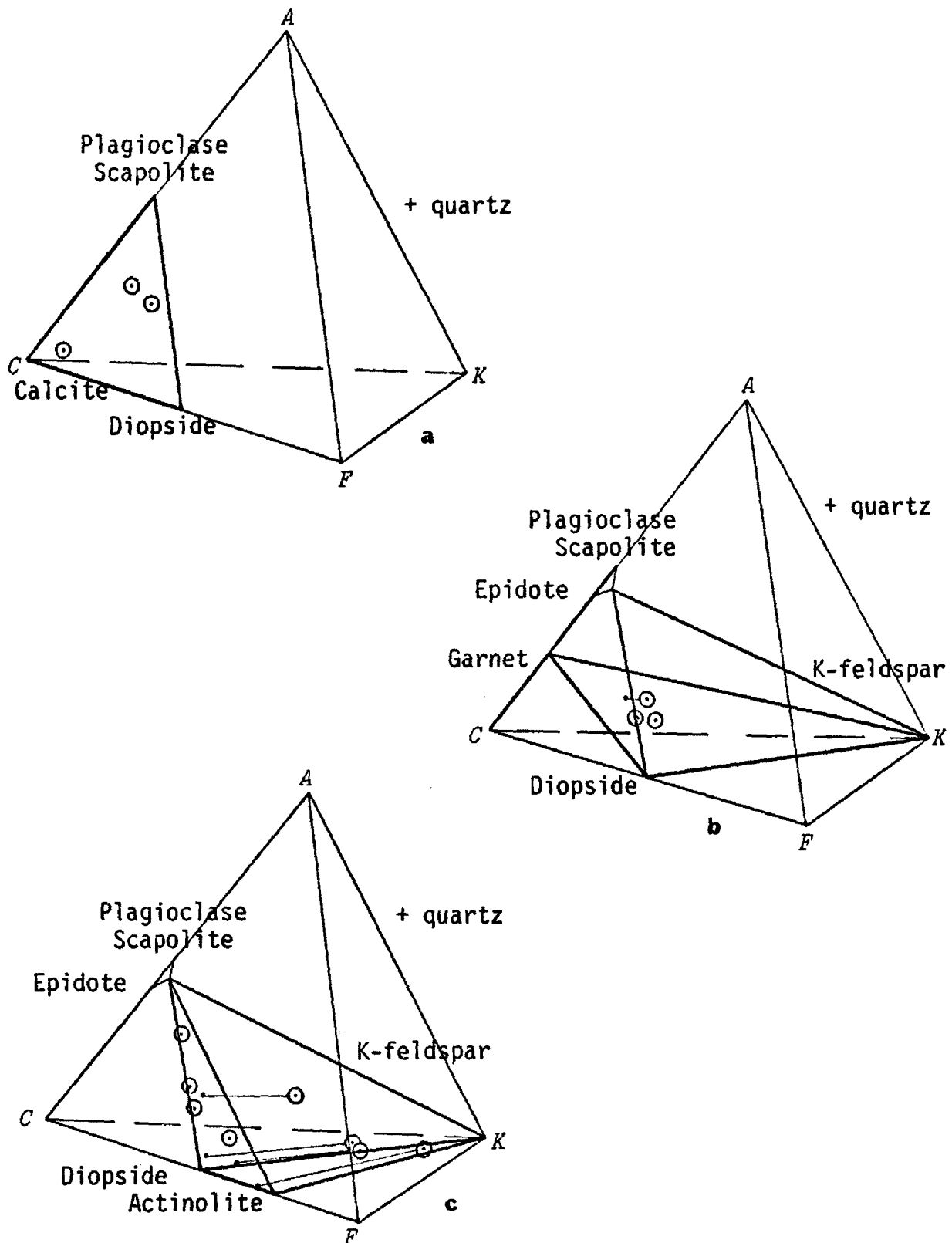


Fig. 3.17. Equilibrium assemblages of calc-silicate bands within predominantly calc-silicate rock of Wallace Formation of amphibolite facies. Positions of biotite and chlorite within their respective fields chosen for ease of projection. See Figure 3.1 for explanation of symbols.

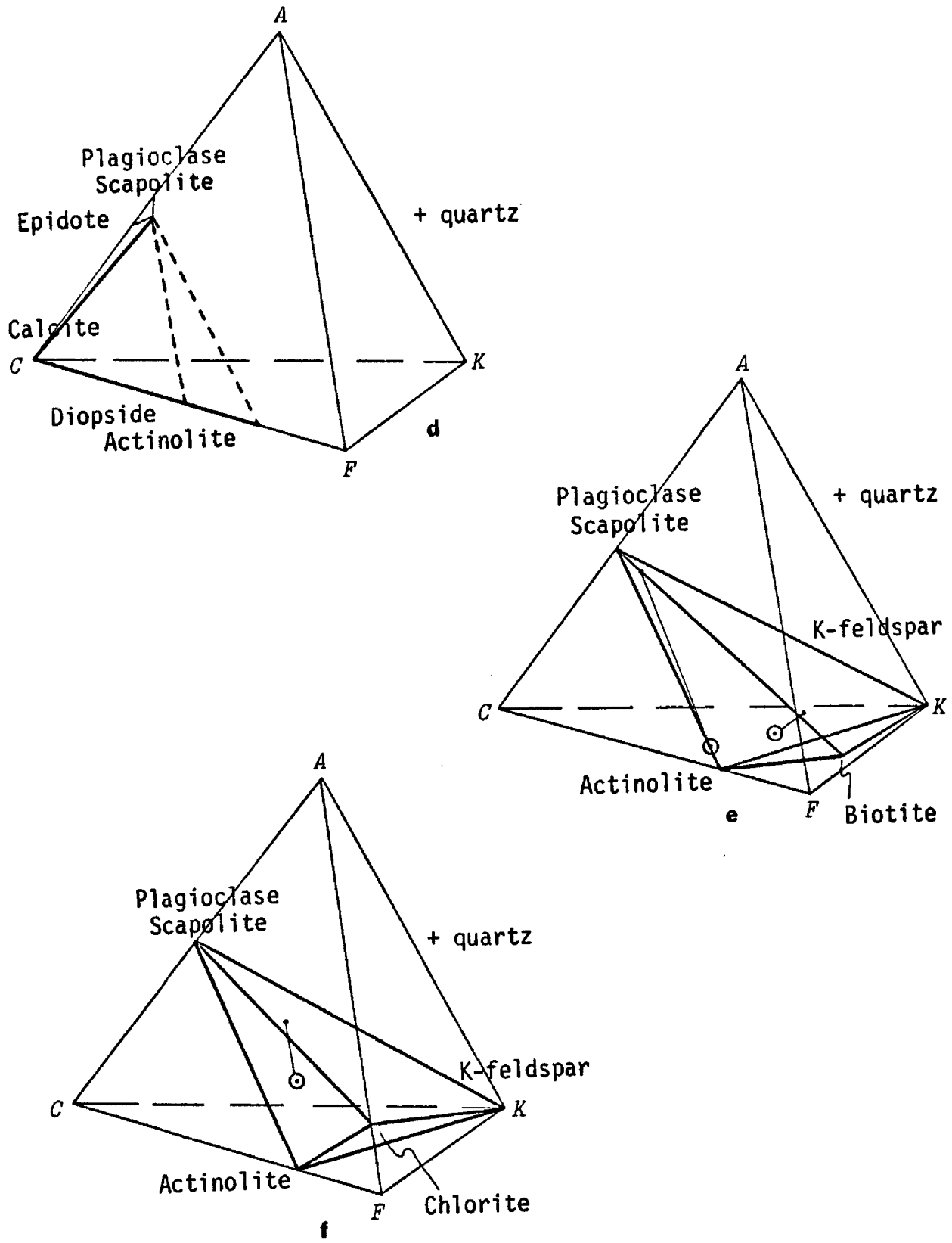


Fig. 3.17 (continued)

Table 3.6. Modal mineralogy of calc-silicate bands within predominantly calc-silicate rock of Wallace Formation of amphibolite facies. Each lettered assemblage (e.g., d) corresponds to the appropriately lettered tetrahedron in Fig. 3.17 and assemblage on page 38.

Assemblage	(a)	(b)	(c)	(d)	(e)	(f)
Mineral %						
diopside	9-35	12-60	10-43	3-35	----	----
tremolite/ actinolite	----	----	1-20	1-40	17-78	37
plagioclase	3-43	0-35	1-50	7-70	4-40	10
K-feldspar	----	1-10	0-46	----	0-5	5
quartz	11-15	10-29	2-52	5-47	6-38	2
calcite	10-70	0-½	0-4	1-52	0-½	----
scapolite	3-45	3-25	0-30	5-40	0-8	28
biotite	0-tr	----	----	----	1-30	----
muscovite	----	tr	0-½	----	0-1	½
epidote	----	tr-3	0-4	1-9	0-2	----
garnet	----	0-2	----	----	----	----
sphene	tr	0-1	0-1	0-1	½	½
apatite	----	tr	0-½	----	0-½	½
chlorite	----	----	----	0-1	0-1	17
zircon	----	----	0-½	----	----	----
opaques	tr-2	tr	0-½	0-2	0-½	----
Number of thin sections	3	3	8	8	2	1

Missoula Group

Only a small portion of rocks mapped as Missoula Group crop out in the study area. They are located in the extreme northeastern portion of the area near the drainage divide. Because of thick soil cover, very little of the rock could be observed. That which appeared to be in place was generally highly fractured and locally sheared.

In hand specimen the rocks are generally massive, white to purple quartzofeldspathic metasediments. Much of the float in the area is at least partially a mud-chip breccia. The purple color of some of the rocks is due primarily to the presence of a high percentage of purple mud chips. Breccia chips are subangular, and generally tend to be aligned along what must have been the sedimentary bedding plane.

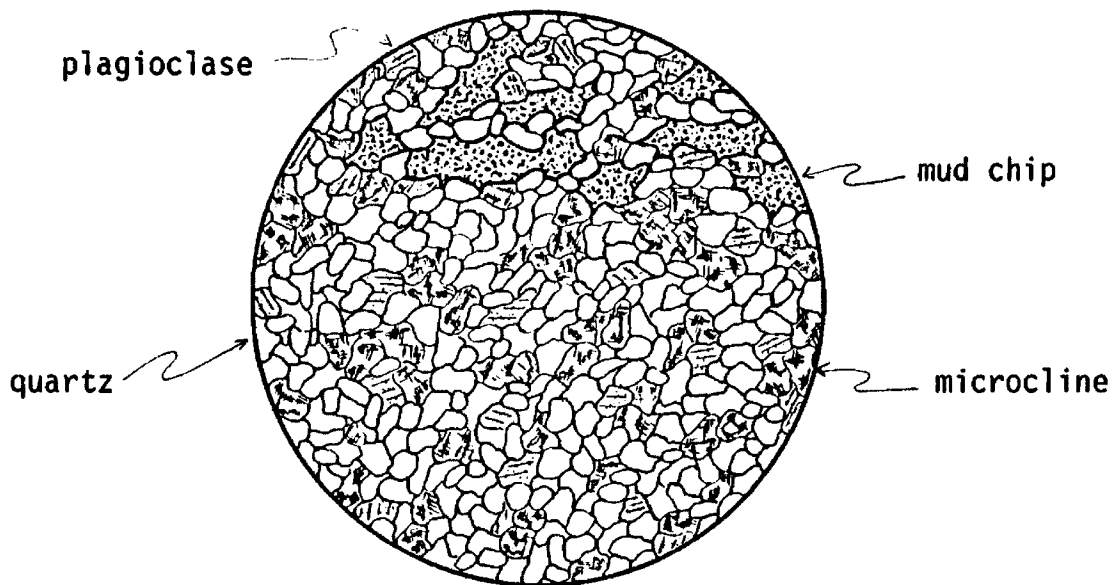


Fig. 3.18. (80X) Thin section sketch of a sample of the Missoula Group (chlorite zone). Incomplete recrystallization is evident from the sedimentary appearance of the sample. Sericitized mud chips have scalloped boundaries, and plagioclase and microcline are well twinned. Note preponderance of microcline over plagioclase. Sample taken at Skalkaho Pass. See text for discussion.

Excluding the mud chips the rock is composed of medium-sized, interlocking grains of quartz, plagioclase, and microcline (Fig. 3.18). Microcline comprises approximately twenty-five percent of the sample and plagioclase approximately ten percent. Preponderance of microcline over plagioclase is considered by Donald Winston (verbal comm., Apr., 1974) to be a valid criterion in the area for distinguishing rocks of the Missoula Group from rocks of the Ravalli Group.

Interlocking texture of the rock has not quite fully developed. Subround grains of quartz surrounded by sericite occur scattered throughout the sample as well as local interstitial sericite along interlocking grain boundaries. In thin section the breccia chips are seen to have been mildly squeezed through nearby grain interstices, producing scalloped mud-chip outlines. Small amounts of chlorite and absence of biotite suggest that the rock is in the chlorite zone of the greenschist facies.

Conditions of Regional Metamorphism

Metamorphic grade in the Skalkaho region ranges from the dolomite-quartz zone of the greenschist facies to at least the sillimanite-muscovite zone of the amphibolite facies, representing a wide range of temperature-pressure conditions during regional metamorphism. In the Belt Supergroup rocks of this area, a Precambrian burial metamorphism is generally accepted as having occurred (Fryklund, 1964; Reid and Greenwood, 1968; Norwick, 1972). Superimposed on the Precambrian metamorphism is a Cretaceous regional metamorphism which caused a higher degree of recrystallization. The later metamorphic event is associated with the emplacement of the Idaho batholith, though the metamorphism was pre-batholithic emplacement (Nold, 1968). It is believed that the metamorphic

rocks in the Skalkaho area were produced by the later metamorphic episode, and that the earlier lower-grade metamorphism has been obscured.

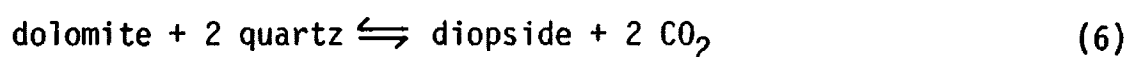
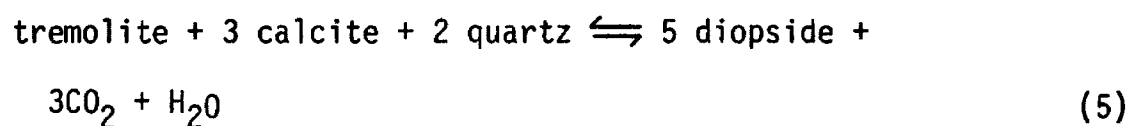
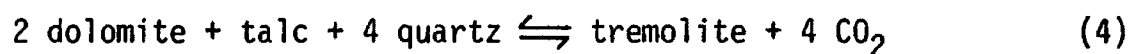
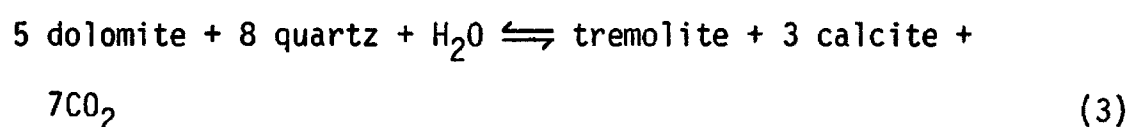
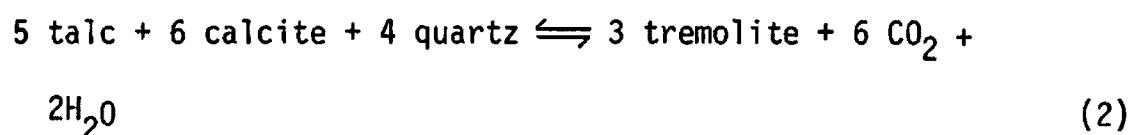
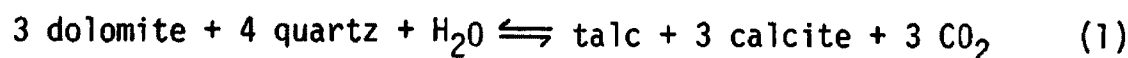
Much work has been done regarding progressive metamorphism of siliceous dolomites, some of the earliest being that of Bowen (1940). Bowen presented a set of fourteen reactions, each of which produces a new higher-temperature assemblage. Each of the reactions also liberates CO_2 into the fluid phase.

Since CO_2 is a volatile, its role is not fully understood. It may be totally confined after formation, completely vented, or maintained at some constant concentration. Although most metamorphic reactions are considered to take place in closed isochemical systems, in decarbonation reactions, the escape of CO_2 is almost a certainty. During decarbonation the increase of gas pressure continues until P_{fluid} is greater than P_{load} , at which time the confining rocks are fractured, releasing the excess pressure (Winkler, 1967).

Since the CO_2 thus formed shares the fluid phase with H_2O , the system has an additional component but the same number of phases. Consequently, the system has an additional degree of freedom in the form of mole fraction CO_2 (X_{CO_2}).

The importance of having X_{CO_2} as a degree of freedom becomes clear when the temperature of a particular reaction is sought. Even under isobaric conditions the reaction temperature depends directly upon X_{CO_2} (fluid phase = $X_{\text{CO}_2} + X_{\text{H}_2\text{O}}$). Since the amount of water present in the rock cannot be even reasonably estimated, X_{CO_2} is not known either. Consequently, identifying reaction temperatures may be impossible.

Based on observed mineral assemblages in both the high- and low-grade rocks, the following reactions considered by Winkler (1967), Metz and Winkler (1968), and Metz and Trommsdorff (1968) may have occurred in the Skalkaho area.



Graphical isobaric representations of these reactions are shown in Figs. 3.19 & 3.20. Of these reactions, only (1), (2), and (5) have been determined experimentally (solid curves). Reactions (3), (4), and (6) have been calculated. The stability field for each assemblage is itself divariant (i.e., two degrees of freedom) when the pressure is specified as it is in this case. Therefore, each reaction boundary or curve is univariant. However, some of the univariant curves must intersect each other at certain invariant points because of the nature of the products produced in the respective reactions.

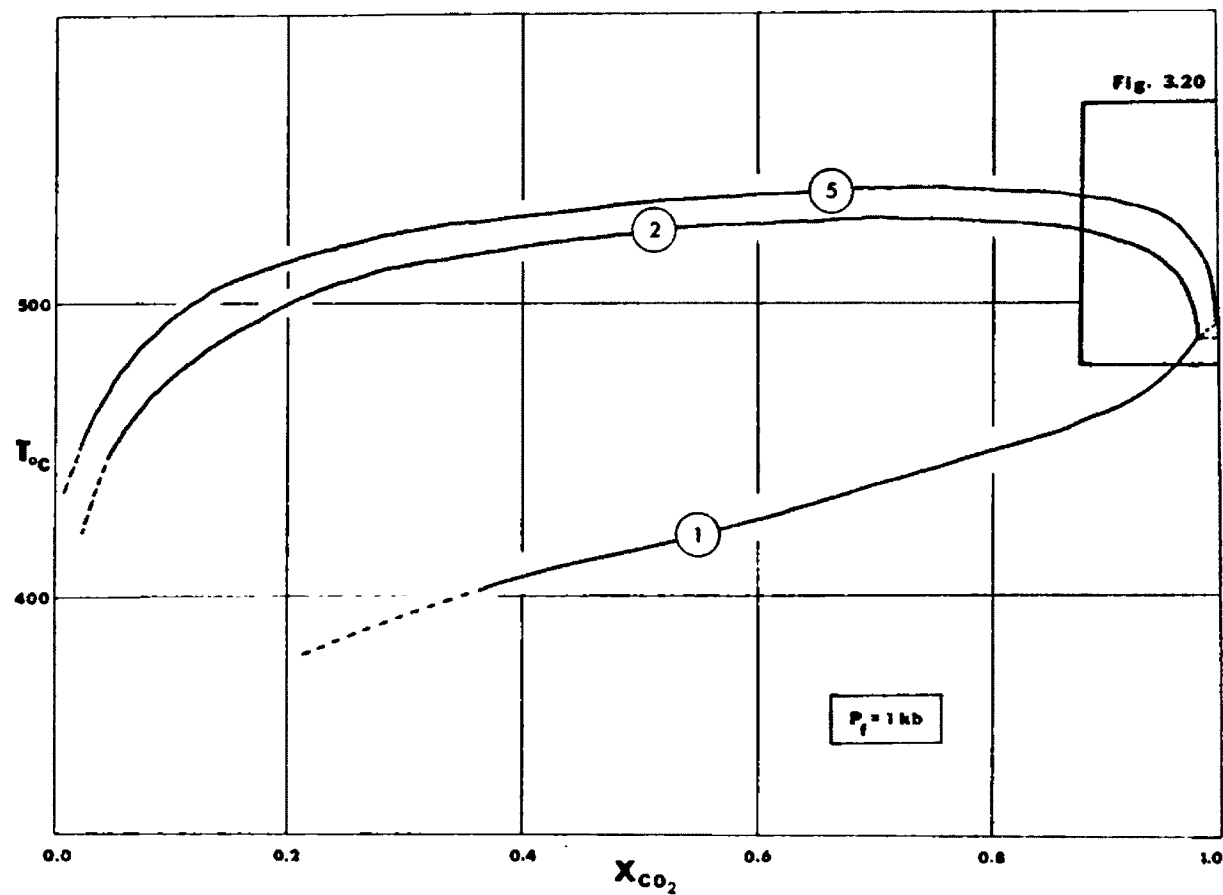


Fig. 3.19. Isobaric graphical representation of reactions 1, 2, and 5 as listed on page 49. Solid lines are experimentally determined; dashed lines are calculated. Boxed in portion on right side of diagram magnified as Figure 3.20 on page 51. Modified from Metz and Trommsdorff (1968).

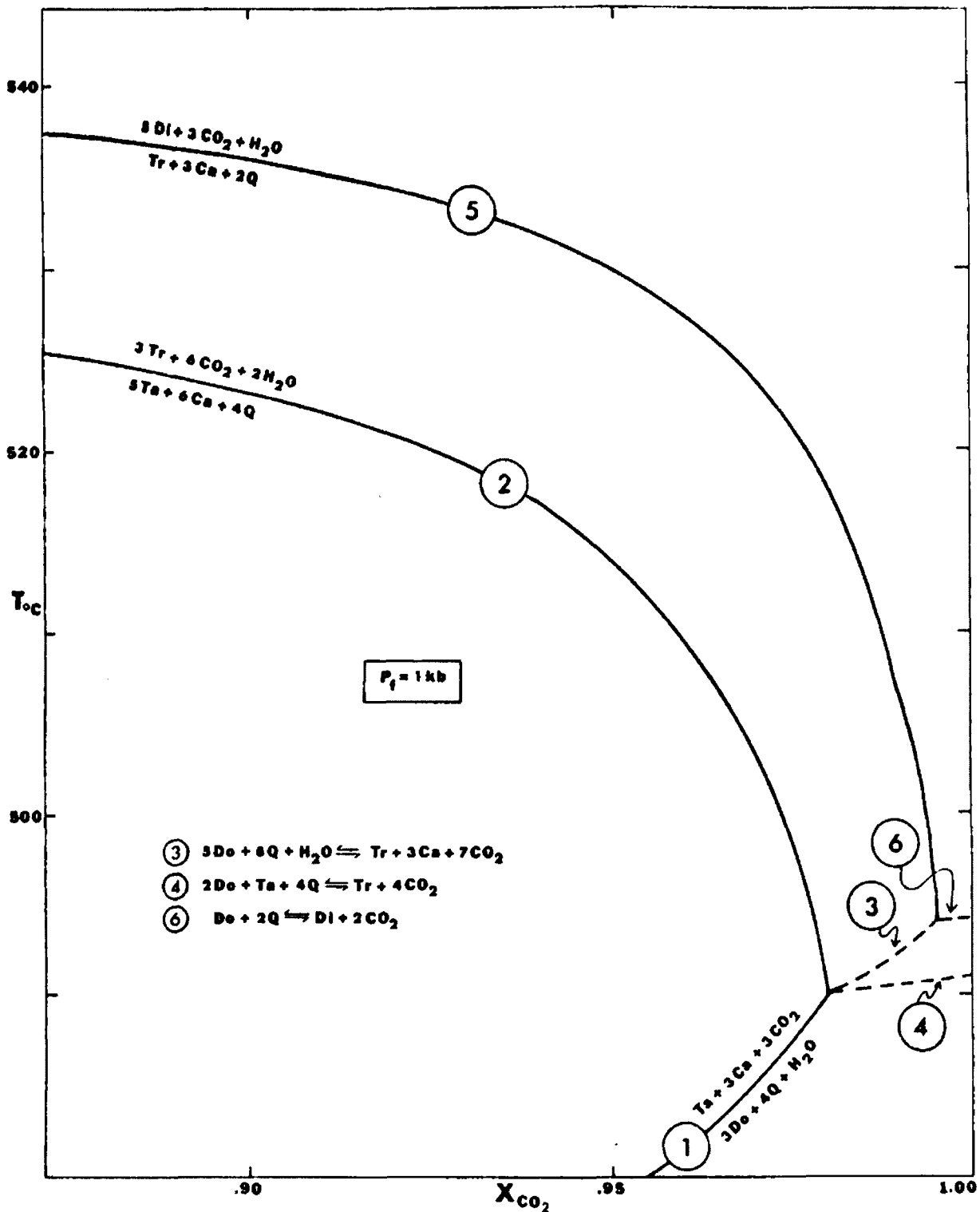


Fig. 3.20. Magnified view of boxed-in portion of Figure 3.19. Reactions 1 through 6 are all possible, but 1, 2, and 5 are most likely (see text). Ca = calcite, Di = diopside, Do = dolomite, Q = quartz, Ta = talc, Tr = tremolite/actionolite. Modified from Metz and Trommsdorff (1968).

These invariant points of intersection are important because they define unique points in space where several assemblages may appear in equilibrium. The position of a system with respect to one of these invariant points dictates which reactions should occur.

Reactions (3), (4), and (6) are much more restricted in their occurrence than are reactions (1), (2), and (5). A fluid phase of essentially all CO_2 would be required for reactions (3), (4), and (6) to occur. Though the possibility is not dismissed out-of-hand by the writer, absence of water in the rocks of the Skalkaho area is considered unlikely. The occurrence of hydrous phases in almost all lower-grade rocks and many higher-grade rocks as well, suggests that reactions (1), (2), and (5), not (3), (4), and (6) were responsible for producing the observed assemblages.

The initial step in the progressive metamorphism of the rocks may have been according to reaction (1), producing talc as a stable phase. However, talc is not a very common phase in metamorphosed siliceous dolomites in nature. The apparent reason is that with a small amount of Al_2O_3 or K_2O in the system, chlorite (Fawcett and Yoder, 1966) or phlogopite (Gordon and Greenwood, 1970) respectively, may be formed instead.

Except for sample L-8-21 (see Fig. 3.8), all samples containing talc also contain substantial amounts of phlogopite. It is suggested that the phlogopite may have been produced by the reaction (Gordon and Greenwood, 1970)



There is no occurrence of K-feldspar in the talc-bearing samples. It is suggested that the limited amount of K-feldspar relative to that of talc has allowed the persistence of the stable assemblage, talc + phlogopite. Several samples taken from the talc zone do not contain talc, but some contain phlogopite. This is consistent with the above considerations, representing the situation whereby sufficient K_2O was available for complete reaction with talc. Curiously, no phase with "excess" K_2O (e.g. orthoclase) is present in these samples.

Most of the tremolite/actinolite was apparently produced through reaction (2). As stated earlier, appeal to reaction (3) is acceptable, but implies highly restricted conditions. Neither talc nor dolomite was observed in tremolite-bearing rocks, suggesting that no matter which paths apply (reactions (2), (3), or (4) above), the reactions were all completed easily, producing a rather sharp reaction boundary (narrow reaction zone) in space.

Formation of diopside by way of reaction (6) is least likely of all above reactions. The fluid phase would have had to have been greater than 99 percent CO_2 . Additionally, no dolomite was seen in any diopside-bearing samples; whereas, many actinolite-diopside samples were studied.

It is no disappointment that it cannot be shown that the reactions which took place were those highly restricted. Although demonstration of such would greatly narrow the range of temperatures necessary to produce the new, higher-temperature assemblages, it would say nothing of the maximum temperature reached by rocks in the diopside zone. The widest temperature range between reactions (3), (4), and (6) is less than ten

degrees Centigrade, yet surely the most deeply buried rocks of the diopside zone were elevated to much higher temperatures than those nearer the surface.

Thin sections of rocks from the Willow Creek area were examined by this author to determine appropriate placement of zonal boundaries consistent with the interpretation of the metamorphic scheme in the Skalkaho area. Chlorite seen in the "biotite-chlorite zone" (Presley, 1970) was probably produced because of excess Al_2O_3 ; the phlogopite was produced because of excess K_2O . Therefore, these rocks apparently lie within the "talc zone" as delineated in the Skalkaho area. Three samples from the "biotite-chlorite zone" also contain tremolite, thus allowing definition of a very narrow "tremolite zone" as well.

Rocks from Presley's "quartz-biotite" stratigraphic unit in the northeast corner of the Willow Creek area were also re-examined. Of the five samples obtained, two contain tremolite and one possibly talc. Clearly this unit is a continuation of the greenschist rocks to the south and southeast, and the stratigraphic boundary mapped by Presley must in fact be a metamorphic zonal boundary (see Fig. 4.7).

Presley's interpretation of the geology in the extreme eastern part of the Willow Creek area was based on examination of relatively few samples from an extremely heterogeneous Wallace Formation. This writer is able to confidently reinterpret the metamorphic scheme in the Willow Creek area only because of close familiarity with similar rocks in the Skalkaho region.

Hietanen (1967) established a correlation between scapolite compositions and temperatures of formation. She concluded that scapolites

in central Idaho of the compositional range Me_{35} to Me_{65} were formed within the temperature range 300 to 600° C at a pressure range of 5000 to 5500 atmospheres. The range of reliable scapolite compositions in the Skalkaho area, Me_{21} to Me_{74} (Table 4.2), suggests a wide temperature range at those pressures. Reconciliation of the one-kilobar curves in Figure 3.19 with fluid pressures of five kilobars or greater (as in the Idaho rocks) is impossible at this time.

Contact Metamorphism

There is some evidence for contact metamorphism in the study area, though it is generally minor. Presley (1970) described contact metamorphic effects on the Wallace calc-silicates by the Willow Creek stock. He observed that samples taken near the margin of the intrusive contained larger crystals (some euhedral) of diopside, and/or well twinned plagioclase.

Similar manifestations of contact metamorphism were observed in the Skalkaho area, but not studied in detail. Several samples collected near the Skalkaho stock exhibited no contact metamorphic features, whereas others showed the same features described by Presley. Though scapolite composition may be affected by high temperature, scapolite from sample L-9-13, collected near the Skalkaho stock, does not appear to be anomalously calcic or sodic (see Chap. IV). This conclusion is to a degree a subjective judgment on the part of the author, because as noted earlier, high-grade regional metamorphism often appears in close proximity to igneous intrusives. Consequently, separation of the contact and regional effects is difficult at best. Sample L-9-13 also contains large

anhedral crystals of diopside as well as garnet, presumably grossularite-andradite. This is the only sample collected which contains garnet, (except for those taken from a small skarn described below). The occurrence of garnet suggests that the sample was affected at least to a minor degree by the Skalkaho stock, probably by an influx of calcium. Several samples collected near the Daly stock also contain coarse-grained diopside and/or well twinned plagioclase. Additionally, zoned scapolite and corroded scapolite occur in these samples, indicating unstable metamorphic conditions. Meionite contents in these rocks all appear anomalously low, indicating that the contact metamorphic effect produced by the Daly stock was to lower, not raise, the meionite content. Such an observation implies that the Daly stock must have supplied something other than just heat, perhaps a pneumatolitic introduction of Cl (see Chap. IV).

A small skarn was observed cropping out along the Skalkaho road at Newton Gulch (Fig. 2.1). Occurring with diopside, tremolite, calcite, and quartz are garnet and vesuvianite. The skarn is approximately one mile from the Skalkaho stock, the nearest exposed large intrusive, suggesting that the Wallace may be underlain at that location by a granitic body very near the surface. Many granitic dikes appear as far away from the main part of the Skalkaho stock as two miles, suggesting that the intrusive responsible for producing the skarn may be one of the larger dikes associated with the Skalkaho stock. A preferred explanation is that a larger granitic mass is in the process of being unroofed.

A small amount of para-amphibolite was observed as float near the western end of Daly stock. Large, very dark green to black, randomly

oriented hornblende crystals up to one centimeter in diameter comprise from fifty to ninety percent of the rock. Some metamorphic banding is present in the form of white plagioclase-quartz layers within the black amphibolite. The remainder of the mineralogy is primarily diopside and actinolite.

A few samples collected are amphibolite-calc-silicate composites. These samples reveal that the amphibolite was produced by metamorphosing to a high grade, calc-silicate xenoliths which had been caught up in the magma of the Daly stock. This is a common genesis of amphibolites (Hyndman, 1972; Turner, 1968).

In thin section the amphibolite-calc-silicate composite (L-4-8B) is seen to be composed of large euhedral crystals of pleochroic hornblende (Z = medium brownish green; X = greenish tan), and interstitial plagioclase, potassium feldspar, and quartz (Fig. 3.21a and b). Most of the hornblende crystals are crudely zoned, containing small cores and narrow rims that are more brown than the rest of the crystal. This probably represents an irregular influx of aluminum during growth. Many hornblende crystals contain inclusions of diopside, particularly those near the contact between amphibolite and calc-silicate. Secondary biotite appears growing along cleavage in the hornblende.

The calc-silicate portion of the sample is composed of medium-grained diopside, actinolite, plagioclase, quartz, scapolite¹, and locally tiny euhedral crystals of black hornblende. Additionally, the actinolite is locally hornblenditic, but primarily appears to be in the process of forming diopside (Fig. 3.21b). The plagioclase exhibits albite and periclase

¹The scapolite was very minor and not analyzed for Me content.

twins, and generally make up the matrix for both diopside and actinolite. Extinction of minor quartz is undulose. Accessories include sphene and zircon.

One specimen (L-7-16-1) was collected near a diabase intrusive. It contains a dark amphibole with Z = medium blue-green and X = light yellow. Clearly this amphibole was affected by the diabase, possibly by introducing additional Fe⁺⁺ into the country rock. This suspicion is supported by the fact that biotite in the sample is very dark with Z = deep brownish olive and X = light yellow. Additionally iron oxide opaques are numerous. Also possible is that the amphibole is nearing the composition of hornblende, but the extinction angle of 16° is apparently too low for hornblende. Biotite and amphibole define the schistosity which bends around subround scapolite porphyroblasts.

Cordierite was observed in one sample (L-8-2) of pelitic rocks of the Ravalli Group. It occurs as large poikiloblasts generally rimmed by an unidentified isotropic mineral. Pleochroic haloes around inclusions of sphene are striking. Epidote poikiloblasts distinguished by their high relief occur in the same sample. Chlorite is common, and a little chlorotoid was seen.

The mineral assemblage is cordierite (10%) + epidote (8%) + quartz (55%) + plagioclase (approx. An₁₅) (10%) + biotite (Z = pale greenish tan; X = very pale yellow) (15%) + chlorite (1%) + chlorotoid (tr). Accessories are sphene and tourmaline. The occurrence of cordierite suggests low pressures. The occurrence of epidote suggests some oxidized iron, thus a high oxygen fugacity.

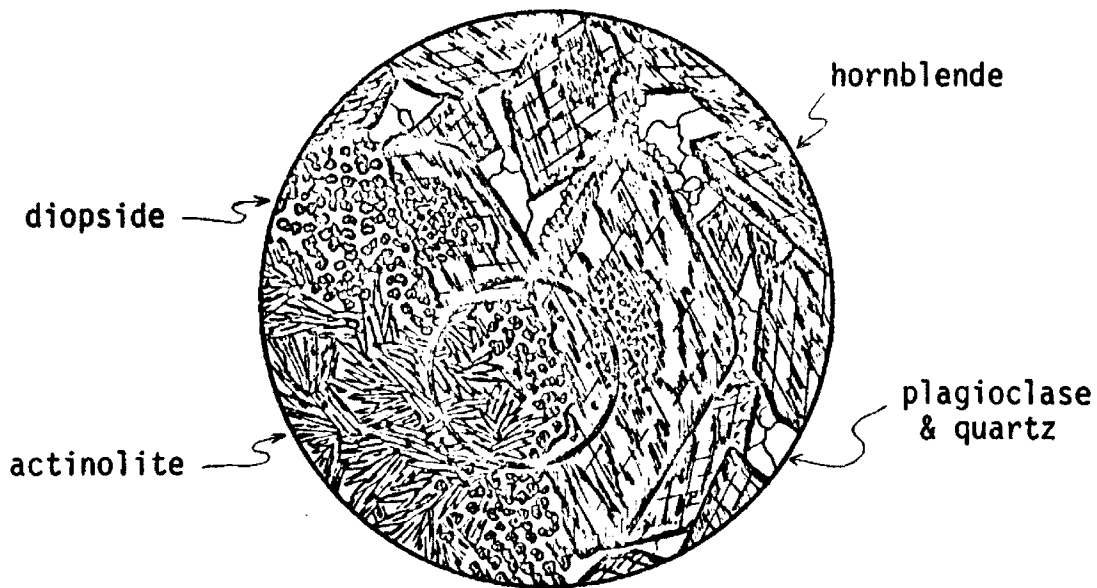


Fig. 3.21a. (10X) Thin section sketch of composite para-amphibolite-calc-silicate xenolith associated with the Daly stock. Coarse, zoned hornblende occurs with medium-grained diopside and actinolite. Sample taken 1 mile west of Gird Point at margin of Daly stock. Circled portion magnified as Figure 3.21b.

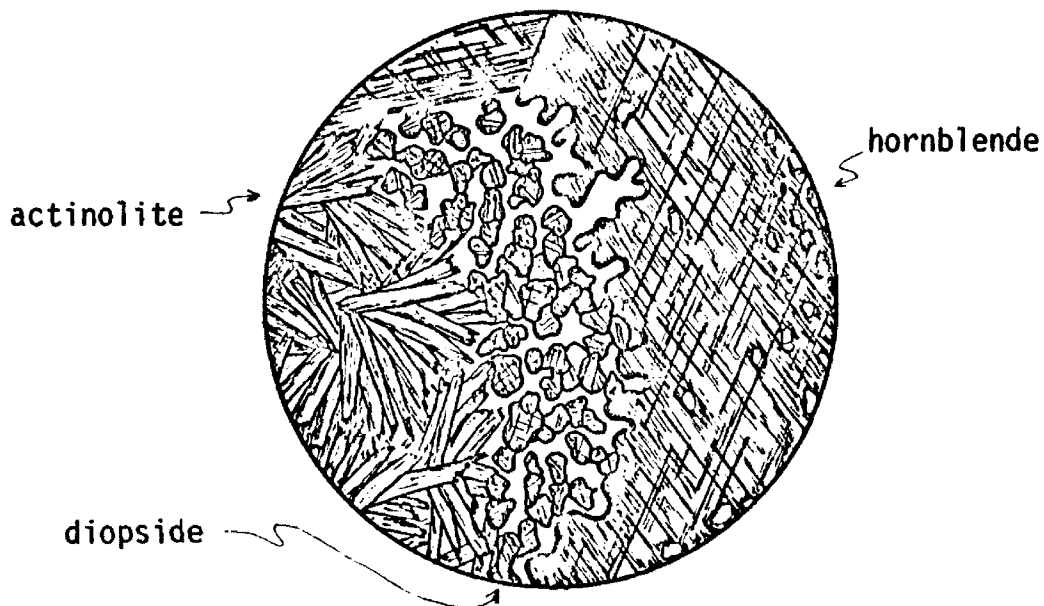


Fig. 3.21b. (80X) Magnified view of indicated portion of Figure 3.21a. Note the occurrence of two amphiboles and diopside in a zoned arrangement. See text for discussion.

CHAPTER IV

SCAPOLITE

Background

Compared to many other rock-forming minerals relatively little is known about scapolite. Much of the work done to date is sketchy, presumably because scapolite has been considered relatively unimportant. Some of the earliest workers were Judd (1889), Sundius (1915, 1916), Winchell (1924), and Barth (1927). Some of the more recent workers are White (1959), Shaw (1960), Hietanen (1967), Haughton (1971), Wehrenberg (1971), and Ulbrich (1973).

The contribution of Shaw (1960) is by far the most comprehensive, tying together all of the work accomplished up to 1960. Hietanen's paper showing the relationship between scapolite composition and metamorphic grade is a significant addition to the accumulated knowledge because it proves the utility of scapolite in solving larger geologic problems.

Scapolite is a member of the tetragonal crystal system and has a negative optic sign. Birefringence is low to moderate, and refractive indices are $\epsilon = 1.540$ to 1.562 , $\omega = 1.546$ to 1.600 . Scapolite is actually a solid solution series with the general formula $W_4Z_{12}O_{24} \cdot R$, where $W = Na, Ca, K$; and $Z = Si, Al$. For the end member marialite $R = Cl, F, HCO_3, HSO_4, OH$; and for the end member meionite $R = CO_3, SO_4, O_2, H_2, (Cl^-)_2, (F^-)_2$ (Shaw, 1960). Except for Cl and CO_3 most of the above components represented by R are minor, and it is sufficient to write

the end members as follows: marialite-- $3\text{NaAlSi}_3\text{O}_8 \cdot \text{NaCl}$; meionite-- $3\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot \text{CaCO}_3$.

The primary substitution which occurs in the solid solution is the same as that in feldspar, i.e., $\text{NaSi} \rightleftharpoons \text{CaAl}$. In natural minerals the end members do not exist, and scapolite compositions range from 14 to 92.7 percent meionite (Ulbrich, 1973).

Even some of the earliest work on scapolite was concerned with the effect of composition on optical properties. In 1927 Barth suggested that all of the optical properties are most dependent on the amount of calcium, sodium, and potassium present in the mineral, but noted that the birefringence can be affected by very high amounts of CO_2 . In 1915 Sundius showed that although each of the two refractive indices (ϵ and ω) varies systematically with a change in composition, the mean refractive index $\left(\frac{\epsilon + \omega}{2}\right)$ is more reliable than either of the single indices. Several years later Winchell (1924) showed that the variation in ω with respect to composition was linear. Since then it has been shown that the variation in the mean index with composition is also essentially linear (Shaw, 1960). Shaw also showed that birefringence varies with composition in a linear fashion. The latter relationship is not as reliable as refractive indices in determining composition because as was suggested by Sundius (1916), scapolite containing large amounts of K_2O , CO_2 , or H_2O may give spurious results.

Very recently Ulbrich (1973) has refined the linear relationship defined by Shaw between refractive indices and composition. Ulbrich suggests that the ω line is more reliable than that of either ϵ or

$\frac{\epsilon + \omega}{2}$ for "normal" (i.e., low in SO_4 , K, etc.) scapolites. His regression lines are the ones used in this study (Fig. 4.6).

Occurrence and Conditions Favoring Formation

Scapolite occurs in various types of metamorphic rocks all over the world. It has not been described in sedimentary rocks nor as a primary mineral in igneous rocks. Essentially restricted to metamorphic environments, it appears to be stable in every metamorphic facies from greenschist to sanidinite, but most common in the amphibolite (Shaw, 1960). It would seem then that scapolite should be much more common than it is; however, as Shaw points out, the composition of scapolite is somewhat exotic. Because even the most calcic scapolite contains some of the marialite molecule, its ability to grow depends in part upon the availability of chloride. The chloride would be a part of the fluid phase of the rock and therefore can be thought of as a partial pressure of Cl^- . A partial pressure of CO_2 is also necessary because even the most sodic scapolite found in nature contains some of the meionite molecule.

Depending upon the specific occurrence being considered, various sources for the Cl and CO_2 have been postulated. Judd (1889) noticed a scapolite-plagioclase intergrowth in a rock specimen and concluded that the scapolite was replacing the plagioclase. He based this on the observation that vacuoles in the feldspar contained Cl^- -rich fluid which reacted with the feldspar forming scapolite. Calkins (1909) also concluded that the Cl in scapolite found in aplite dikes of the Phillipsburg batholith in Montana was originally present in the rock in the form of assimilated limestone. Regionally metamorphosed rocks in

Milendella, Australia were believed by White (1959) to contain all the necessary ingredients for scapolite formation.

Other workers have appealed to the introduction of Cl from an outside source. Sundius (1915) prefers this origin to any other for the Kiruna rocks in Sweden, primarily because of the lack of other constituents in the original rock necessary for scapolite growth. Choudhuri and Banerji (1974) noted that scapolite in the Visakhapatnam district, India, was locally present only in areas of heavy pegmatitic activity, and concluded that metasomatic introduction of Cl^- and Na^+ was responsible for converting preexisting plagioclase to scapolite.

Scapolite in the Wallace formation of central Idaho and the Willow Creek basin of western Montana is interpreted by Hietanen (1967) and Presley (1970), respectively, to be a result of the availability of Cl and CO_2 in the original dolomitic sediments. Part of Hietanen's cogent argument is that with scapolite occurring on a regional scale, if the Cl had been introduced from an igneous source, one would expect to find scapolite concentrated near the intrusive. This spatial relationship is not found in central Idaho nor in the Willow Creek area. It seems reasonable to conclude that no matter the source of Cl, if it and CO_2 are available scapolite may be formed.

Scapolite does not always form, however, even under what would seem to be ideal conditions (Shaw, 1960). Fyfe, Turner, and Verhoogen (1958) attempted unsuccessfully to produce scapolite by cooking anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) in the presence of CaCO_3 and CaCl_2 at 400 - 700° C and at 500 bars H_2O pressure. Had the authors added Na to the system, the experiment may have been successful. Clearly the factors affecting the formation of scapolite have not all been recognized.

Relationship to Metamorphic Grade

The occurrence of scapolite in the Wallace Formation of central Idaho has been thoroughly studied by Hietanen (1967). The most significant feature of her study was the establishment of a correlation between composition of scapolite and metamorphic grade. Her findings are tabulated in Table 4.1.

Hietanen showed that scapolite found in the lowest-grade rocks (muscovite-biotite subfacies of the greenschist facies) had low percentages of meionite, ranging from Me_{33} to Me_{44} . In the next higher grade (biotite-almandine subfacies of the epidote-amphibolite facies) the range was Me_{32} to Me_{42} , also low. In the staurolite-kyanite subfacies the Me content was 39 to 51, representing a slight increase.¹ The kyanite-almandine subfacies exhibited a range of Me_{52} to Me_{58} , and the highest-grade rocks (sillimanite-muscovite subfacies) showed a range of Me_{62} to Me_{66} .

Hall (1968) and Nold (1968) also examined a little of the scapolite found in their respective study areas in western Montana. Nold noted that refractive index determinations on scapolites found in sillimanite- and lower-amphibolite-grade rocks yielded compositions of Me_{72} and Me_{52} respectively. Hall reported a composition of Me_{28} for scapolite found in rocks of the greenschist facies.

The overall trend appears to be real, but it is general and not apparent if restricted to lower-grade rocks. Hietanen established the trend with only twenty-five samples; therefore, the findings could hardly be called statistical. Intercalated pelitic rocks made approximate location

¹One sample of Me_{68} was collected near a small gabbro intrusive and was interpreted to have been influenced by that body.

Table 4.1 Scapolite determinations from central Idaho. Facies and subfacies determined primarily from pelitic rocks; meionite contents determined from mean refractive indices (N_m). Note the general increase in meionite content with increasing grade. See text for further discussion. (Modified from Hietanen, 1967, Table 8).

FACIES	SUBFACIES	SAMPLE	N_e	N_w	N_m	%Me	MEAN	RANGE
Greenschist	Muscovite- Biotite	105	1.546	1.567	1.556	43		
		107	1.543	1.560	1.551	33		
		84	1.544	1.563	1.5535	37		
		A-287	1.547	1.564	1.555	40	40	11
		A-38	1.547	1.565	1.556	42		
		121	1.547	1.567	1.557	44		
Epidote-Amphibolite	Biotite- Almandite	A-30	1.5426	1.560	1.551	32		
		A-282	1.543	1.561	1.552	34		
		1910	1.546	1.564	1.555	40	38	10
		1789	1.546	1.566	1.556	42		
		1915	1.547	1.565	1.556	42		
Epidote- Staur- ite- Kyanite	Kyanite	1917	1.545	1.564	1.555	39		
		1543	1.546	1.565	1.5555	41		
		1580	1.545	1.574	1.5605	51	44	12
		2073	1.556	1.583	1.569	68		
Amphibolite	Kyan- ite- Alman- dite	1260	1.547	1.575	1.561	52		
		1438	1.547	1.575	1.561	52	54	6
		1262	1.550	1.578	1.564	58		
	Sillimanite- Muscovite	1233	1.551	1.581	1.566	62		
		75	1.549	1.584	1.567	63		
		2152	1.551	1.582	1.5665	63		
		70	1.550	1.584	1.567	64	64	4
		424	1.551	1.583	1.567	64		
		11	1.552	1.584	1.568	66		
		351	1.551	1.585	1.568	66		

of metamorphic subfacies or zones fairly easy, yet in the lower-grade rocks which account for forty-four percent of the analyses, the scapolite-determined distinction between zones is nonexistent. Indeed the meionite content for scapolite in the greenschist facies is 1.8 percent higher than that for the higher-grade biotite-almandine subfacies. Beginning with the staurolite-kyanite subfacies the trend becomes slightly visible for the first time and increases through the highest-grade rocks.

In any one subfacies a measure of the inconsistency (or scatter) of the meionite contents within that subfacies can be determined by obtaining the range, that is, the difference between the highest and lowest value. Ranges determined for Hietanen's analyses are in Table 4.1 above. Clearly the higher-grade rocks reflect the highest consistency within any one subfacies. However, again the distinction is lost in the lower-grade rocks.

The purpose of the above discussion is to point out that in central Idaho the reliability of correlation between meionite content and metamorphic grade is directly related to increase in metamorphic grade. That is, the correlation should be much more reliable when applied to higher-grade rocks, and its extension into lower grades would be general. Attempted use of the correlation solely in lower grade rocks of central Idaho would be dangerous and pointless.

In 1961 Hietanen suggested that the temperature range of the metamorphism in central Idaho was from 300 to 600⁰ C, and the pressure range 5000 to 5500 atmospheres. Therefore, the scapolite composition range from approximately Me₃₅ to Me₆₅ corresponds to crystallization temperatures ranging from 300 to 600⁰ C, and scapolite with a composition greater

than Me_{65} should crystallize at temperatures greater than $600^{\circ} C$ (Hietanen, 1967).

Hietanen (1967) also examined the relationship of scapolite compositions to compositions of coexisting plagioclase. She found that scapolite is consistently displaced closer to the calcium end member than is the plagioclase. Turner and Verhoogen (1951) and Barth (1952) also showed this relationship to be present in rocks they examined. But Shaw (1960) examined eighteen coexisting pairs and found the relationship to be unreliable. Haughton (1971) examined forty-three pairs with the electromicroprobe and concluded that whereas scapolite in general is more calcium-rich than coexisting plagioclase, at high calcium contents plagioclase tends to be more calcic than coexisting scapolite.

The scapolite-plagioclase pair will need to be studied more extensively in the future. Presumably, there is a partitioning of calcium which controls their respective compositions (Haughton, 1971) which may prove useful as a geothermometer. Scapolite-plagioclase pairs occur in the Skalkaho region, but a study of these pairs is beyond the scope of this report.

Scapolite in the Skalkaho

General. The mode of occurrence of scapolite in the Skalkaho region is somewhat variable. In some samples the percentage of scapolite is as high as forty-seven percent, but in most of the samples collected scapolite is not present at all. This scarcity of scapolite is not seen in the Willow Creek area immediately north of the present study area. Although not emphasizing scapolite, Presley (1970) devoted some discussion to its occurrence because of its near ubiquity in the Willow Creek rocks.

Presley noted two modes of occurrence, euhedral to subhedral crystals and poikilitic balls. Some of the balls are up to five millimeters in diameter and all scapolite has overgrown the sedimentary layering. Meionite compositional range of the scapolite in the Willow Creek area was reported by Presley to be Me_{50} to Me_{75} . These values were determined by using the birefringence vs. meionite-content curve in Deer, Howie, and Zussman (1963). However, as noted above birefringence determinations are subject to substantial error. Refractive index determinations by this author on scapolites of the available Willow Creek rocks put the lower end of the range at least as low as Me_{27} . The most calcic Willow Creek scapolite examined by this author is only Me_{56} , but more calcic scapolite may exist in rocks not included in the University of Montana collection.

Although the modes of occurrence described by Presley are exhibited to a small degree in the Skalkaho region, occurrence of scapolite in the Skalkaho is highly irregular and generally much less well defined. Six general modes have been identified as follows: Large poikiloblasts of regular or irregular outline, medium-sized anhedral grains with or without numerous inclusions, lenticular aggregates of two or more grains, euhedral to subhedral medium-sized grains, compositionally-zoned anhedral grains, and scapolite-plagioclase intergrowths. Each of these modes is described in detail below.

Field description. Scapolite which occurs in the greenschist facies is generally visible on the outcrop. If the scapolite has had a chance to fully develop, it appears as euhedral tetragonal prisms scattered uniformly in a massive groundmass. More commonly, however, scapolite

appears as light-colored, medium-sized dots or spots in a darker ground-mass. Many of these rocks are foliated as described above in Chapter III. The scapolite is controlled by the foliation only to the extent that it occurs in the dark bands where plagioclase or albite is prevalent, and not in lighter calcite-rich bands.

The restriction thus represented suggests that the controlling factor in scapolite formation was either availability of the plagioclase component or availability of Cl. If it were the latter, the inference would be that the more-pelitic layers contained more Cl in the original sediments than did the more-calcareous layers. The author is not prepared to argue that such a layer-controlled distribution of Cl was present, except to suggest that perhaps the more-pelitic layers contained more water (presumably saline) than did the calcareous layers.

Unlike rocks of the greenschist facies, scapolite is generally not evident in hand specimen in rocks of the amphibolite facies. Examination of the Willow Creek rocks in the University of Montana collection has revealed that the same is true of many of those rocks.

Where dark green actinolite is a predominant constituent of the sample, the light-colored scapolite may be seen easily. But where light green diopside is predominant, the scapolite is hidden, particularly if it is not well formed.

There appears to be a general decrease in the amount of scapolite present from north to south within the Willow Creek-Skalkaho region. Presley (1970) states that scapolite is more conspicuous in the northern part of the Willow Creek area than in the southern part, even in hand specimen. Ease of recognition as well as abundance dies out toward the

south, and once into the Skalkaho region, scapolite becomes locally scarce to totally absent. No crystals or aggregates the size and purity of which were seen by this author in many of the Willow Creek rocks were found in the Skalkaho rocks. Clearly, conditions favorable to scapolite growth were much more prevalent to the north than to the south.

Petrography. Eighteen thin sections containing scapolite were examined in detail, ten from the amphibolite facies and eight from the greenschist. The six modes of occurrence mentioned above generally tend to cross facies boundaries; therefore, each mode is discussed separately below.

Five of the thin sections studied exhibited scapolite in the form of large, highly poikiloblastic grains (Fig. 4.1). In some cases, each poikiloblast is subround, two to three millimeters in diameter. These poikiloblasts tend to be isolated from each other by the groundmass. Other poikiloblasts are not necessarily round but locally abut neighboring poikiloblasts. This mode of occurrence is predominant in the amphibolite-grade calc-silicate gneisses. The scapolite is crudely confined to certain layers within the gneiss, and lack of subround habit is a direct result of growth being confined to individual layers. In more massive calc-silicates, the subround habit is common.

Scapolite in the form of balls or oblong (egg-shaped) grains is the most common mode of occurrence, having been observed in nine thin sections (Fig. 4.2). Some are subhedral, but to a minor degree only. Abundance of inclusions is variable and ranges from slight to extreme. Inclusions include feldspar, quartz, and calcite, and tend to be very fine grained.

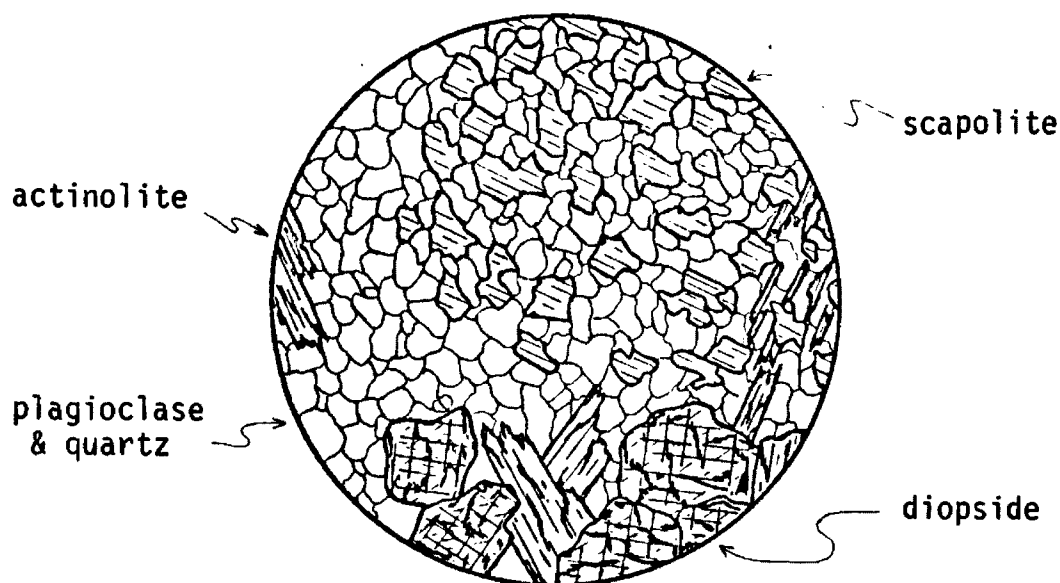


Fig. 4.1. (80X) Thin section sketch of a large poikiloblast of scapolite from the Skalkaho area. Sample taken 2 miles southwest of Buckhorn Saddle.

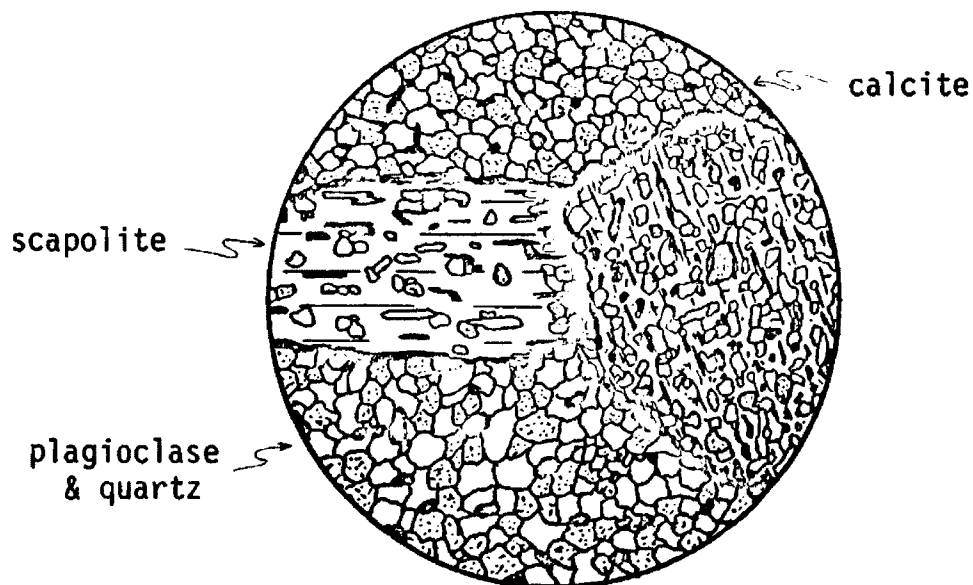


Fig. 4.2. (80X) Thin section sketch of medium-sized oblong poikiloblasts of scapolite. This mode of occurrence is the most common in the Skalkaho area. Inclusions are quartz and calcite, considerably smaller than their counterparts in the groundmass. Unidentified isotropic material lines poikiloblast boundaries. Sample taken 4¼ miles southeast of Buckhorn Saddle.

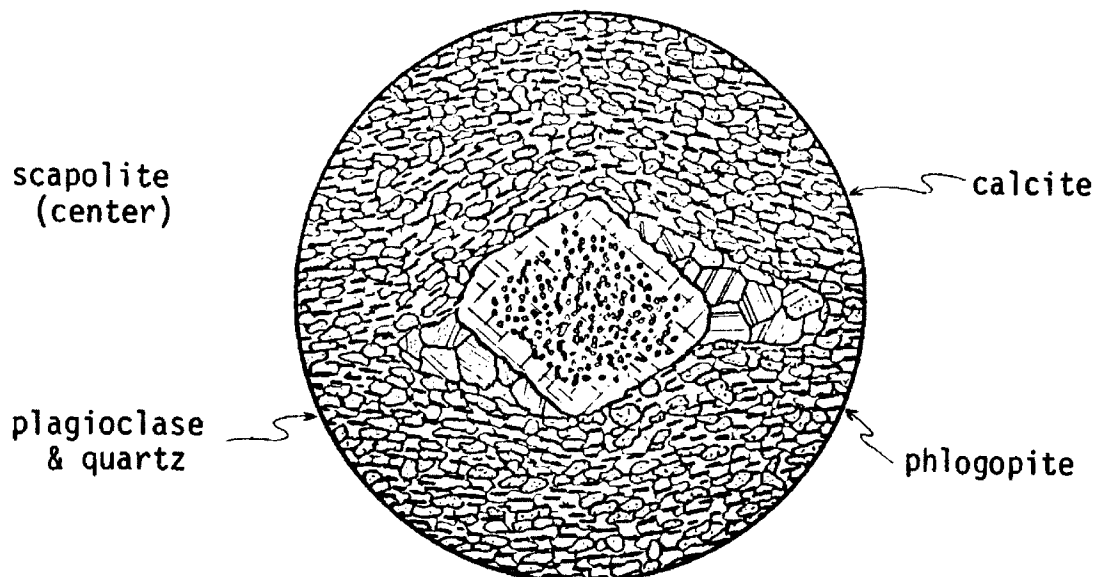


Fig. 4.3. (30X) Thin section sketch of a subhedral scapolite porphyroblast. Schistosity defined by phlogopite is bent around the porphyroblast which is moderately poikilitic. Calcite has grown in low-pressure "shadows" adjacent to the scapolite indicating that the scapolite is supporting the stress. Sample taken $1\frac{1}{2}$ miles northeast of Gird Point.

In contrast, inclusions in the large poikiloblastic balls mentioned above tend to be about the same size as the grains making up the groundmass. Two of the above nine specimens exhibited scapolite which is compositionally zoned and are discussed below.

In four of the thin sections scapolite was seen to have grown as euhedral to subhedral grains. In one of these specimens, it occurs as medium-sized porphyroblasts around which a foliation of phlogopite is wrapped (Fig. 4.3). Pressure shadows of calcite occur on both sides of the porphyroblasts, giving the scapolite-calcite aggregates crudely lenticular shapes. This textural evidence suggests that scapolite had begun to grow in the metamorphic process, prior to development of the foliation.

Scapolite in one sample occurs as lenticular multi-grain aggregates, enclosed within lenticular pods of actinolite in a groundmass of biotite, actinolite, and potassium feldspar. The composition of scapolite in this sample is Me_{74} , the most calcic found in the Skalkaho area.

Plagioclase-scapolite intergrowths were observed in two thin sections. In one sample (L-4-16) the intergrowths are such that the plagioclase-scapolite boundaries are indistinct upon close inspection (Fig. 4.4a). In some grains the intergrowths have a graphic appearance. Each grain is primarily scapolite (Me_{20}) with patchy plagioclase forming a pattern of subangular to "wormy" stringers throughout. A few grains in this sample have "clean" scapolite cores, surrounded by plagioclase-scapolite patchwork. This texture suggests that what was originally scapolite is being corroded and converted to plagioclase. Presley (1970), having observed similar textures in Willow Creek rocks, noted that the rocks were inside the contact metamorphic aureole of the Willow Creek stock. He concluded that heat from the stock was in the process of driving off volatiles of the scapolite, leaving plagioclase as the stable phase. This conclusion is reasonable if applied to the present sample which was collected in close proximity to the western end of the Daly stock in the Skalkaho area.

However, the scapolite (Me_{45}) in sample L-7-4-2 appears to be still growing. It occurs as poorly terminated strips or blades which encroach even into quartz grains. In some places, scapolite no bigger than thin needles is aligned parallel to larger blades of scapolite.

In other grains, a predominantly plagioclase grain is filled with subrectangular blocks and needles of scapolite (Fig. 4.4b). Along the margins of the scapolite blocks potassium feldspar "shadows" occur in

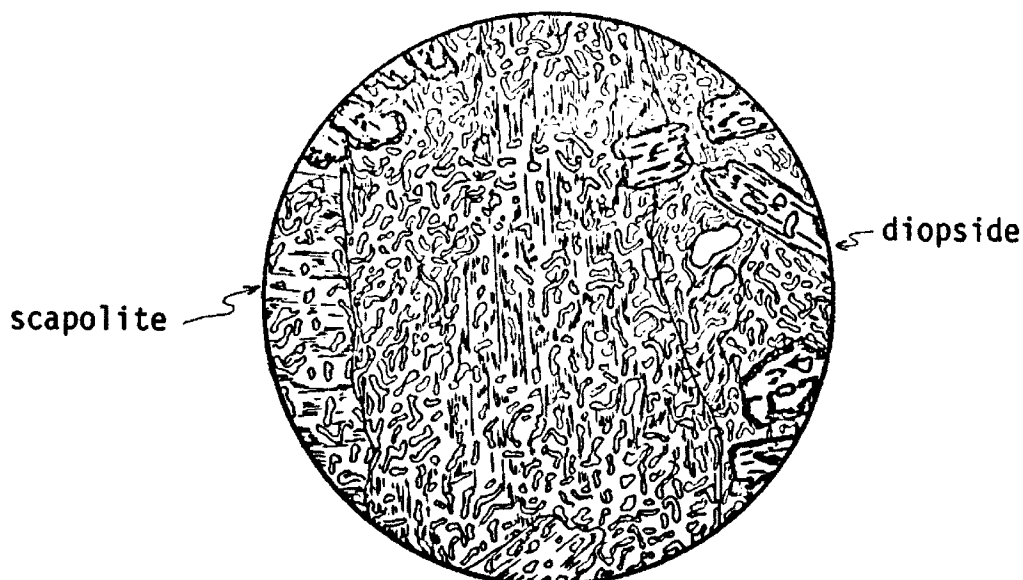


Fig. 4.4a. (80X) Thin section sketch of plagioclase replacing scapolite. Generally visible only under crossed nicols, poorly defined micrographic intergrowths of plagioclase occur mostly in wide rims around slightly "cleaner" cores of scapolite. Sample taken 1/10 mile west of Daly stock. See text for discussion.

the plagioclase. Unlike sample L-4-16, this specimen was not collected near the igneous rocks; therefore, a breakdown of scapolite due to an external heat source seems unlikely. If scapolite is indeed still growing, some source for Cl must be present. No such source was seen, and the scapolite growth cannot be explained by this author.

Replacement of plagioclase by scapolite has been described by Choudhuri and Banerji (1974). These authors observed the intergrowths at all stages of completion, describing a progressive growth of scapolite from the margins to the interior of preexisting plagioclase grains.

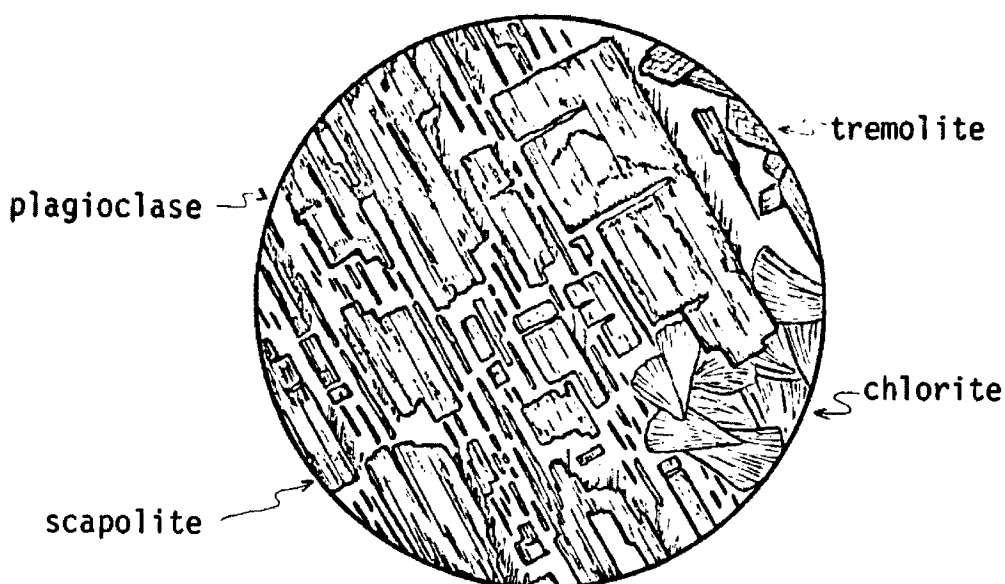


Fig. 4.4b. (80X) Thin section sketch of scapolite replacing plagioclase. Well-defined blocky and bladed scapolite appears to be growing inside a large plagioclase grain. "Shadows" of K-feldspar have developed in the plagioclase along some margins of scapolite. Actinolite and chlorite are also present. Sample taken 2/3 miles east-southeast of Buckhorn Saddle. See text for discussion.

Zoned scapolite. Two specimens of scapolite are compositionally zoned to such an extent as to be striking in thin section (see Fig. 4.5). Interference colors of the rims are dark gray to yellow, and the cores orange to blue, depending upon the orientation of the grain. A less distinct inner core is visible in a few grains.

Because of its zoned nature refractive indices were not determined on these scapolites. However, they were examined using an electron microprobe, and determined to be of the following composition:

<u>Sample</u>	<u>Rim</u>	<u>Outer core</u>	<u>Inner core</u>
L-4-14	Me ₂₇	Me ₄₂	Me ₅₂
L-8-7	Me ₃₈	Me ₅₆	Me ₅₃

Each zone was analyzed for Na, Al, Si, Ca, and K, and the percent meionite content was taken to be $\text{Ca} / (\text{Ca} + \text{Na} + \text{K})$.

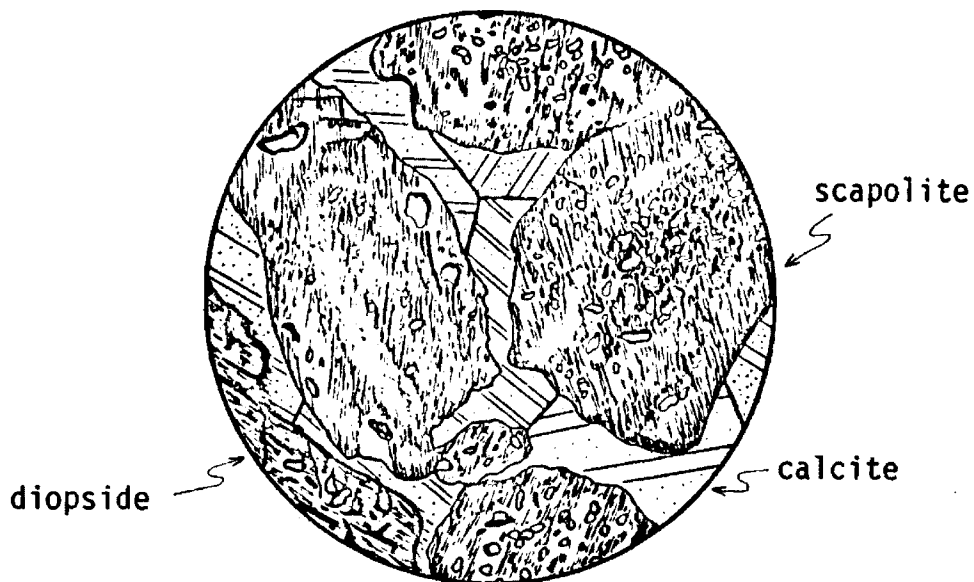


Fig. 4.5. (60X) Thin section sketch of "normal" compositional zoning in scapolite. Meionite content (calcic nature) of scapolite increases from rim to core. Inclusions are calcite and quartz. Sample taken 1/3 mile west of Daly stock. See text for discussion.

Some of all the outside cation substitutions that occur in scapolite, that by potassium is by far the most common, it was deemed important to determine the potassium content of the scapolites. In both cases potassium was minor, accounting for only 1.17% oxide weight in the most potassium-rich zone. As should be expected, the highest concentration of potassium was in the sodium-rich rims. Complete analyses are listed in the Appendix.

It should be noted that the most calcic part of each grain lies inside a more sodic rim. The rims are probably too wide to have been caused by retrogressive metamorphism, but may represent a sudden change in temperature and/or pressure during growth. Minerals which are visibly zoned commonly occur in igneous rocks where the temperature change during growth is from high to low. In metamorphic growth the temperature change is from low to high. However, if equilibrium is attained, no zoning occurs in either case.

In "normally" zoned igneous plagioclase the grain gets progressively more sodic from the center to the rim, a change which is generally attributed to lack of time for equilibration or sudden release in pressure. But zoned plagioclase in metamorphic rocks is usually "reversed" zoned, i.e., sodic cores and calcic rims. Since the calcic end member is the high-temperature end member in both plagioclase and scapolite, zoning in metamorphic scapolite should also be reversed.

According to Shaw (1960) only a few occurrences of zoned scapolite have been reported, one by Tomlinson (1943) in which scapolite occurred in an altered diabase in French Creek, Pennsylvania. However, zoning in this scapolite is reversed. Bernard Evans (verbal comm., Feb., 1974) did not seem surprised at the occurrence of normal zoning in the Skalkaho scapolite, but did not offer an explanation as to its formation.

In the presence of abundant calcium and sodium, the composition of scapolite is dependent upon the amount present of two highly volatile constituents, CO_2 and Cl. J. P. Wehrenberg (verbal comm., Mar., 1974) believes that since the composition of scapolite is highly delicate, zoned scapolite should be more common than it is. However, he believes that under the influence of an external heat source (e.g., an igneous intrusive) the Cl would be driven off more easily than the CO_2 , and the rims would be more calcic than the rest of the grain. Hietanen (1967, p. 35) applied the same reasoning when she attributed the anomalously high meionite content of one scapolite sample to the influence of a small gabbro intrusive.

Since both samples from the Skalkaho area exhibiting compositional zoning occur very near granitic intrusives, they were probably influenced by these intrusives. Perhaps a metasomatic introduction or remobilization

of Cl in the presence of abundant sodium caused the growth of more sodic rims.

A sudden venting of CO₂ in the fluid phase would cause the chemical potential of CO₂ to suddenly increase in the solid phase scapolite. An adjustment toward equilibrium would presumably result by the mineral releasing some of its CO₂ into the fluid phase. However, it is difficult to see why the Cl would not also be vented during this process.

Although it is beyond the scope of the present study, the zoning phenomenon in scapolite should be investigated more fully.

Significance of scapolite composition. Hietanen's (1967) correlation of scapolite composition with metamorphic grade is apparently the only such study to have been reported. As discussed above, the correlation appears to be crude, but present. To test its applicability to a different region, a similar study (though on a smaller scale) has been carried out in the Skalkaho-Willow Creek area of Montana.

The Skalkaho-Willow Creek region was chosen primarily because of its availability and access within an area of metamorphism associated with the Idaho batholith, but fortuitously the region is one in which several aspects of the scapolite problem may be examined. The assets afforded by the region are listed below:

(a) The region contains a sufficient amount of scapolite to make the undertaking feasible.

(b) The region is bounded on the west by granitic intrusives, presumably parts of the Idaho batholith.

(c) The structure in the region varies from very simple in the north to much more complex in the south and southeast.

(d) A wide range of metamorphism is exhibited, though cross-checking zonal or subfacies boundaries with pelitic assemblages is impossible.

(e) The study area is large enough to effectively eliminate distortion caused by topography.

Determination of meionite content of the scapolites was to have been through X-ray fluorescence; however, most of the scapolite collected was extremely poikilitic with material which would have produced incorrect results (e.g., plagioclase, calcite). Calcite-scapolite composite grains were common, particularly in the greenschist facies rocks. These could have been cleaned by treatment with acid, but it was feared that breakdown of the scapolite might occur, again yielding erroneous data. An electron microprobe was not readily available for all the analyses. It was concluded that the most straightforward method (and essentially the only method available) for determining the meionite content was through measurement of refractive indices.

Using Cargille immersion oils and sodium light, the refractive indices were determined on at least one (but commonly more than one) scapolite grain from each scapolite-bearing sample available. A portion of each sample was ground, sieved, and washed. The size fraction 100-120 mesh was found to be most suitable.

Many grains were composites of scapolite and another phase; consequently, an absolutely convincing match with the oil was not always possible. In such cases two to four grains from that sample were examined to insure accuracy within limits necessary to the study.

The oils are graduated in increments of 0.002 and can be measured to within 0.0001 on the refractometer. With possible judgment error substantially reduced through crosschecking of additional grains, the refractive indices reported here are considered accurate to within 0.001.

The refractive index vs. meionite content regression lines of Ulbrich (1973) were used in this study (Fig. 4.6). Ulbrich included not only the omega-index line, but also the mean-index line which may be used fairly confidently. The real error in Ulbrich's omega line is $\pm 5\%$; that of the mean line is $\pm 7\%$. However, relative values for Me content read from these lines is not affected by the position of the lines, and only slightly affected by small slope changes. Thus, when applied to the omega line, an index value accurate to 0.001 allows determination of relative Me values accurate to one and one-half percent meionite.

In this study the mean line was used only as an internal confidence check on the meionite value arrived at through use of the omega line. In most cases the meionite value obtained using the mean line was identical to or varied by one percent from that obtained using the omega line. One difference as high as four percent was recorded, but checks on an additional grain indicated that the variance was real. In all cases the omega index was used for final determination of meionite content.

Refractive indices measured and corresponding meionite values are listed in Table 4.2. A clear increase in meionite content from the talc zone, through the tremolite zone, through the amphibolite facies can be

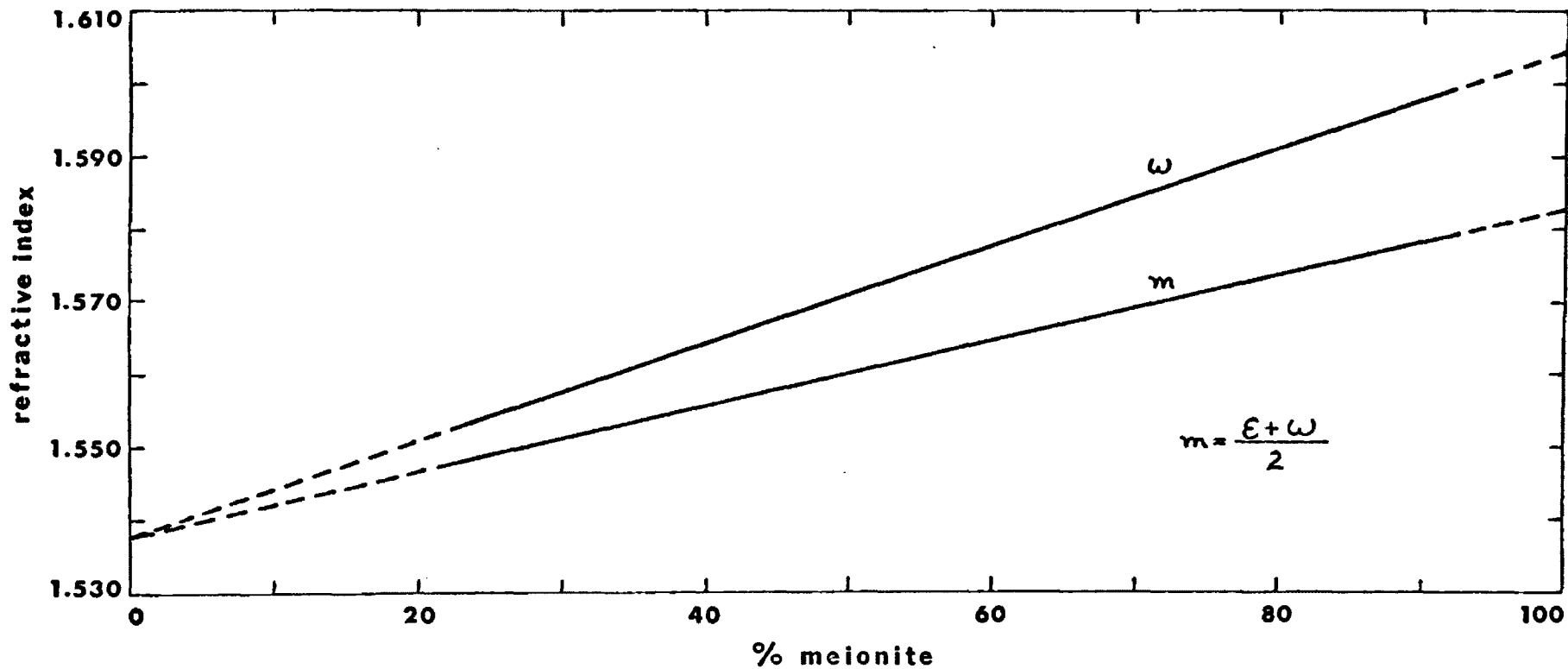


Fig. 4.6. Relationship of scapolite refractive indices to percent meionite. Both omega and mean indices vary directly in linear fashion with meionite content. Omega-index line is considered more reliable for "normal" scapolites. Dashed portions of lines are extensions unsupported by experiment (after Ulbrich, 1973).

seen, though the inability to delineate mineralogical zones within the amphibolite facies produces a wide spread of values within the facies.

Because the samples were collected within the contact metamorphic aureoles of intrusives, some of the low values in the amphibolite facies are considered anomalous, and are so identified in Table 4.2. The special nature of these anomalous scapolites (e.g., zoned) is discussed above.

All scapolite values not considered anomalous are interpreted to be reflections of regional metamorphic conditions under which the scapolite was formed. They have been plotted on a map of the region in the locations where the samples were collected (Fig. 4.7). Contours connecting points of equal meionite content have been drawn superimposed on the geology of the area. Several general observations can be made:

(a) There is a general decrease in meionite content from west to east.

(b) In the lower part of the map there is a general decrease in meionite content from south to north.

(c) The contours are roughly parallel to the amphibolite-greenschist boundary.

Wehrenberg (1967), Chase (1973), and others have postulated that the Sapphire Range slid east off the "frontal zone gneiss" of the east flank of the Bitterroot Range during emplacement of the Idaho batholith. Small granitic plutons such as the Skalkaho and Willow Creek stocks are generally presumed to be associated with the Idaho batholith, having been displaced to the east through sliding. Since the Idaho batholith forms the axis of the regional metamorphic belt in this region, metamorphic grade of the surrounding rocks falls off with distance from the batholith.

Fig. 4.7. Meionite-contours and metamorphic zonal boundaries superimposed on geologic map of Skalkaho-Willow Creek area. Data for numbered locations are in Table 4.2. Note rough concentricity of (a) contours, (b) greenschist facies-amphibolite facies boundary, and (c) contact of the Wallace with the Ravalli and Skalkaho and Willow Creek stocks. Metamorphic zones shown are Di = diopside, Tr = tremolite, Ta = talc, and Do-Q = dolomite-quartz. WCS = Willow Creek stock, h-s = hornblende-syenite; other geologic symbols shown in Fig. 2.1, p. 3a. (Willow Creek area geology modified from Presley, 1970, 1973).

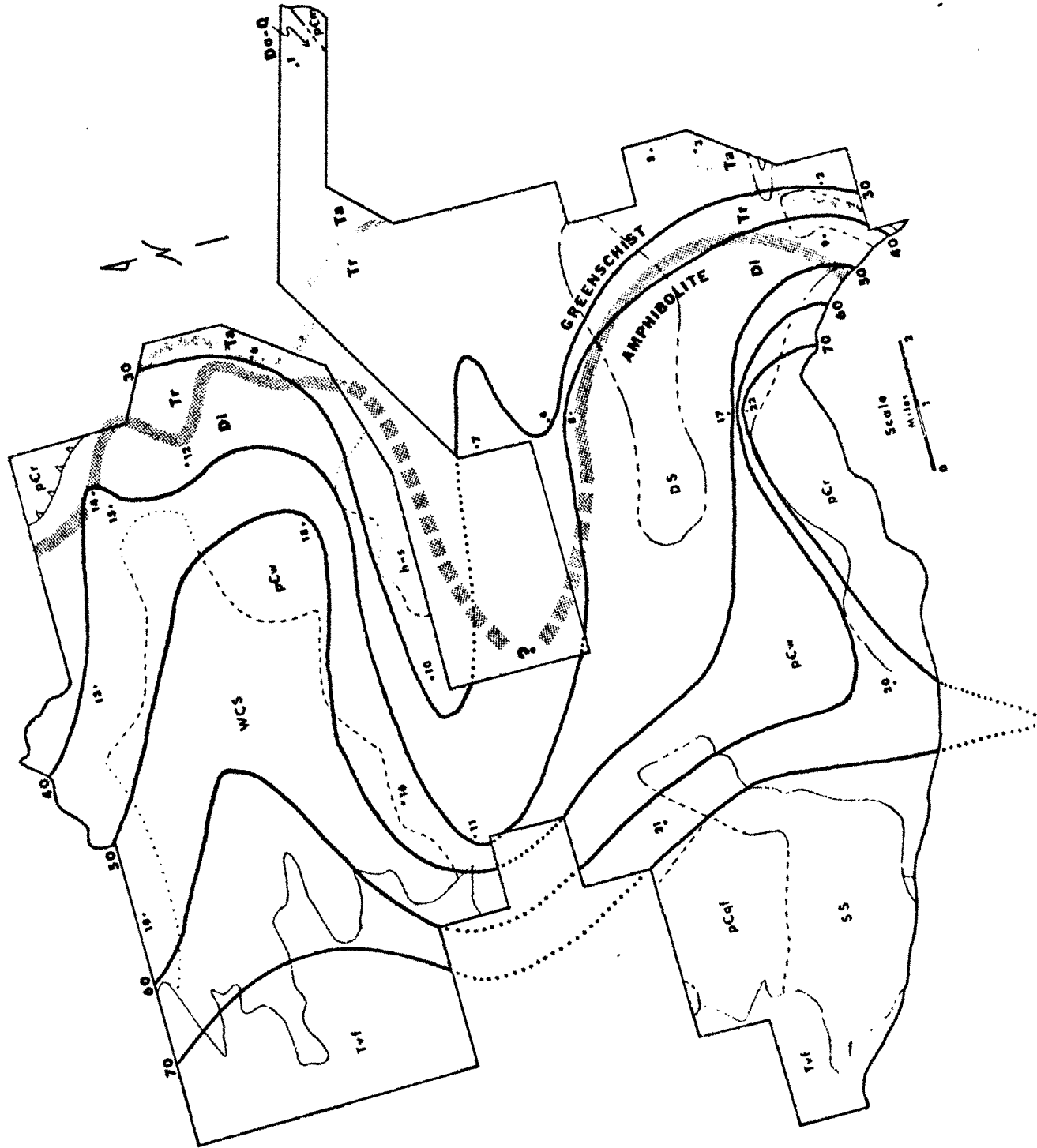


Fig. A.7

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Table 4.2 Scapolite determinations from Skalkaho-Willow Creek area. Facies and zones determined from calcareous mineral assemblages; meionite contents determined from omega refractive indices (N_ω). Map nos. refer to numbers plotted in Figure 4.7. Meionite values in parentheses are unreliable as regional metamorphic indicators (see text); therefore, they are not plotted in Figure 4.7.

FACIES	ZONE	MAP NO.	SAMPLE	N_ϵ	N_ω	N_m	% Me	MEAN	RANGE	
Greenschist	Talc	1	L-6-28	1.545	1.553	1.549	23	24.5	4	
		2	L-8-8	1.544	1.554	1.549	24			
		3	L-8-18	1.545	1.554	1.550	24			
		4	L-7-18	1.542	1.556	1.549	27			
	Tremolite			L-8-7				(38-56)		
		5	L-8-19	1.543	1.552	1.548	21	34	24	
		6	WC15-6	1.547	1.557	1.552	29			
		7	L-7-24	1.547	1.562	1.555	36			
		8	L-7-16-1	1.545	1.565	1.555	41			
9	L-8-4	1.545	1.568	1.557	45					
Amphibolite	Diopside		L-4-16	1.539	1.551	1.545	(20)	48	47	
			L-4-14				(27-52)			
			L-4-18	1.546	1.556	1.551	(27)			
			L-8-13	1.543	1.556	1.550	(27)			
		10	WC9-6	1.543	1.556	1.550	27			
		11	WC9-1	1.544	1.562	1.553	36			
		12	WC15-1	1.547	1.563	1.555	38			
		13	WC12-5	1.547	1.565	1.556	41			
		14	WC13-6b	1.548	1.565	1.557	41			
		15	WC13-7	1.544	1.565	1.555	41			
		16	WC21-4	1.545	1.567	1.560	44			
		17	L-7-4-2	1.548	1.568	1.558	45			
		18	WC18-4	1.545	1.572	1.559	52			
19	WC17-1	1.553	1.575	1.564	56					
20	L-1-10	1.555	1.579	1.567	62					
21	L-9-13	1.552	1.581	1.567	65					
22	L-7-3-2	1.556	1.587	1.572	74					

Meionite values of scapolite in the Skalkaho-Willow Creek area generally fall off with increasing distance from the Skalkaho and Willow Creek stocks.

The deep westward protrusion of the contours in the center of the map is consistent with the westward protrusion of the eastern margin of the granite which likely is continuous below the deep valley fill.

In the Willow Creek area, the contours reveal a simple pattern of metamorphism. Presley (1970) concluded that the underlying structure of this area is a simple, broad, openly-folded syncline into which the Willow Creek stock has intruded. Simple patterns of regional metamorphism seem consistent with simple structure.

In the Skalkaho region much of the structure could not be easily worked out due to its complexity and lack of outcrop continuity. However, bedding attitudes plotted in the western and southwestern portions of the area reveal the structure to be a large plunging anticline (see Chapter II). The Ravalli Group which lies stratigraphically below the Wallace Formation, comprises the core of the anticline. In conformable contact with the Ravalli is the lower Wallace, that is, that portion of the Wallace buried deepest during the accumulation of sediments. If degree of metamorphism undergone by buried sediments is indeed directly related to the depth of burial (Norwick, 1972) then this portion of the Wallace should have been metamorphosed more than all other Wallace rocks in the area. Occurrence in the lower Wallace of some of the most calcic scapolite in the region suggests that this is the case.

Although the study area did not extend south of Skalkaho Creek, in the western part of the area calc-silicate gneisses of the Wallace crop

out south of the creek at least for a short distance southward. However, no calc-silicates were observed cropping out along Sleeping Child Creek which lies only two and one-half to three miles south of Skalkaho Creek. Some high-grade pelitic schists and gneisses were observed along Sleeping Child Creek, but most of the exposed rocks are granitic. It is reasonable to assume that within two to three miles south of Skalkaho Creek in this area, the Wallace pinches out, and Ravalli rocks are impinged upon by the granite. Consistent with this conclusion, the meionite contours also pinch out southward in this area.

In the southeastern corner of the area, the structure is more complex. This author was unable to decipher the structural picture with the data available, and placement of the meionite contours is subject to question. It does seem, however, that the structural deformation there is local; consequently, it may not seriously affect the regional picture.

Superimposed on the meionite contours in Figure 4.7 are the zonal boundaries between the talc, tremolite, and diopside zones. The fit of the facies boundary with the meionite contours is not precise, but an approximate parallelism is obvious. Considering that placement of the normal zonal boundaries was arrived at through a totally different procedure from placement of the contours, the correlation must surely be real.

It is noteworthy that whereas Hietanen's study established a very good correlation between metamorphic grade and meionite content in higher-grade rocks (discussed above), the present study establishes a fairly good correlation in lower-grade rocks. Had good control of metamorphic zones within the amphibolite facies been available, the results of the study may have been even more convincing.

Speculation. The utility of meionite content as an indicator of metamorphic grade seems now to be certain. Although it is probably impossible at this time to suggest strict placement of zonal boundaries based on Me content alone, the amphibolite-greenschist boundary seems to lie in the vicinity of Me₃₀ to Me₄₅. Further work will perhaps make strict placement feasible.

Interestingly, the meionite contours appear to reveal simple structure at least to minor degree. For example, if one had accepted the correlation between meionite content and metamorphic grade as a starting assumption in the Skalkaho region, he would have necessarily been led to the conclusion that the Ravalli forms the nose of a plunging anticline.

CHAPTER V

SUMMARY

Three major units of the Belt Supergroup, the Ravalli Group, Wallace Formation, and Missoula Group, are exposed in the Skalkaho area. The region is characterized as regional metamorphic terrane, intruded by two granitic stocks, the Skalkaho stock and Daly stock. Numerous other minor igneous bodies, diabase dikes, carbonatites, felsic volcanics, and granitic dikes, occur in the area as well.

Rocks of the Ravalli Group (oldest) have been metamorphosed to sillimanite grade; those of the Missoula Group (youngest) are in the chlorite zone. The Wallace Formation which is intermediate in age exhibits the widest variation in lithology, mineralogy, and metamorphic grade. A potassium-rich quartzofeldspathic unit lying below the Wallace may be part of the Ravalli Group, but is considered separately.

The Ravalli Group is massive quartzofeldspathic rock with a preponderance of plagioclase over K-feldspar. The K-rich quartzofeldspathic unit is a high-grade gneiss, generally characterized by a large amount of sillimanite occurring in pods with muscovite and quartz. The Missoula Group is a low-grade quartzofeldspathic rock characterized by presence of chlorite and much microcline.

The predominantly calcareous Wallace Formation was studied in greatest detail. Based on examination of fifty-five thin sections the following four metamorphic zones, in order of increasing metamorphic

grade, were identified: dolomite-quartz zone, talc zone, tremolite zone, and diopside zone.

Only one thin section from the dolomite-quartz zone was examined, but the apparently stable assemblage dolomite + quartz suggests that the metamorphic grade was less than that necessary to produce diopside, tremolite, or even talc.

In the talc zone, talc was identified petrographically. Attempts at verification with X-ray diffraction analysis were unsuccessful because of the scarcity of the mineral. A few samples contain no talc, but the occurrence of phlogopite suggests an excess of K_2O having reacted with talc at this grade to form the mica. One sample apparently on the dolomite-quartz-talc reaction boundary was examined. Here talc occurs primarily along decaying boundaries of idioblastic dolomite, in contact with quartz and calcite.

Numerous samples from the tremolite zone, in which tremolite/actinolite is the stable calc-silicate phase, were examined. The occurrence of the amphibole in grain-to-grain contact with quartz and calcite and the absence of diopside indicate that the grade is lower than that needed to produce diopside. The amphibole occurs as either aggregates of fibrous to needle-like crystals or broader, bladed prisms.

The diopside zone (amphibolite facies) is the highest grade and of the greatest areal extent in the study area. Generally, diopside is present, but some samples contain actinolite as the stable calc-silicate phase, although not in the presence of calcite. Apparently actinolite persists into higher grades provided that no calcite or quartz is available for reaction. Much diopside appears to be forming from

actinolite, in which case both calc-silicate phases appear in the same sample in intimate association with each other. This reaction-zone assemblage is quite common in the Skalkaho area, and suggests that the reaction is sluggish.

Scapolites occurring in several of the Skalkaho samples and samples from the Willow Creek area to the north were analyzed for meionite-endmember content using refractive-index methods. These meionite values were scrutinized, and those which were seemingly influenced by factors other than regional metamorphism (e.g. contact metamorphism) were noted. The reliable values were plotted on the reconnaissance geologic map and contoured. The contour pattern is roughly concentric with margins of the Skalkaho and Willow Creek stocks (presumably parts of the Idaho batholith) and consistent with a plunging anticline in the southern part of the study area, suggesting that the meionite values are controlled by the same factors which produced the regional metamorphism.

Plotted on the same map, the tremolite-diopside zonal boundary appears to be generally concentric with the contour pattern of the meionite values, strengthening the argument that both are results of the same process, regional metamorphism. It is concluded that in the absence of pelitic index minerals, the areal layout of the metamorphism in a calc-silicate terrane can be closely approximated using meionite content of scapolite.

The following sequence of events appears to fit the observed geology of the Skalkaho area. Deep burial of the sedimentary pile during Precambrian time produced a low-grade metamorphism, probably no higher than greenschist facies. During Cretaceous time, a higher-grade regional

metamorphism, spatially associated with the Idaho batholith, was superimposed on the earlier burial episode. The latter metamorphic event generally obscured the earlier by exceeding it in intensity and producing a foliation associated with the intense folding of the rocks. The regional metamorphic episode is probably responsible for formation of the presently observed scapolite. Later during Tertiary time the Idaho batholith and associated stocks intruded the overlying meta-sediments, probably further deforming the rocks, and locally superimposing narrow, contact metamorphic aureoles. Subsidence of tectonic activity made way for extensive erosion of the new mountains, eventually exposing the granites. The common occurrence of large fragments of Belt rocks "floating" in the Skalkaho stock and the occurrence of characteristically contact-metamorphic features (e.g., skarn) far from any exposed intrusive, suggest that parts of the intrusive complex are just now being unroofed in the Skalkaho region.

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APPENDIX

Modal Analyses of Two Zoned Scapolites as Accomplished with the Electron Microprobe, Department of Geological Sciences, University of Washington, Seattle, Washington, January, 1974.

SAMPLE L-4-14

Zone	Element	Oxide WT	Element WT	% Me*
RIM	Na	11.18	8.29	
	Al	21.43	11.34	
	Si	59.84	27.98	27%
	K	1.17	.97	
	Ca	4.55	3.25	
	Total	98.16	51.83	
OUTER CORE	Na	8.70	6.45	
	Al	21.24	11.24	
	Si	59.70	27.91	42%
	K	.79	.66	
	Ca	6.94	4.96	
	Total	97.37	51.22	
INNER CORE	Na	7.99	5.93	
	Al	23.55	12.46	
	Si	53.44	24.98	52%
	K	.67	.55	
	Ca	9.67	6.91	
	Total	95.31	50.83	

$$*\% \text{ Me} = \frac{\text{Ca}}{\text{Ca} + \text{Na} + \text{K}}$$

APPENDIX (continued)

SAMPLE L-8-7				
Zone	Element	Oxide WT	Element WT	% Me*
RIM	Na	10.05	7.46	
	Al	22.10	11.69	
	Si	57.28	26.78	38%
	K	1.00	.83	
	Ca	6.81	4.87	
	Total		97.23	51.62
OUTER CORE	Na	7.88	5.85	
	Al	24.51	12.97	
	Si	53.86	25.18	56%
	K	.66	.55	
	Ca	10.86	7.76	
	Total		97.77	52.31
INNER CORE	Na	6.11	4.53	
	Al	17.61	9.32	
	Si	66.79	31.23	53%
	K	.49	.40	
	Ca	7.49	5.36	
	Total		98.49	50.84

Samples were prepared by polishing with $\frac{1}{2}$ micron grit, then carbon coating in the normal manner. Accelerating velocity was 15 KEV, sample current was 0.02 MA, and beam width was 10 microns. Standards used were Na - albite standard, K and Si - orthoclase 1 standard, and Ca and Al - anorthite glass standard, all of the University of Washington collection.

Raw data obtained were processed through computer program UWPROBE; the resulting data were then processed through an empirical correction program BAEDER. Results are listed in the table above.

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