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Igneous and metamorphic geology of the Willow Creek drainage basin southern Sapphire Mountains Montana

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IGNEOUS AND METAMORPHIC GEOLOGY OF THE WILLOW CREEK DRAINAGE BASIN, SOUTHERN SAPPHIRE MOUNTAINS, MONTANA

by

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I. Introduction

Scope and Purpose

This report is a study of the igneous and metamorphic petrology of the Willow Creek drainage basin in the Southern Sapphire Mountains, Montana, (Fig. 1). It includes:

(1) the mapping of the lithologic units,

(2) the determination of compositional variations within the Willow Creek stock, a granite body in the center of the Willow Creek area, and

(3) the description of metamorphic assemblages along with the mapping of isograds.

A major problem in working with batholithic granites is separating the purely regional metamorphic events from deep seated contact metamorphic events. If one assumes that the granite melts form in the highest grade portions of regional metamorphic terrains, the magma will intrude into lower grade rocks and cut across the regional isograds; contact metamorphism surrounding the granitic intrusions will thus be superimposed on the regional metamorphism. This can occur in a wide range of pressure conditions, shallow intrusions forming typical low pressure, hornfels-like contact metamorphism, whereas deeper intrusions will develop coarser-grained, higher-pressure contact aureoles.

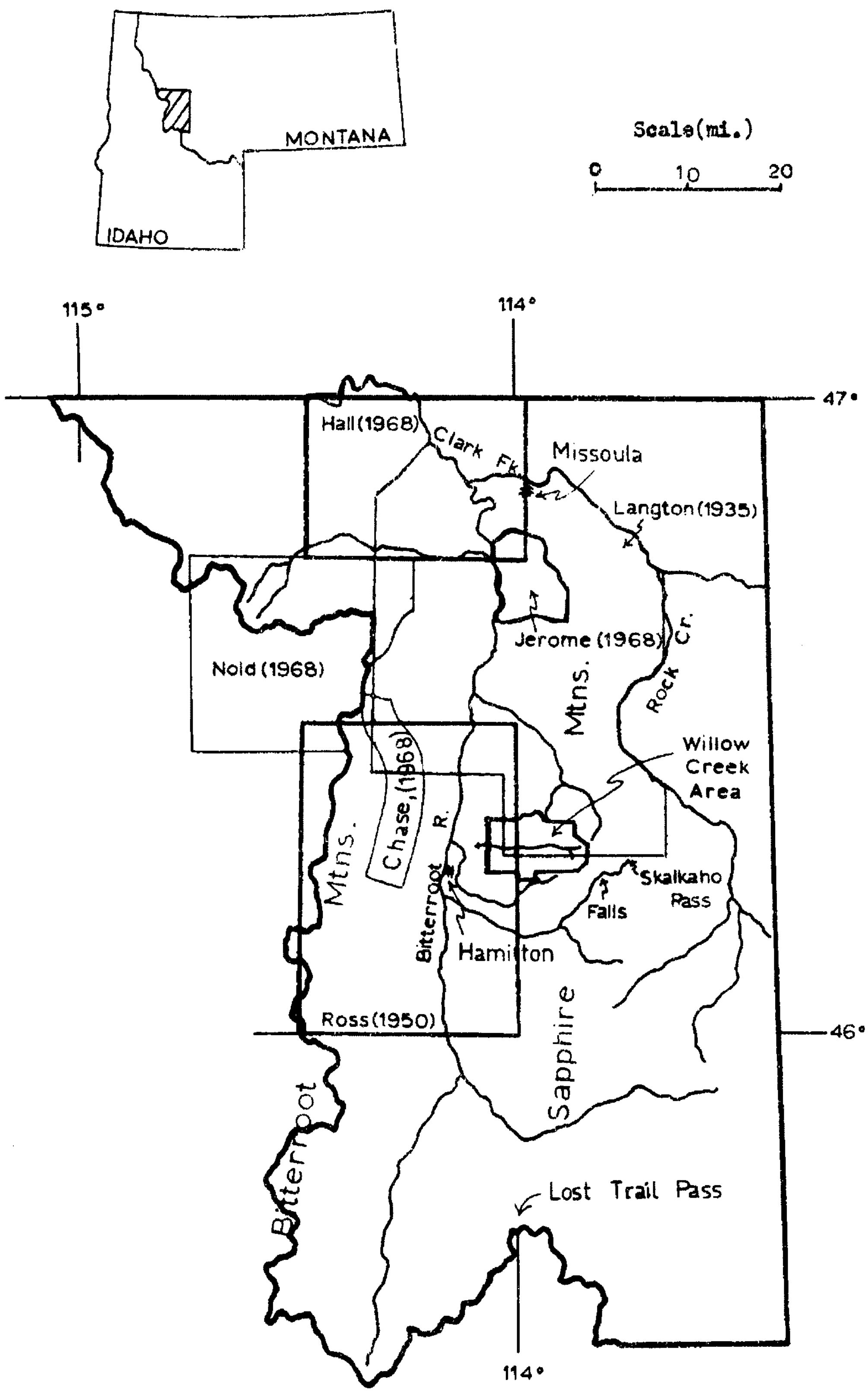


Figure 1. Index map showing Bitterroot Valley in western Montana. Areas of previous work are shown and labeled by author.

This research shows that the Willow Creek stock has been intruded into amphibolite grade regional metamorphic rocks under moderate to high pressures, and has superimposed a coarse-grained, high pressure aureole on the country rocks.

Previous Work (Refer to Fig. 1)

The first mapping to include part of the Willow Creek area was done by Langton (1935), who mapped the Sapphire Mountains north of Willow Creek. His work excluded the southern half of the Willow Creek drainage. Ross (1950) mapped the far western edge of the Willow Creek area as part of the Hamilton 30' Quadrangle. Stewart Ness (1968) outlined the general nature of the Willow Creek stock and the surrounding metamorphics in a senior paper at the University of Montana.

This paper is the first detailed work on the metamorphic and igneous environment in the Willow Creek area. Nold (1968) mapped zones of the amphibolite and greenschist facies in the Lolo Pass area of the northern Bitterroot Mountains, approximately 30-40 miles northeast of Willow Creek. Hall (1968) continued the biotite zone of the greenschist facies into the northern Sapphire Mountains east of Lolo, Montana. Hall's isograds extended into Jerome's (1968) area in the Sapphire Mountains between Miller Creek and Eight-Mile Creek. The metamorphism has not been studied between Hall's area and Willow Creek.

II. General Relationships

Willow Creek drains westward out of the Sapphire Mountains into the Bitterroot Valley of western Montana (Fig. 1). The area defined by the Willow Creek drainage was chosen for this mapping because (1) it has structurally simple metamorphic rocks overlying a small stock, with well defined intrusive and metamorphic relationships, and (2) it lies in the eastern border zone of the Idaho batholith, in which little detailed work has been done. Statements relevant to the Willow Creek area will aid in the study of the batholith as a whole.

Granitic rocks of the Idaho batholith proper outcrop approximately 10 miles westward, across the Bitterroot Valley, in the Bitterroot Mountains (Fig. 1). The Sapphire Mountains on the eastern side of the Bitterroot Valley are buttressed with granitic rocks from the area of Willow Creek, south to the area southwest of Lost Trail Pass, where the Sapphire Mountains merge with the Bitterroot Mountains, and the Sapphire granites connect with the Idaho batholith.

The structure of the Bitterroot Valley itself has been discussed in several papers. The front of the Bitterroot Mountains is exceptionally linear. Pelitic gneisses, which form a narrow border to the Idaho batholith, underlie this front, and gneissic layers tend to parallel this frontal lineation. This alignment is thought to be fault controlled, either as a normal fault (Lindgren, 1904) or as a zone of gravity sliding off of an uplifted Idaho batholith block (Wehrenberg, 1967). As an alternative, Ross (1950) suggested that the gneisses had simply been pushed aside and domed by the batholith, without the necessity of a fault.

The Sapphire Mountains are not aligned to form a linear front and there is no faulting or shearing parallel to the Bitterroot Valley in the area north of Willow Creek, so there are no major indications of a fault zone along the eastern side of this valley. But the Sapphire Mountains do appear to form an uplifted block, with the structural and stratigraphic trends ending abruptly against the valley.

The total Willow Creek basin covers approximately 45 square miles, an area which is oval shaped toward the east and cut off on the west by Tertiary and Pleistocene deposits filling the Bitterroot Valley. Willow Creek drains to the west to join the Bitterroot River. The valley deposits were mapped by McMurtney and Konizeski (1956) and are not covered in this report. Total relief in the area is 4000-5000 feet, the highest mountains being 7500-8500 feet in elevation.

Approximately 17 square miles of the central portion of the Willow Creek area is underlain by a granite to granodiorite stock containing muscovite and biotite. The granite crops out in the central valley area and on a pediment surface extending westward from the mountain front. It is deeply weathered and can be separated by a sharp break in slope from the metamorphics underlying the higher mountains to the east.

The metamorphic rocks are a thick sequence of calc-silicate rocks, structurally above and in sharp contact with the granite. They are metamorphosed to greenschist grade in the southeastern part of the area, increasing to lower amphibolite grade in the west. A contact aureole extending up to several hundred meters past the granite contact is superimposed on the regional metamorphic rocks.

III. Structure

The only mesoscopic structural feature within the calc-silicate unit is compositional layering. These rocks are thinly-layered throughout, with beds up to 5 cm. thick. There is no cleavage or foliation observable in hand specimen. In thin-section C-axes of quartz are commonly aligned to show preferred orientation with ε (epsilon) perpendicular to the layering. Amphilboles often show preferred orientation parallel to the layering.

Close to the granite contact and confined to the contact zone, blocks of metamorphic rocks appear to have been shifted and small scale faulting can be observed.

Little evidence for folding is found on the outcrop scale. At two places north of the granite contact, small warps were found with a wave length of one-half meter, confined to several layers within the outcrop. One is in the contact zone of a diabase dike, the other close to the granite contact. Layering within a single outcrop is generally continuous. Changes in orientation of compositional layering can be observed between outcrops, but direct evidence for folding causing these changes is lacking.

The macroscopic structure of the area can best be described as a broad synclinal warp with opposite limbs of the syncline on opposite sides of the granite contact (Figs. 2 and 3). The axis of this warp strikes approximately NE-SW. Dips of compositional layering are quite shallow, averaging 20-35 degrees and in most cases not greater than 45 degrees. A contoured equal area plot of poles to compositional layers is shown in Figure 4. This defines a small circle.

A small circle distribution on a stereographic plot implies conical shaped folds, that is, folds resulting from doming and sagging, or the refolding of previous concentric-style folds. Cylindrically shaped folds would form a great circle distribution. The small circle shown in Figure 4 could indicate that the warping in the Willow Creek area is due to sagging over the magma chamber.

Burnside and Steele (1970) found that bedding data taken from Langton (1935) showed a well defined small circle for the area of the Sapphire Mountains north of Willow Creek.

In the northeastern part of the area, Precambrian Ravalli formation is thrust above the calc-silicate unit. This thrust and others to the northeast were mapped by Langton (1935). They are part of a larger regional structural trend, of eastward-dipping thrust faults in the Sapphire Mountains. These regional structures are not part of the subject matter of this thesis, and this fault will not be considered in detail.

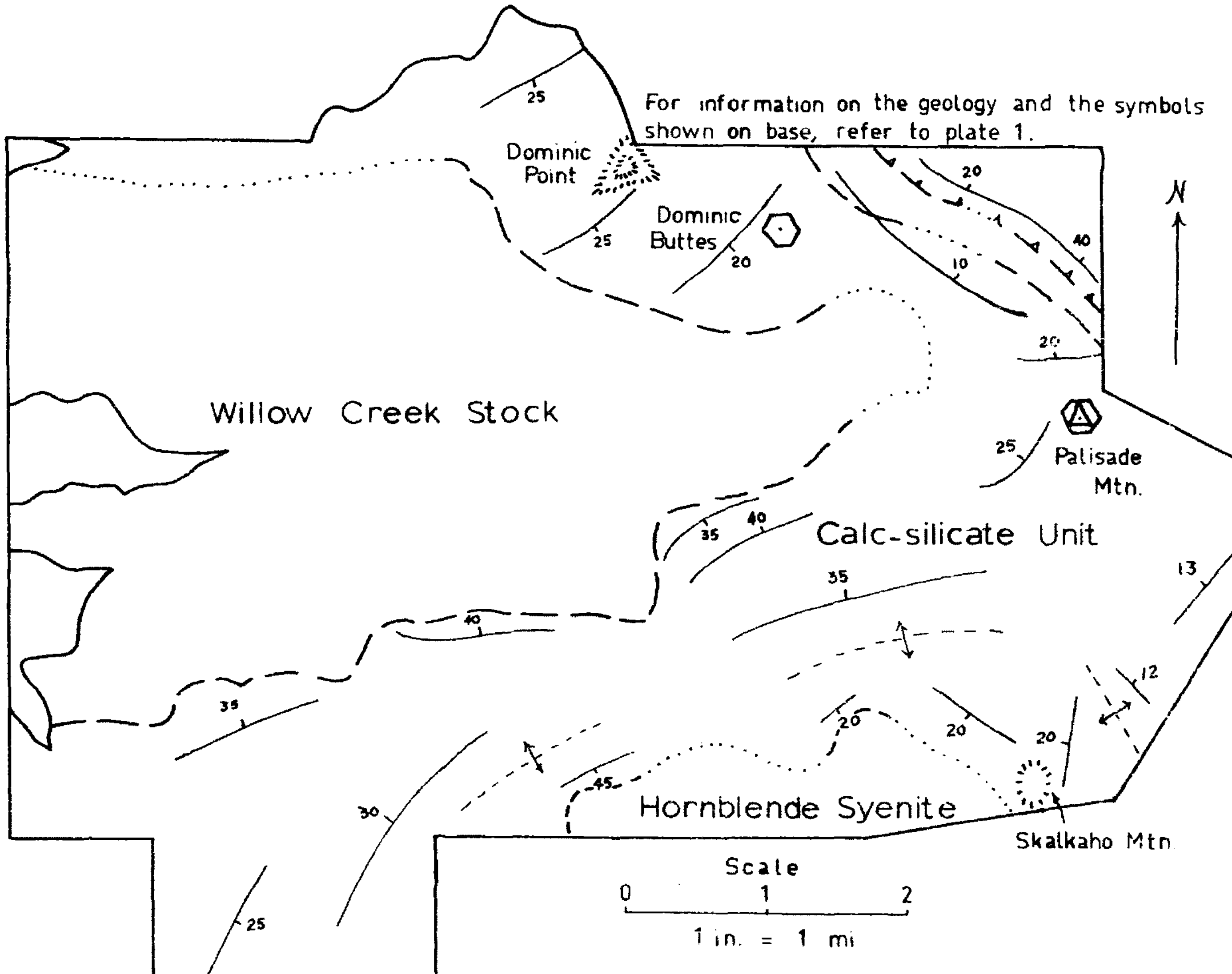


Figure 2. Generalized dips of compositional layers within metamorphic units of the Willow Creek Area.

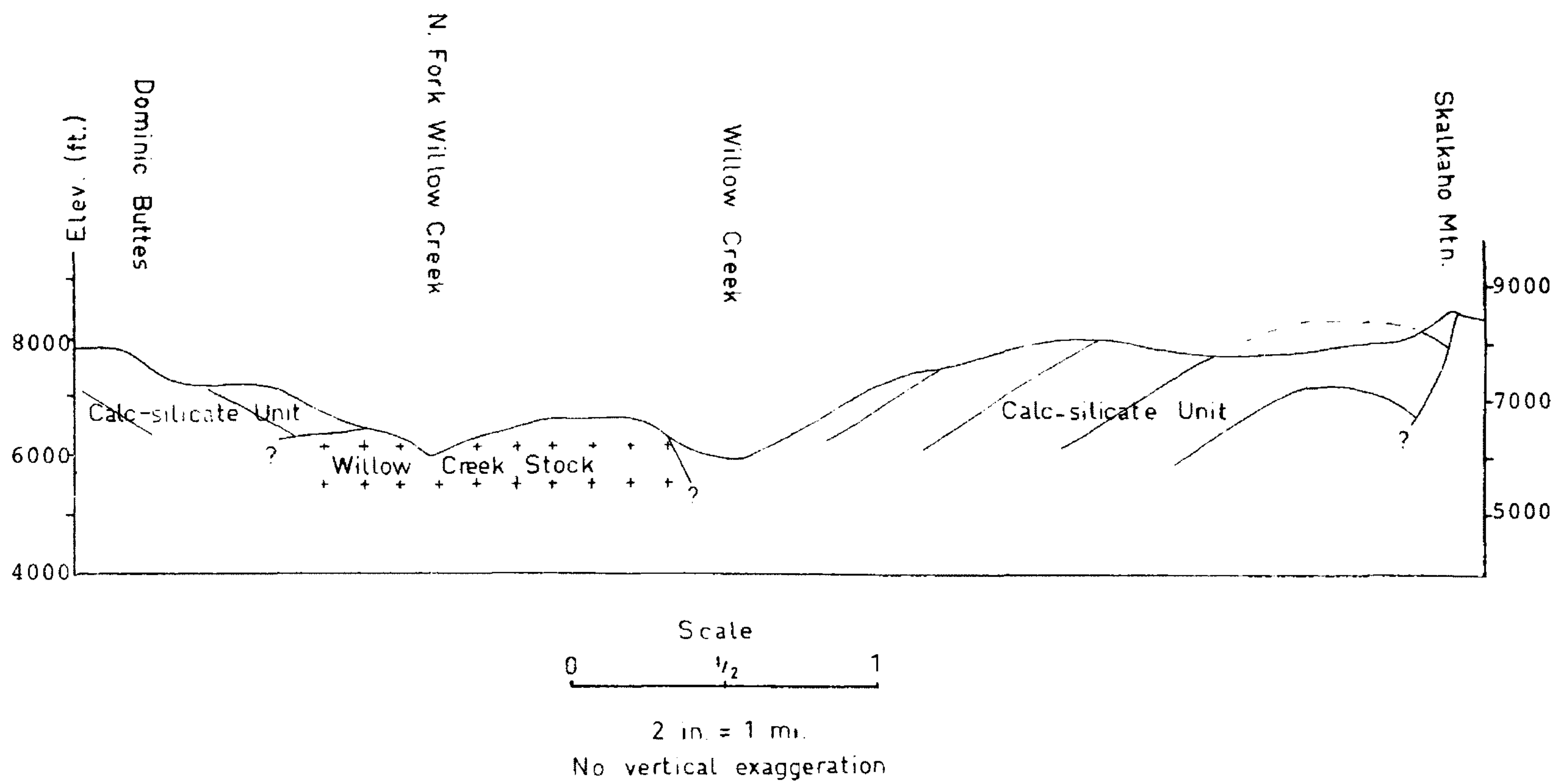


Figure 3. Diagrammatic cross-section across the Willow Creek drainage from the area of Dominic Buttes to the area of Skalkaho Mountain.

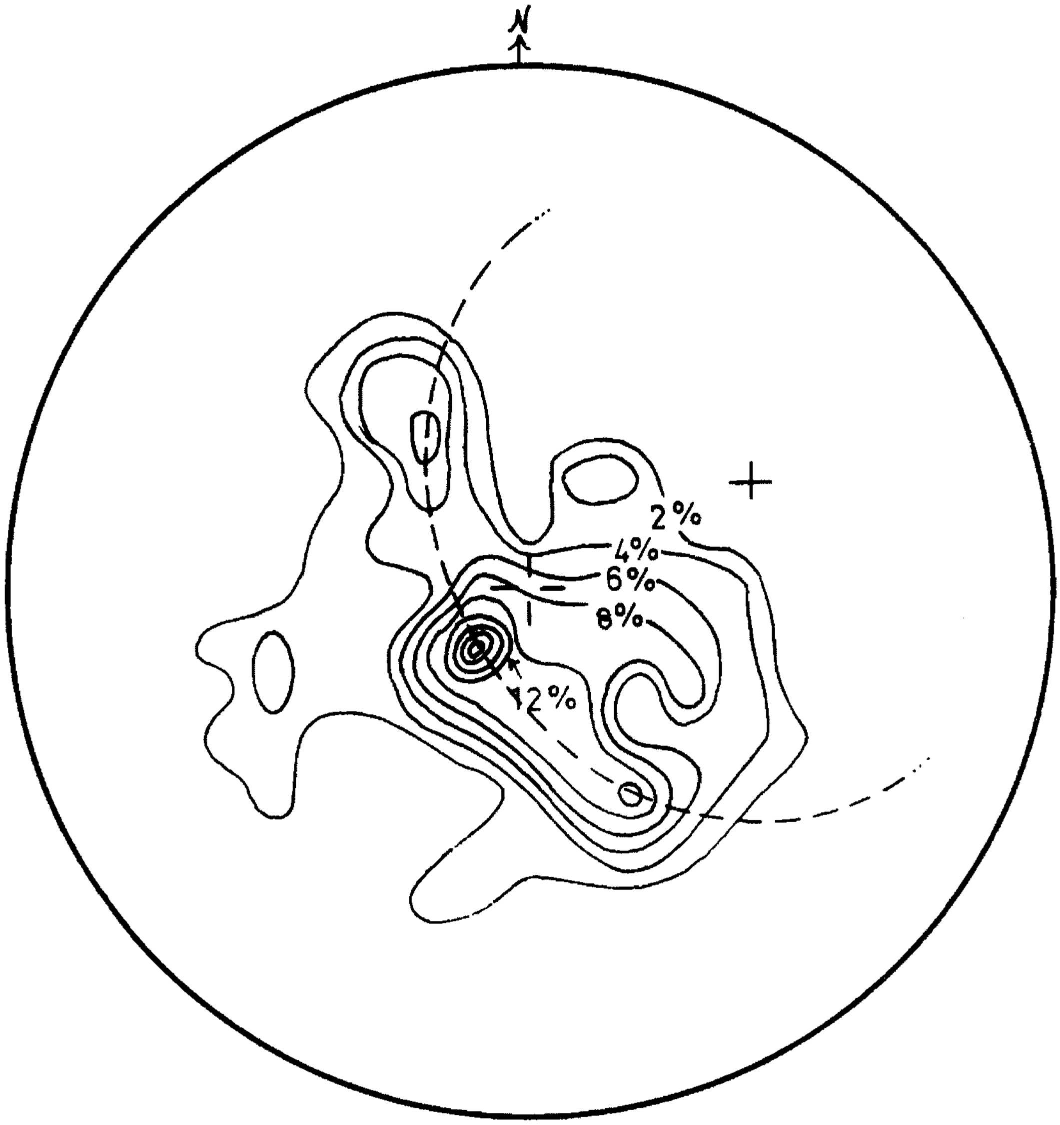


Figure 4. Lower hemisphere, equal area plot of poles to compositional layering. The pole to the small circle girdle plunges N65E, 50NE. Contours are based on 53 data points. Contour interval equals 2% of data, with 2% to 18% contours represented

IV. Willow Creek Stock

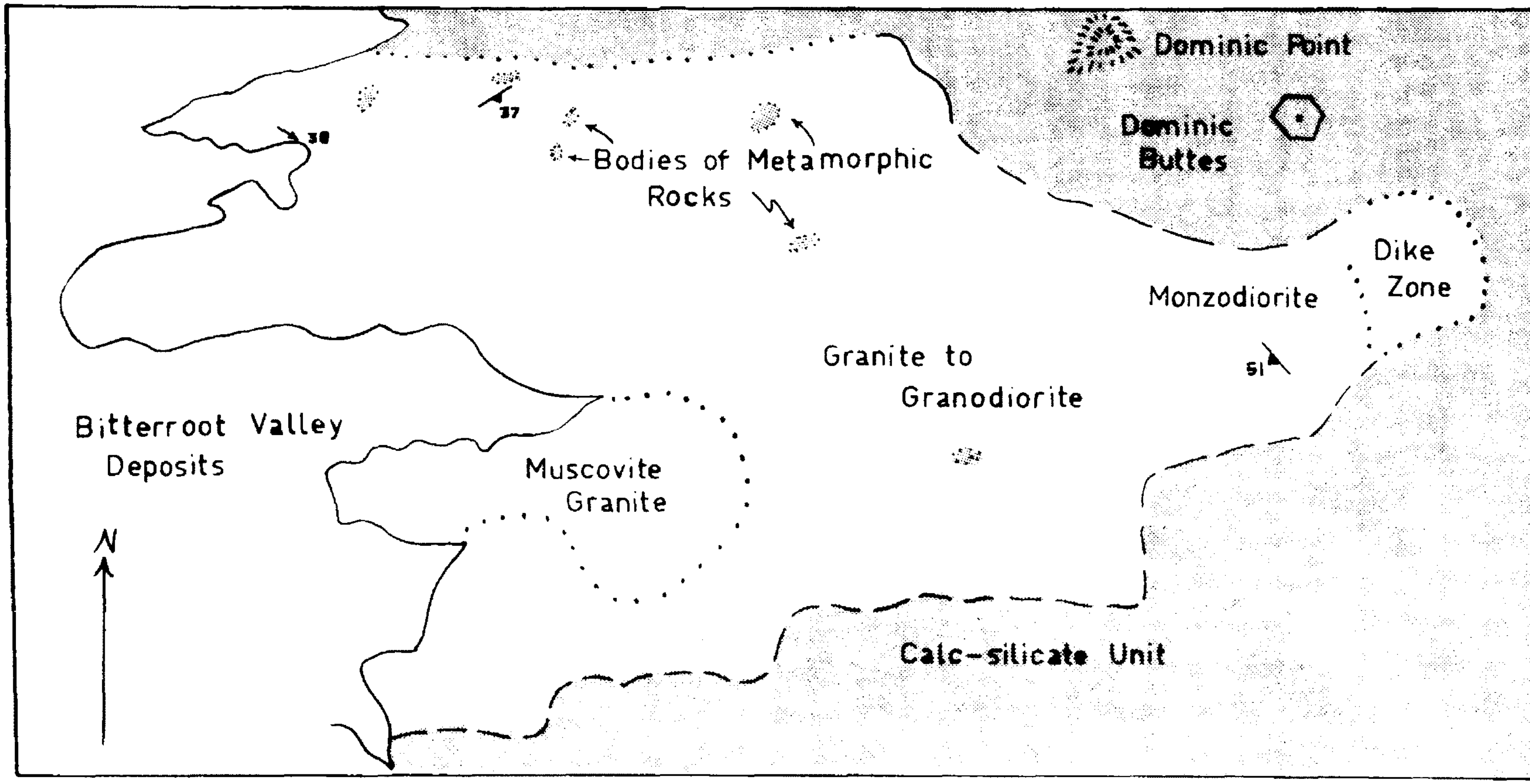
General Relationships

Willow Creek has eroded through the cover of metamorphic rocks to expose the roof of the Willow Creek stock in the center of the valley. Since the trace of the contact between the granite and the metamorphics "V's" well upstream in the Willow Creek Valley, the contact appears to have a generally shallow dip; but detailed field evidence, from individual outcrops indicates that in many places the contact surface is locally steeply dipping. In the eastern outcrop area, for example, the granite underlies a large ridge outside of the central valley. The contact in this area must cut bedding at a high angle.

Bedding and compositional layers within the metamorphic rocks are not closely concordant with the contact. Dips of bedding are shallow and tend to intersect the contact at rather low angles. The transition from granite to calc-silicate rock is quite sharp. Granitic dikes and pegmatites extend into the country rocks and in many places have isolated and stoped metamorphic blocks into the stock. Slight adjustment of the metamorphics by faulting can be observed within the contact zone. A contact metamorphic aureole, which extends up to several hundred yards into the country rocks, has been formed under medium to high pressure. Both the pressure-temperature conditions and the metamorphism are discussed in later sections.

In general, the stock is granite to granodiorite in composition (Figs. 5 and 6). A zone of muscovite granite (minor biotite) crops out in an area of approximately $1\frac{1}{2}$ square miles in the western portion of the stock, south of Willow Creek. This body of rock is light-colored, fine-grained, with no foliation and no evidence of associated aplite, pegmatite, or granitic dikes.

In the remainder of the stock, muscovite is found in apparent equilibrium with biotite. The percentage of micas tends to be higher than that found in the muscovite granite, but nowhere is greater than 10%. These rocks tend to be fine to medium-grained, and commonly contain up to 1-2% potassium-feldspar megacrysts. At one outcrop (station 19-5) a zone of 50% megacrysts can be observed. The megacrysts have an average size of 1x1x2 cm. In two outcrops the long axis of the megacrysts were lineated along foliation planes. In the northern contact zone and especially in the eastern end of the stock, the mafics within monzodiorite composition rocks were foliated and banded. No other foliations or lineations were found.



Legend

Strike & Dip of mafic layers 51

Strike & Trend of megacrysts 38

Indefinite Contact (dotted)

For information concerning the base map and metamorphic rocks, refer to Plate 1.

Scale (1 in.=1 mi.)

0 1 2

Figure 5. Geology of the Willow Creek stock. The surrounding metamorphic rocks and blocks of metamorphic rocks included within the stock are stippled.

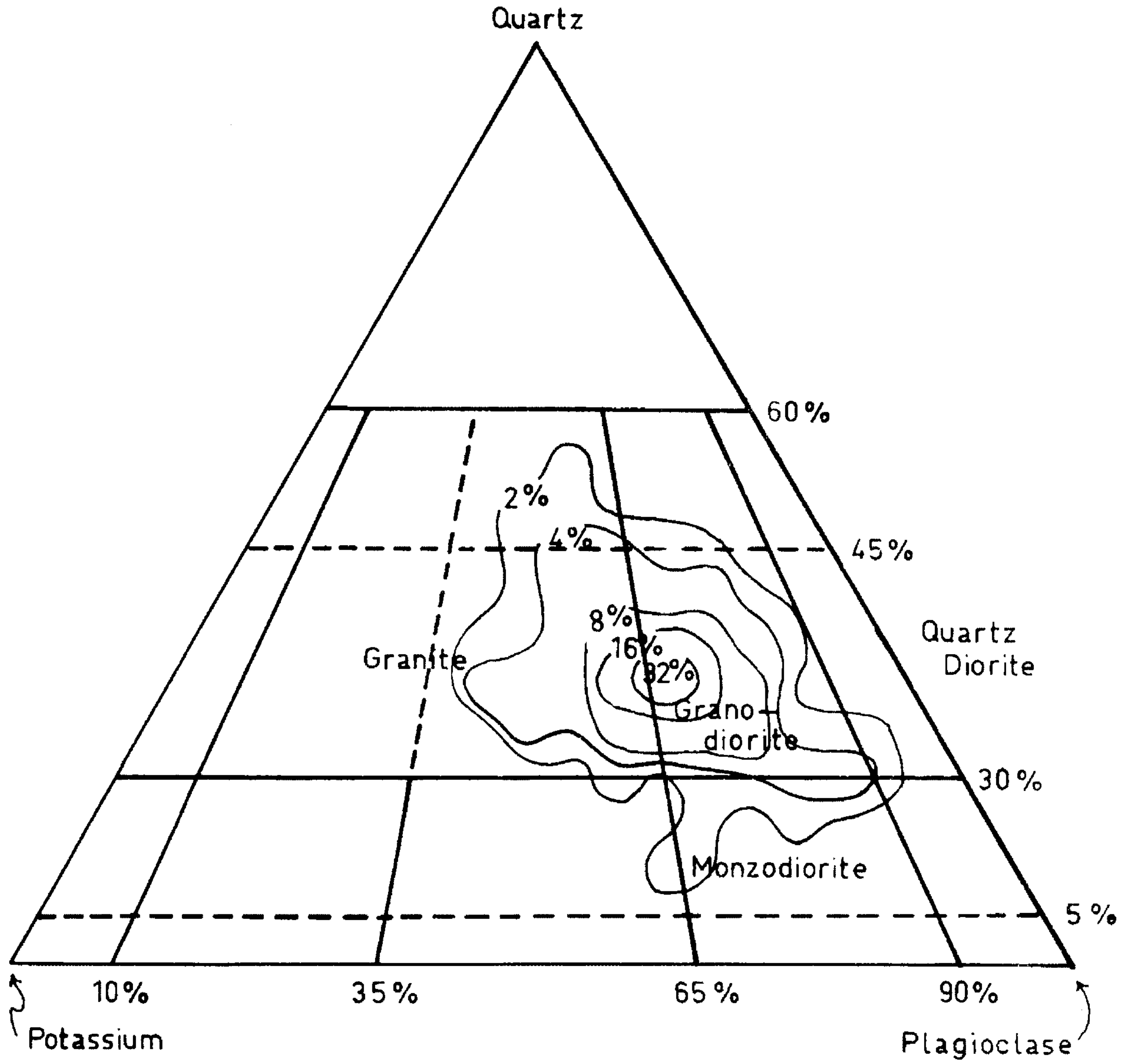


Figure 6. Contour plot of plagioclase, potassium feldspar, and quartz from the Willow Creek stock. Contours are based on 49 data points. Note the logarithmic progression of the contour interval. Composition fields are based on the classification of Streckeisen (1967).

The extreme eastern outcrop area of the stock is interpreted as a complex of granitic dikes and isolated metamorphic blocks. Exposure is poor, so the exact extent or nature of the body in this area is uncertain.

A mechanism for the emplacement of the granite can be developed from structural data. As was mentioned above, in the section on structure, the small circle distribution of poles to compositional layering shown in Figure 4 could indicate that the warping of the metamorphics above the stock was due to sagging. Were the pressure relieved on the magma chamber by some mechanism such as venting, the metamorphics could have sagged into the magma. Slight adjustment of the country rocks by faulting and folding as seen in the contact zone could have taken place along the edge, metamorphic blocks could have been broken and stoped into the granite during warping, while the magma squeezed its way into weaker portions of the chamber roof. Evidence for activity such as this can be found in the contact zone.

An alternate interpretation is that the warping existed before the intrusion of the stock, and the stock stoped and forced its way into place. The fact that the northeast extension of the axis of the warping plunges to the northeast, away from the stock, argues against the sagging hypothesis.

Pending further structural investigation of the Sapphire Mountains north and east of the Willow Creek area, a sagging hypothesis is favored, since it lends itself to a reasonable interpretation of the structural data and the contact relationships. It is also complementary to Wehrenberg's (1967) idea of passive folding and faulting in the eastern border zone of the Idaho batholith.

Petrography

Thin sections of 50 granites and pegmatites from the Willow Creek stock indicate a generally homogeneous body, with local variations in mineralogy and texture, especially in the contact zones and the area of muscovite granite.

Plagioclase crystals in the rocks are subhedral and in many cases enclosed in quartz and potassium feldspar. Twinning is generally by the albite law, commonly by the pericline law and in rare instances by the albite-Ala B law. Carlsbad twins are rare, and were not used in composition measurements. Zoning is minor. Generally the cores of plagioclase crystals are normally zoned out to oscillatory rims. Small plagioclase crystals commonly contain myrmekitic quartz.

There are two textural types of potassium feldspar. One is generally finer grained with plaid twinning typical of microcline, only slightly perthitic along scattered, stringy segregations, contains very few inclusions of other minerals, and is typically found filling intergranular spaces. The second type is the potassium feldspar megacryst. The megacrysts are quite large, in some cases contain Carlsbad twins and many inclusions of plagioclase, quartz and biotite, and adjust to the outlines of the adjacent grains. In two thin-sections, one a pegmatite and the other a megacryst-rich rock, near the contact, large sections of plagioclase crystals appear to have been altered to potassium feldspar.

Quartz crystals are large with irregular boundaries and show undulatory extinction. In general, they are rather free of inclusions.

Muscovite and biotite, along with minor magnetite, occupy intergranular spaces. Biotite is pleochroic (Y & Z = dark brownish black, X = light brown), often encases magnetite, and is in some cases altered to chlorite. Well-formed muscovite crystals are often found altering from plagioclase. The majority of the muscovite grains show no relationship to plagioclase and are primary. Biotite makes up 25-100% of the micas, but there is no regular variation.

Texturally, from thin-sections, the granite has no foliation or lineation, except in the contact areas, where the biotites in scattered examples show preferred orientation. Individual minerals are not scattered randomly through the rock, but have a tendency to segregate into groups.

In the center of the northern contact zone textural evidence possibly indicates that the rocks shifted slightly before final crystallization. Individual quartz and plagioclase crystals float in a matrix of fine grained quartz, plagioclase, muscovite, and biotite. Potassium feldspar crystals occur randomly through the rocks and contain many inclusions. The potassium feldspar appears superimposed on an earlier texture.

The muscovite granite differs slightly from the remainder of the stock; plagioclase is highly altered to white mica, microcline crystals have well formed plain twinning. Some larger crystals have many quartz, plagioclase and muscovite inclusions, biotite occurs only in trace amounts in several of the rocks and muscovite is associated with traces of magnetite.

Compositional Variations

A compositional study of the granite was made to determine variations in mineralogy and rock type. Specific gravities were calculated using hand specimens weighing one-half to one kilogram. Modal analyses were made on polished end slabs of the same hand specimen. Potassium feldspar in the slabs was stained with sodium cobaltinitrite, so that four mineral types could be distinguished: plagioclase, potassium feldspar, quartz and mafics. Muscovite was grouped with magnetite and biotite under the heading mafics. Plagioclase An-contents were calculated from randomly selected thin sections using a four-axis universal stage and the curves of Slemmons (1962) and by the flat-stage bisetrix method using the curves of Moorhouse (1959). For a tabulation of values and details of analysis procedure refer to Table 1.

Modal analyses for quartz, plagioclase, and potassium feldspar were recalculated to 100% and plotted on the triangular diagram shown in Figure 6. This plot shows a range in compositions from granite through monzodiorite, following the classification of Streckeisen (1967).

Specific gravities were used for a quick, general determination of compositional variations by Cain (1965) within a granodiorite pluton, and by Ehinger (1968,1970) in his study of the Philipsburg, Montana batholith.

Specific gravity values of the 49 samples from the Willow Creek stock are contoured on the map view of the stock shown on Plate 2A. A specific gravity low coincides with the zone of muscovite granite. Specific gravity values tend to decrease from the northern contact and grade into this area. Directly northeast of the muscovite

TABLE 1. Determinations on Granite Samples.

Sample	Specific Gravity	Modes (%) mafics	plag	kspar	quartz	An Content core/rim
1	2.638	5.0	45.0	27.4	27.1	An_{26}
3	2.626	2.9	32.6	26.9	37.5	An_{23} (An_{27} in rim against kspar)
4	2.652					An_{26}*
5	2.648	4.5	43.6	28.4	23.5	An_{26}*
6	2.663	3.4	46.6	19.3	30.7	An_{23}/An_{25} $An_{26}/An_{24}/An_{26}$*
1-1a	2.613	2.2	42.7	30.4	24.6	
1-3a	2.671	4.6	56.9	20.4	18.1	
1-3b	2.666	4.1	54.2	15.9	25.6	
1-5	2.680	6.2	46.0	18.9	28.8	
2-1	2.654	3.1	43.7	24.0	29.2	
2-2	2.665	3.8	48.2	17.0	31.1	An_{24} An_{29}/An_{29}
2-3	2.662	5.0	38.7	27.9	28.4	An_{29}/An_{27}
2-5	2.608	2.0	32.4	24.1	41.5	
2-5b	2.646	1.5	26.4	20.9	51.1	An_{31} An_{31}*
3-1	2.641	2.4	53.1	21.5	23.1	
3-2d	2.671	7.0	62.3	12.1	18.6	$An_{29}/An_{24}/An_{27}$
3-3	2.710	9.5	62.2	8.3	19.9	
3-5	2.672					
3-8	2.653	7.5	47.6	20.4	24.5	
4-1	2.649	3.4	22.9	44.1	29.5	

TABLE 1 (Continued)

Sample	Specific Gravity	mafics	Modes (%) plag	kspar	quartz	An Content core/rim
4-2	2.635	4.4	41.2	21.4	32.8	
4-3	2.639	4.4	41.0	22.9	31.8	An_{24}
4-4	2.649	3.3	43.1	25.4	28.1	
4-6	2.642	0.9	35.1	28.4	35.7	An_{27}
4-9a	2.644	2.8	41.9	25.8	29.5	
5-2	2.659	4.3	51.9	19.1	24.6	
5-3	2.633	2.4	29.3	37.3	31.1	
5-7	2.645	4.1	47.0	19.6	29.4	An_{27} $An_{26}/An_{21}/An_{24}$* An_{24}*
16-1	2.663					
16-2	2.675	4.5	58.0	26.2	11.3	
16-3	2.658	6.1	50.7	11.9	31.2	
19-1	2.631	5.5	43.2	30.0	21.3	
19-2	2.623	4.6	36.2	17.3	41.8	
19-3	2.651	2.8	63.0	15.5	18.7	An_{25}*
19-4	2.622	5.6	53.9	16.7	23.8	
19-5	2.650	4.1	32.2	36.9	26.8	
19-6	2.664	5.8	53.1	18.5	22.6	An_{29}/An_{25}
19-8	2.648	5.4	47.1	22.1	25.3	
19-9	2.666	3.9	44.8	25.7	25.7	
20-1	2.633	3.7	46.1	19.5	30.7	
20-2	2.595	1.4	27.9	27.6	43.1	An_{28} An_{30}*

TABLE 1 (Continued)

Sample	Specific Gravity	Modes (%) mafics	plag	kspar	quartz	An Content core/rim
20-3	2.639	4.1	36.1	31.2	28.6	An_{24}/An_{26}*
20-4	2.618	3.0	44.5	12.2	40.3	
20-5	2.588	3.2	43.9	16.9	36.0	An_{25}/An_{27}*
21-1	2.628	4.4	44.0	17.9	33.5	
21-2	2.658	3.4	43.2	23.8	29.6	
21-3	2.658	4.0	30.7	32.2	33.2	
21-7a	2.581	0.4	33.9	37.7	27.9	
21-8	2.628					

PROCEDURE:

1. Specific gravity determinations were made using a modified "Jolly" balance. A wire net was suspended into a large container of water from a triple beam balance. The balance was leveled to compensate for the added weight of the wire. Dry, one-half to one kilogram sized hand specimens were weighed while resting on the balance pan above the wire, with the wire submerged in water up to a marked level. The hand specimens were then allowed to sit in water over night, to allow complete saturation, and were measured again for weight submerged in water, resting in the wire net. The level of water in the container was kept constant. Second weighings indicated an accuracy to ±0.2 gm, which allowed accuracy of three to four significant figures in the weights. The specific gravity was then obtained by use of the formula:

$$S.G. = \frac{W_{air}}{W_{air} - W_{water}} .$$

2. Modes were obtained by using an automatic point counter and identifying the minerals at 1200 randomly selected points, on stained end slabs of granite. The cut slabs were stained by etching for 10 to 15 seconds, submerged in concentrated HF, washing briefly, and submerging in a saturated solution of sodium cobaltinitrite for 1 minute. After the excess sodium cobaltinitrite was washed off by a brief, light water rinse, the potassium feldspar was stained a bright yellow. It was found that the minerals were more sharply etched, if the slab was initially ground smooth using a 600 grit grinding compound.
3. Plagioclase compositions were determined using a universal stage microscope and the curves of Slemmons (1962), and by the flat-stage bisetrix method, using the curves of Moorhouse (1959). Flat-stage bisetrix determinations are marked with an (*).

granite there is a ridge and trough of specific gravity data which wraps around the low specific gravity area.

Plates 2B and 2C show contours of mafic mineral and plagioclase modes respectfully. In general, the mafic percentages show a decrease into the low specific gravity area. Contours in the northern half of the stock tend toward parallelism with the specific gravity contours.

Plagioclase modes also decrease into the low specific gravity regions. They tend to pattern the specific gravity contours in the northern half of the stock, and follow the ridge and trough system northeast of the muscovite granite.

These plagioclase contours may be interpreted as rock types. The plagioclase modes tend to be scattered along a line, drawn on the triangular diagram in Figure 6, from the center of the quartz-potassium feldspar leg of the triangle to the plagioclase corner. By giving a position along this line, the plagioclase modes illustrate a variation from granite to monzodiorite. The lower the plagioclase percentage, the closer to granitic composition. The rocks containing the low plagioclase values in the low specific gravity area are largely granites, whereas the remainder of the stock is granite to granodiorite.

Plagioclase compositions vary from An_{23} to An_{31} (Table 1). The values were either taken on whole grains with no zoning; or if zoning was present, on cores and rims. In several instances, an intermediate composition within the zoning was calculated. Crystals zoned outward normally from the core decrease in composition by 3-5% anorthite component. The increase in An-component in some rims can be explained in several ways, including (1) the late addition of calcium to the melt, (2) a late stage increase in temperature, (3) a late stage increase in pressure, or (4) an alteration of once normally zoned plagioclase, after final crystallization.

Although values from the muscovite granite tended to be slightly higher than the stock as a whole, no variation trends of An-composition could be observed across the stock.

Discussion of Composition Data

It is apparent that the variation of specific gravity in the Willow Creek stock is controlled by variations in the percentages of plagioclase and mafics. Petrographic work suggests that the composition of major minerals within the stock remains constant, and the controlling factor is the mode. No such systematic variation could be observed with potassium feldspar and quartz. The specific gravity may also be controlled by variations in the relative amounts of muscovite and biotite. Muscovite, being slightly less dense than biotite, would aid in lowering the specific gravity of the muscovite granite. Although the contacts of this body appear gradational with the remainder of the stock, the area of low specific gravity defined by this body could be a secondary compositional effect superimposed on a larger regional trend.

Ehinger (1970) discussed two magmatic processes operative in the emplacement and crystallization of granite batholiths, which could be responsible for broad scale compositional changes: assimilation and differentiation. He preferred a process of differentiation in situ, which as outlined by Vance (1961) involves crystallization inward from the borders of the granite body, and enrichment of the center of the pluton in residual fluids rich in potash and silica. The specific gravity would also decrease toward the center. Such a process, although difficult to define on such a small scale, could be operative in the Willow Creek area.

Pressure Conditions

Muscovite within the Willow Creek stock is found both as grains in intergranular spaces associated with biotite, and as inclusions within plagioclase crystals. The upper limit of muscovite stability has been examined by Yoder and Eugster (1955), Evans (1965), Velde (1966) and Crowley and Roy (1966). Curves for their work with the reaction,

(1) muscovite $\rightleftarrows$ sandidine + corundum

are shown in Figure 7. The curve of Evans (1965) for the reactions,

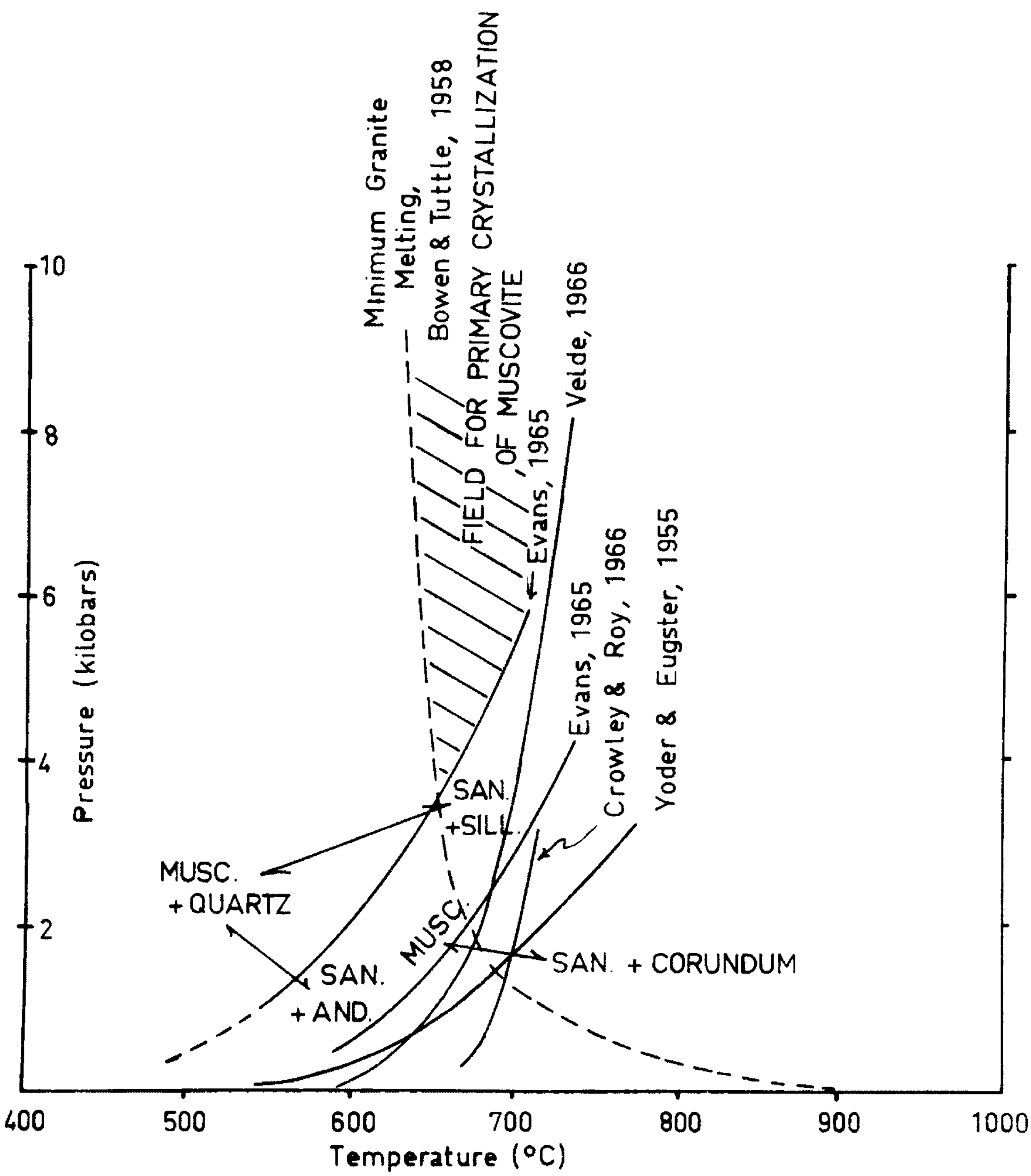


Figure 7. The stability of muscovite and muscovite plus quartz. The curves are explained in the text. Mineral abbreviations are: musc. = muscovite, san. = sanadine, sill. = sillimanite, and. = andalusite.

(2) muscovite + quartz $\rightleftarrows$ sanidine + andalusite, and

(3) muscovite + quartz $\rightleftarrows$ sanidine + sillimanite,

is also shown in Figure 7 and falls at lower temperatures than the curves for the breakdown of muscovite by itself. The curve of Evans intersects the alkali granite melting curve of Tuttle and Bowen (1958) at approximately 3½ kb. Using this data, the muscovite could form as a primary phase in the crystallization of granite magmas at pressures of at least 3½ kb., and only in the solid state (eg. deuteric) below this pressure.

The granite melting curve is based on crystallization at the ternary minimum. Compositions of granite to granodiorite such as those found in the Willow Creek stock would crystallize at temperatures higher than the ternary minimum and shift the granite melting curve in Figure 7 to the right. Also, the presence of microcline, plagioclase, and biotite, as well as quartz or impurities such as sodium in the muscovite, might lower the stability temperatures below that of the muscovite plus quartz stability curve. The effect of all these changes would be to increase the pressure requirements necessary for the formation of muscovite in a crystallizing granite magma.

Assuming that the muscovite is primary, the Willow Creek stock was emplaced at a pressure of 3½ kb. or greater.

V. Additional Igneous Rock Types

Diabase Dikes

A series of diabase dikes are found through the central portion of the area. They intrude both the granite and the metamorphics and develop contact zones in both. A biotite-plagioclase-scapolite-tremolite skarn is found in the biotite-quartz unit next to a diabase dike, north of Willow Mountain. These dikes, along with a series of quartz-latite dikes, must be later than both the regional metamorphism and intrusion of the granite (Tertiary ?).

In outcrop, the dikes never measure more than a few tens of feet in thickness, and are usually weathered and stained by iron oxides. They often have developed an "onion like" weathering pattern as adjacent joints break off in rounded exfoliation surfaces. The rocks range in color and grain size from glassy, massive, black basalt with no crystals or phenocrysts visible, to a fine-grained diabase with plagioclase and pyroxene visible in hand specimen.

In thin section, the rocks contain:

(1) augite as small granular phenocrysts,

(2) zoned plagioclase, as both phenocrysts (An_{77}) and within the groundmass (An_{58}), (both plagioclase compositions were single determinations on separate thin sections, using a universal stage and the curves of Slemmons, 1962),

(3) glass, in varing amounts up to 20 to 30 percent,

(4) and commonly, amygdules with zeolites.

Some examples show a strong lineation, in thin section, defined by plagioclase needles.

Quartz-Latite Dikes

Quartz-latite dikes are abundant both within the Willow Creek stock and the metamorphic rocks. No cross-cutting relationships between these dikes and the diabase were observed in the field, although both tend to occur in the same general areas. The dikes measure up to 10 meters in thickness.

Phenocrysts measure up to 5 mm. long and include:

(1) plagioclase, of composition An_{25} to An_{31} (3 universal stage determinations), in many cases slightly zoned,

(2) up to 3 percent fine-grained biotite, X = brown, Y & Z = dark black-brown, and

(3) in two examples, sanidine, with a negative $2V<10°$.

The groundmass consists of approximately equal percentages of quartz, sanidine, and plagioclase, although the modes vary within wide limits, and the glass content is small.

Two examples display a moderately good lineation, in thin-section, of fine-grained plagioclase needles. Plagioclase tends to dominate the foliated rocks in both groundmass and phenocrysts, and the glass, biotite, and phenocryst percentages are higher.

Syenite and Vermiculite Deposits

An intrusive body, which crosses into the southern part of the area west of Skalkaho Mountain, is mainly a syenite containing hornblende and aegerine-augite. The major outcrop area is along the divide separating the Willow Creek drainage from that of Gird Creek to the south. The intrusion does not readily form outcrops, but instead weathers to bouldery piles.

Contact relationships are not clear. Offshoot from the body can be found well into the metamorphic rocks, and there is apparently no contact metamorphism.

Two thin-sections from the syenite showed the following mineralogy:

(1) plagioclase, of composition An_{23} (1 determination using a flatstage bisetrix method, after Moorhouse, 1959),

(2) potassium feldspar, containing string perthites,

(3) aegerine-augite, with a $Z \wedge C$ of approximately 50°, and moderately strong pleochronism, Z = light golden green, Y = light green, and X = green,

(4) hornblende, which is possibly altering from the pyroxene, pleochronism, X = olive green, Y = golden green, Z = dark golden green,

(5) apatite, and

(6) euhedral zircon crystals, which grow quite large and are twinned on one face.

The syenite is unfoliated. In hand specimen, the potassium feldspar crystals form coarse rectangular crystals (up to 2 cm. long). These tend to dominate the texture of the rock with other minerals resting in intergranular positions. Potassium feldspar, pyroxene, hornblende, and apatite are visible in hand specimen.

Bodies of segregated rock with greater than 75 percent dark minerals are common within the syenite body, are fine- to coarse-grained, and are often foliated. Two thin sections from this rock contained hornblende and aegerine-augite, with optical properties similar to those found in the syenite. Euhedral zircon and apatite are abundant, and in one of the thin sections, potassium feldspar filled intergranular spaces.

The hornblende forms an interesting texture in the segregated bodies. It forms in large (up to 3 cm. long) crystals which engulf the pyroxenes, apatites and zircons. They appear superimposed on an original granular pyroxene matrix.

Vermiculite deposits on the west side of Skalkaho Mountain have been discussed by Perry (1948). Prospecting was carried out in the early 1930's, and additional investigations were made in 1948. A personal interview with the resident geologist at the Libby, Montana vermiculite mine (Zonolite Division, W. R. Grace & Co.) revealed that the Skalkaho Mountain deposits are not worked at present due to the low concentration of vermiculite.

An investigation of one of the prospect pits at Skalkaho Mountain during the present research revealed no vermiculite in outcrop, although chips were common along the road workings. A sample of the apparent host rock from the front of the pit, is medium-grained, foliated, hornblende-pyroxene rock, which appears to be one of the segregated hornblende-pyroxene bodies within the syenite. No vermiculite is observed in thin section.

The vermiculite appears to be developed along the contact zone between the syenite and the metamorphosed Wallace formation, and closely parallels the occurrence of the Libby vermiculite. Both deposits are found associated with syenite bodies and rocks rich in pyroxene, and both lie in Precambrian Belt series carbonate-rich rocks. A study of the Skalkaho Mountain vermiculite could lead to an interpretation of the origin of both deposits.

VI. Metamorphism

Rock Descriptions and Stratigraphy

Metamorphic rocks in the Willow Creek area include parts of the Wallace and Ravalli formations of the lower Precambrian Belt series of western Montana. The stratigraphy is outline in Figure 8. The Wallace is divided into two mappable units: (1) a section characterized by calcium-rich minerals, such as diopside and tremolite, and (2) a thin, brown, biotite-rich unit. The Ravalli is thrust above the Wallace in the area north of Palisade Mountain. Complete sections of the two formations are not available and no attempts have been made at closer correlation.

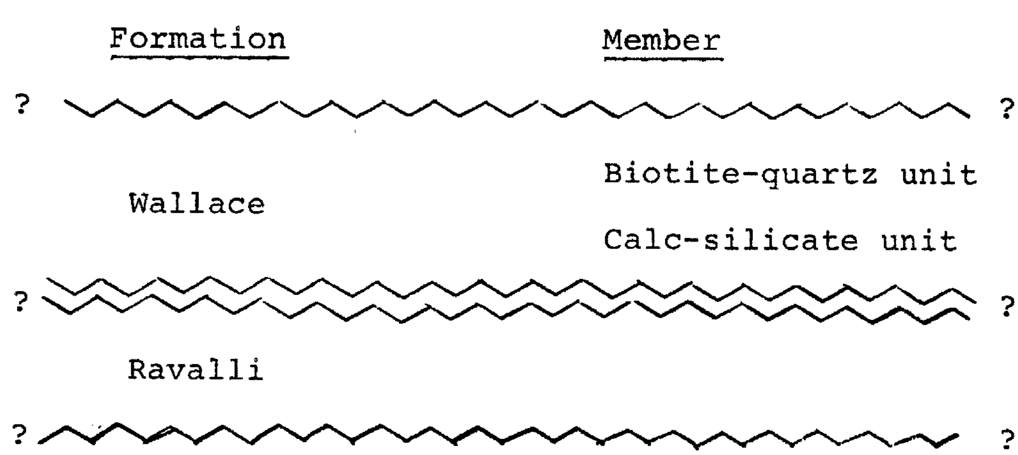


Figure 8. Stratigraphic units.

Calc-Silicate Unit

The calc-silicates are white and green in outcrop, fine- to medium-grained with layers of varying thickness up to 5 cm. Generally the layers are grouped into larger zones of 1 meter thick. The minerals imparting the green color are diopside and actinolite, depending on the bulk composition and grade of metamorphism. Many interlayered, brown, fine-grained, biotite-quartz beds are common throughout the section. In hand specimen, the fine-grained minerals appear segregated into layers and bundles, but no foliation is evident.

Variation of metamorphic grade can be observed in outcrop within this unit, increasing generally from east to west (Fig. 10). Rocks in the eastern portion of the area south of Palisade Mountain are characterized by an absence of diopside and the preservation of many macroscopic sedimentary features, including fine algal layers up to 5 mm. thick. Many sedimentary layers appear to have been distorted by soft sediment deformation.

Sedimentary features are obliterated in the higher grade rocks of the calc-silicate unit. These rocks contain diopside, and are found to the west of a line drawn approximately from Palisade Mountain to Skalkaho Mountain. Compositional layers within these rocks are believed to be remnants of original sedimentary layering. Euhedral, coarse-grained, scapolite crystals and white, round, scapolite balls up to 5 mm. in diameter can be observed in some hand specimens. Scapolite is especially conspicuous within the calc-silicate rocks north of the Willow Creek stock.

The calc-silicate unit is the only metamorphic formation found in exposed contact with the Willow Creek stock. Contact metamorphic effects are discussed in a later section.

Biotite-Quartz Unit

In the northeastern part of the area, east of Willow Mountain, there is a 100-300 meter-thick section of a brown, fine-grained, finely layered, biotite-rich rock, containing white scapolite balls, up to 5 mm. in diameter, superimposed over the layering. The percentage of white scapolite varies from less than 5% to 50% from one layer to another. Except for the scapolite, this unit resembles the biotite layers found within the calc-silicates. Calc-silicate rocks which outcrop below this unit are highly scapolitized.

The lower contact is transitional, with the brown, white-spotted, biotite-quartz layers interbedded with diopside rich layers. The upper contact is the thrust surface mapped by Langton (1935).

Blue-Gray Quartzite Unit

Above, and in fault contact with, the biotite-quartz unit is a blue-gray, fine-grained, massive quartzite, with scattered fine-grained, argillitic layers, which was mapped as Ravalli. Although two thin sections were made from samples of this formation for determination of metamorphic grade, the present mapping ended at the base of this unit.

Regional Metamorphism

Regional metamorphic rocks increase in grade from east to west (Fig. 9). Two major metamorphic assemblages are recognized. These fall to either side of the isograd which marks the lower limit of the amphibolite facies with the first appearance of diopside. Rocks which lie physically above this isograd, and therefore were higher in the crust at the time of metamorphism are probably related to the highest temperature portion of the albite-epidote amphibolite facies. Lower grade rocks are mapped as a biotite-chlorite zone in this report. Higher grade rocks of the diopside zone probably fall within the lower amphibolite facies.

Biotite-Chlorite Zone

Biotite-chlorite zone rocks include only a small fraction of the metamorphic rocks studied in the Willow Creek Area, and outcrop only in a small area east of Skalkaho Mountain. One thin section cut from rocks collected at Skalkaho Falls on the Skalkaho Pass road, approximately two

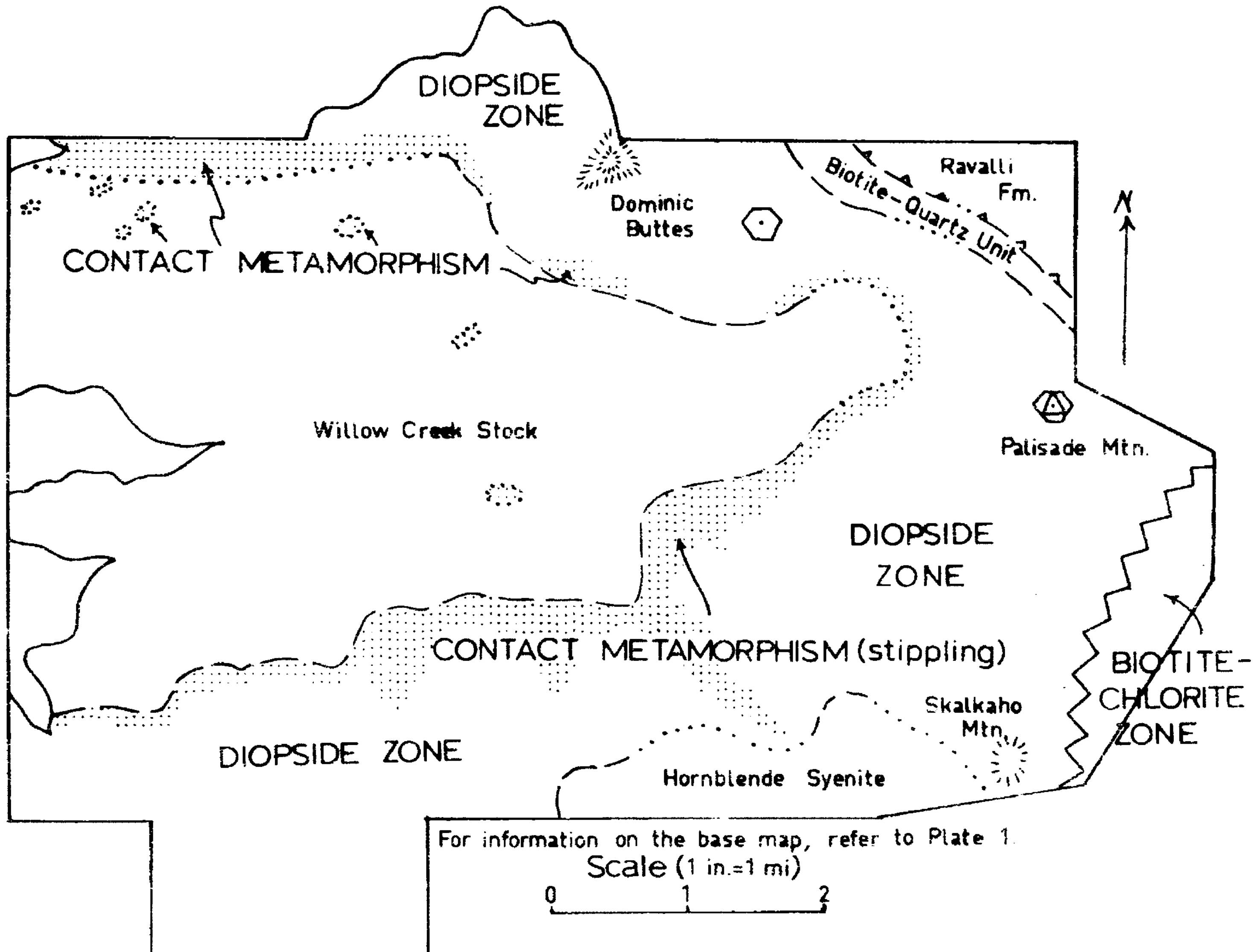


Figure 9. Metamorphic zones in the Willow Creek Area. Areas of contact metamorphism are stippled.

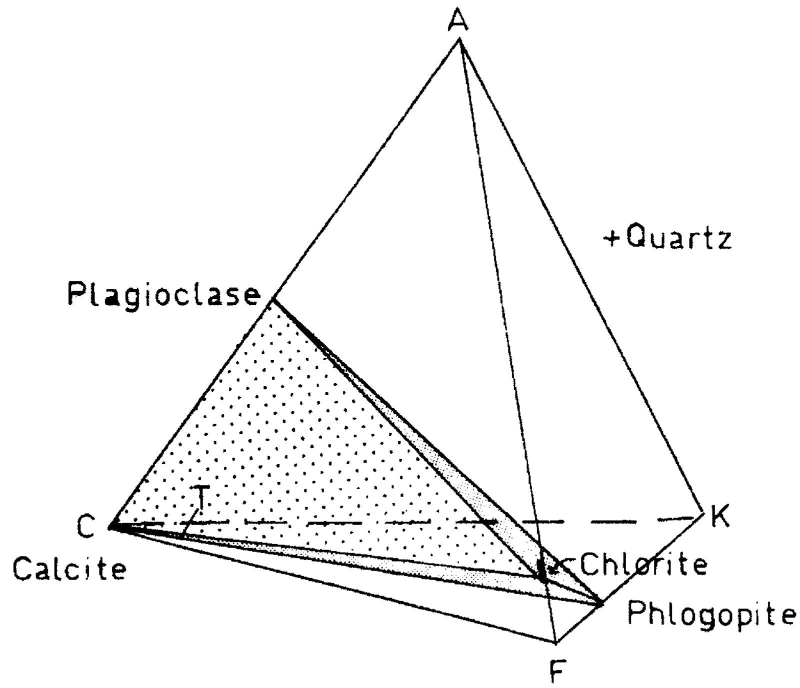
miles southeast of the mapped biotite-chlorite zone rocks, shows a continuation of this zone, or a lower-grade zone, in an easterly direction. Structurally these rocks are near the top of the stratigraphic section exposed in the Willow Creek area.

These rocks are characterized by the presence of chlorite, lack of diopside, and a high percentage of calcite, generally up to 50 percent of the rock. In hand specimen, many of the original sedimentary structures are preserved, including features such as molar tooth and other algal structures, as well as fine sedimentary laminations defined by scatterings of graphite or magnetite. All sedimentary features have been recrystallized to varying degrees, but without any apparent metamorphic differentiation.

Stable mineral phases are illustrated on the ACKF tetrahedron in Figure 10, along with the bulk composition of rocks in this zone. Mineralogic data are listed in Table 2.

Approximate refractive index determinations on biotite and chlorite indicate that the compositions of these minerals are close to the magnesium-rich end of their respective mineral groups. This evidence, in addition to the presence of calcite, indicates an original dolomitic sediment.

There are some mineralogic indications of instability in this zone at the time of metamorphism. Altered muscovite crystals are found associated with biotite and chlorite in



Calcite-plagioclase-biotite-chlorite-quartz
(3 samples)

Figure 10. Biotite-chlorite zone metamorphic assemblages.

TABLE 2. Mineralogical Data. Biotite-Chlorite Zone.

Mineral	Notes	Range of Modes (visual est.)
calcite		30-50
chlorite	colorless, $\Delta \approx 0.006$, R.I. $\approx$ 1.56 - 1.57	5-10
phlogopite	pleochroic, X = clear-pale brown, Y & Z = light orange brown	10-15
plagioclase	An_{32}-An_{34}*	0-20
quartz		10-50
muscovite	associated with calcite-chlorite-biotite as "decayed" grains.	0-1
Accessory minerals:	opaques, sphene	

* Two determinations were made on plagioclases from this zone, one using the universal stage and the curves of Slemmons (1962), and the other using the flat-stage bisetrix method and the curves of Moorhouse (1959).

calcite-rich segregations, and one highly altered diopside crystal is encased in a calcite-quartz matrix. Since the biotite-chlorite rocks in this area were extremely close to the pressure-temperature conditions of the diopside isograd, it can be suggested that the single diopside crystal could have formed under slightly variable chemical, pressure, or temperature conditions within the upper biotite-chlorite zone. The muscovite is anomalous, since it is not common to the higher grade rocks, and possibly formed as a retrogressive phase. Broad retrogressive metamorphism is not likely, since there is no evidence of former metamorphic textures.

The biotite-chlorite zone rocks are fine-grained. In thin-section the micas commonly display a poor to moderate preferred-orientation, while grains of plagioclase and quartz form a sutured matrix. Hand specimens are brown, blackish brown, gray and white in color.

Diopside Zone

Diopside zone rocks cover most of the remaining metamorphic terrane. Diopside first appears directly to the west of the biotite-chlorite grade rocks. Primary chlorite is not found in this zone, the rocks tend to be coarser-grained, and carry a smaller percentage of calcite, than the rocks of lower metamorphic grade.

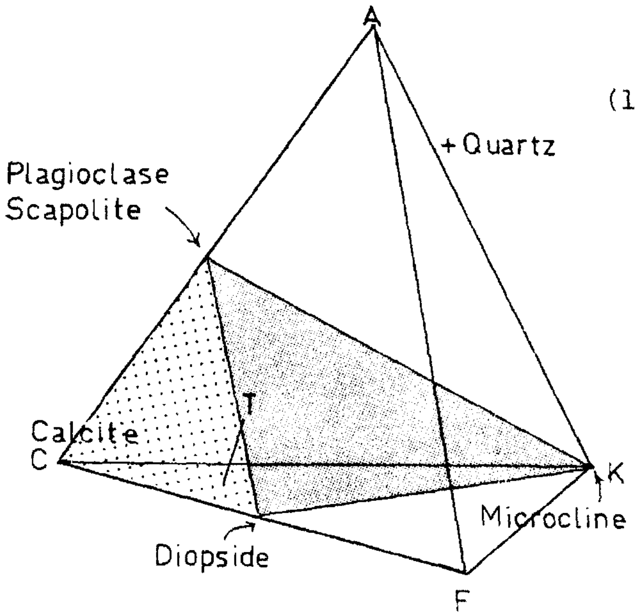
The bulk composition of the Wallace formation tends to vary from one assemblage to another, resulting in several possible major assemblages of minerals. Figures 11 and 12, illustrate on ACKF tetrahedra the major assemblages mapped within this zone. The bulk compositions shown are variable within reasonable limits, but appear unique to each assemblage. The major change between the layers is in the type of magnesium-rich phase, either diopside, tremolite, or phlogopite. Two groups of layers have been separated:

A. layers rich in calcium-magnesium silicates such as tremolite and diopside, with phlogopite only as an accessory mineral, in Figure 10, and

B. layers rich in phlogopite, with a tendency toward a lower calcium-content, in Figure 11.

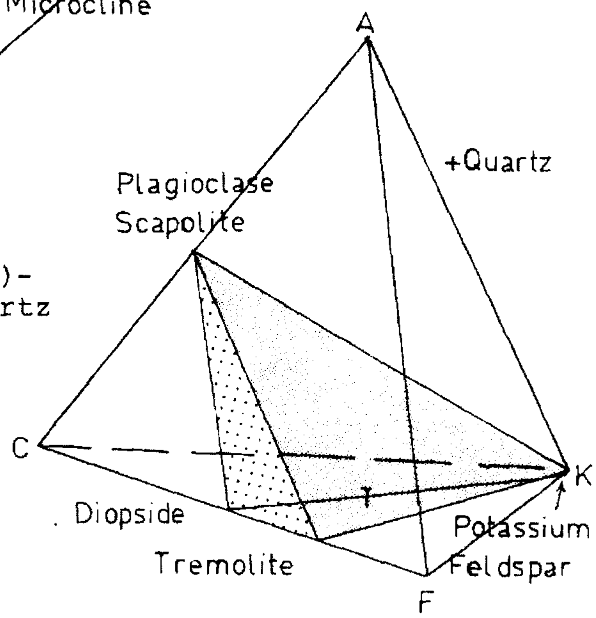
Rocks found in the biotite-quartz unit of the Wallace formation would be included in this group.

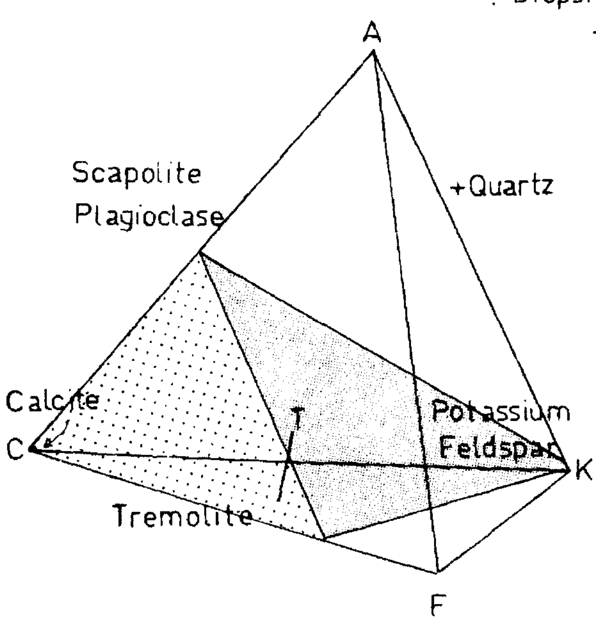
Assemblages (1) and (3) in Figure 10 are the same except for the type of calc-silicate phase; but the bulk composition in assemblage (3) is closer to the AKF face. Assemblage (2) has diopside and tremolite in equilibrium. All of the rocks containing this assemblage lie to the outside edge of the contact metamorphic zone surrounding the Willow Creek stock. It is suggested that the coexistence of these minerals is the result of a reaction in which tremolite is passing to diopside. In at least one sample the diopside is found with the tremolite in quartz veins.



(1) diopside-calcite-plagioclase-(scapolite)-microcline-quartz (20 samples)
Also:
diopside-calcite-scapolite (1 sample)
diopside-calcite-potash feldspar (3 samples)

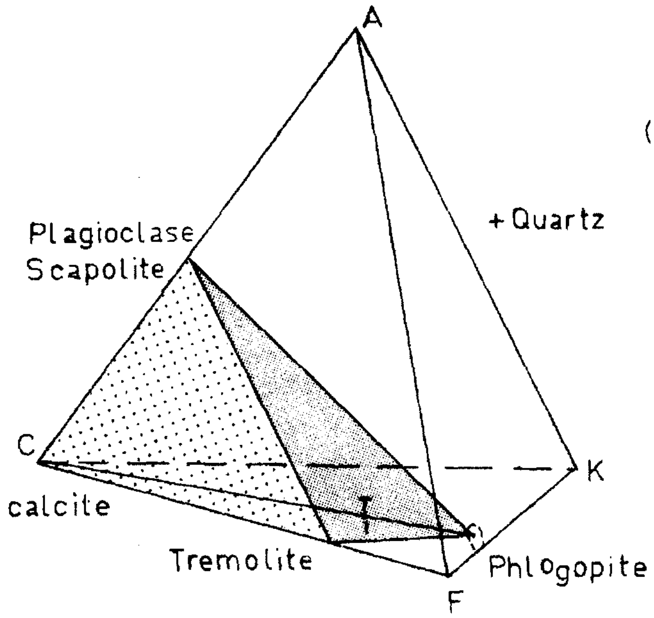
(2) diopside-tremolite-plagioclase (scapolite)-potassium feldspar-quartz (6 samples)





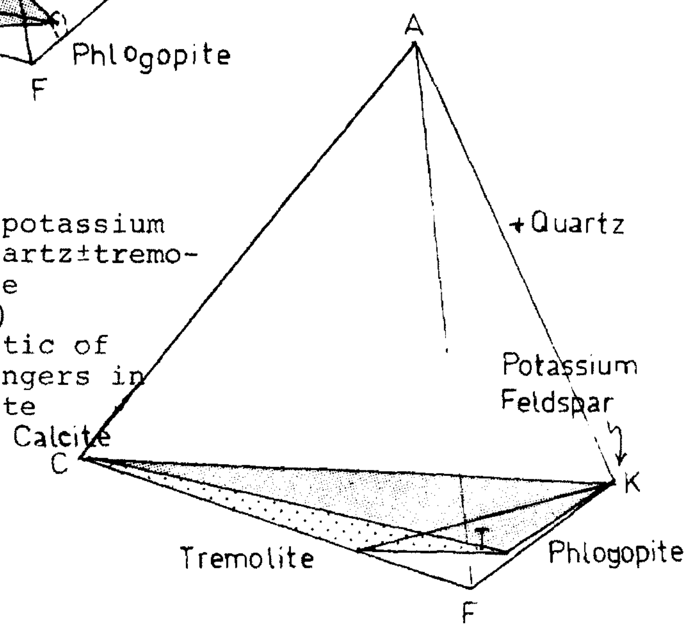
(3) tremolite-calcite-plagioclase (scapolite)-potassium feldspar-quartz (11 samples)

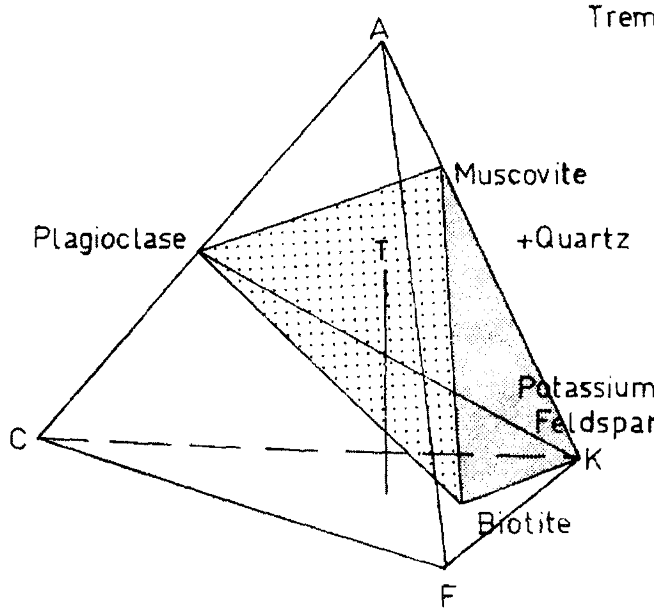
Figure 11. Calcium silicate metamorphic assemblages. Diopside zone. T = bulk composition.



(4) phlogopite-tremolite-plagioclase (scapolite)-quartz±calcite
(9 samples)
Characteristic of the biotite-quartz unit and similar lithologies in the calc-silicate unit.

(5) phlogopite-potassium feldspar-quartz±tremolite±calcite
(5 samples)
Characteristic of peltic stringers in calc-silicate rocks





(6) quartz-muscovite-biotite-plagioclase±potassium feldspar
(2 samples)
Ravalli Formation

Figure 12. Biotite-quartz metamorphic assemblages. Diopside zone. T = bulk composition.

In a rock within the contact zone, remnant radiating tremolite crystal patterns are found preserved within diopside crystals.

Assemblage (4) in Figure 11 is characteristic of the biotite-quartz unit and related lithologies in the calc-silicate unit. Assemblage (6) is found in the Ravalli formation.

Mineralogical data for each assemblage is given in Table 3. Except in the case of biotite, optical properties of the minerals do not vary significantly between assemblages

Phlogopite is commonly found as an accessory mineral in assemblages (1) and (3). It tends to be associated with tremolite and diopside, as inclusions in scapolite crystals, or in areas devoid of potassium feldspar. Its presence can be explained by any number of minor assemblages, and is not considered significant.

In hand specimen the rocks are green, gray, white and brown in color, and are fine- to medium-grained. In thin section, the rocks display only poor to moderately good foliation involving amphiboles and biotites crystallized in preferred orientations. In scattered instances, quartz and potassium feldspar also appear crystallographically aligned. Amphilboles and pyroxenes commonly form radiating bundles. End sections of the pyroxenes or amphilboles can generally

TABLE 3. Mineralogic Data. Diopside Zone.

Mineral	Notes	Range of Modes by Assemblage in Figs. 10 & 11 (visual est.) (1)	(2)	(3)	(4)	(5)	(6)
calcite		0-40	tr-2	0-40	0-10	0-20	---
diopside	colorless, ZΛC = 37-42°	20-50	5-30	---	---	---	---
microcline, potassium feldspar	plaid twins common, but not ubiquitous	5-30	5-30	tr-15	---	30-40	0-3
biotite, phlogopite	variable pleochroism, 1. in calc-silicates, X = pale brown Y & Z = light brown. 2. in biotite-quartz rocks, X = pale brown, Y & Z = light orange-brown. 3. in Ravalli formation, X = light brown, Y & Z = dark olive brown.	tr-2	---	tr-2	10-30	10-30	1-3
muscovite		---	---	---	---	---	3-10
quartz	no straining	2-50	30-70	10-60	10-50	20-50	80-90
plagioclase	An_{24}-An_{35}* albite twins	0-30	tr-30	0-30	0-10	0-tr	1-3
scapolite	Me_{55}-Me_{75}** Δ = 0.022-0.030	0-50	0-20	0-30	10-20	0-20	---
tremolite	no pleochroism, colorless to pale green	---	5-20	10-40	0-30	0-30	---
sphene		tr-1	tr-2	tr-2	tr	2-3	tr
flourite		tr	---	---	---	---	---
zircon		tr	---	---	---	---	---
apatite		---	tr	---	tr	---	---
opaques		tr	tr	tr	tr	tr	tr

* Plagioclase compositions were determined using a universal stage microscope and the curves of Slemmons (1962).

** Scapolite compositions using birefringence measurements from thin sections and reading the composition from the curve of Deer, Howie, and Zussman (1963), v. 4, Figure 101. See footnote Table 4.

be found in the center of these bundles, indicating a spherically radiating body.

Contact Metamorphism

A contact metamorphic aureole, the major effects of which extend up to several hundred feet into the country rocks, surrounds the Willow Creek stock. Contact metamorphic assemblages are also found in the blocks of metamorphic rocks enclosed within the granite.

Rocks in the contact metamorphic zone are separable from the regional metamorphism on the basis of texture. As was shown above, the granite was probably intruded under pressures of at least 3 kb. This could have been quite close to the stability pressures expressed in the mineralogy of the regional metamorphic rocks. The contact metamorphic effects grade into the regional metamorphism, leaving no sharp boundaries. The extent of obvious contact metamorphic effects is quite variable. Extending deep into the country rocks in some areas. Regional metamorphic rocks are often preserved close to the granite contact, possibly the result of shifting and displacement of the country rocks in the contact zone.

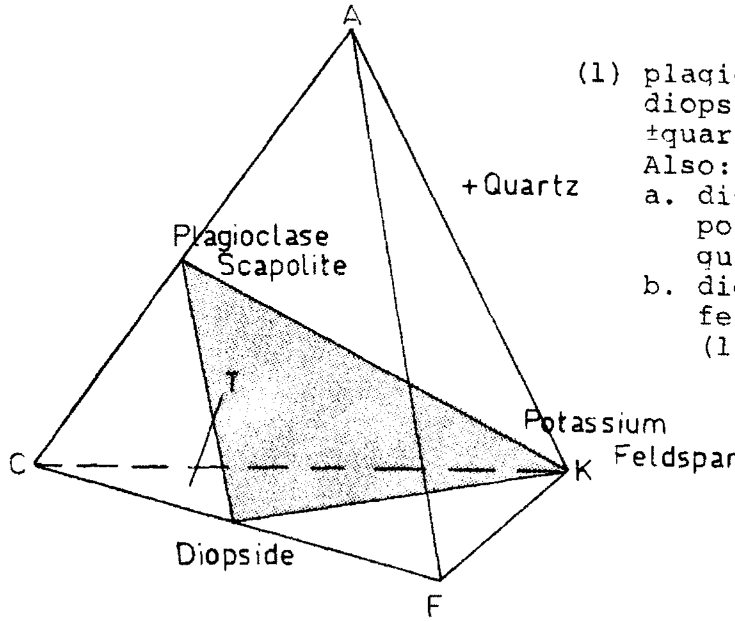
The extent of contact metamorphism gives some clues to the shape of the granite-metamorphic contact. Along Butter-fly Creek the contact zone extends approximately one mile up the valley bottom, whereas the ridge crests 2000 to 3000 feet higher are largely unaffected by the contact metamorphism. The contact must have a shallow dip through this area to allow the extension of such a zone.

The ACFK tetrahedra in Figure 13 illustrate the assemblages in this zone, along with the bulk composition of layers containing these assemblages.

Assemblage (1) is similar to assemblage (1) of the diopside zone, except for the lack of calcite. Rocks of this type tend to be coarse-grained, green and white in outcrop, and with no apparent foliation. In thin section, diopside is commonly found as subhedral crystals, along with well twinned plagioclase. Calcite is found in veins and alteration zones, and rarely in trace amounts within the matrix of the rocks in the outer limits of contact metamorphism. Scapolite is not abundant in this assemblage and often appears as "decayed" grains enclosed in plagioclase.

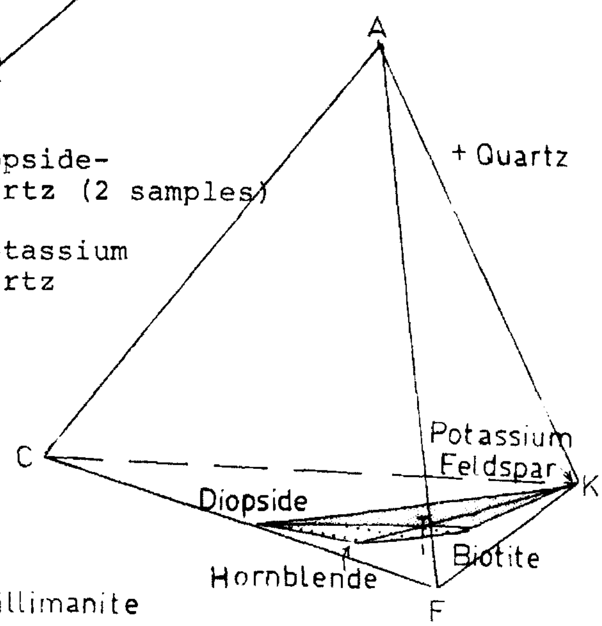
Assemblage (2) and the additional assemblages listed at the bottom of Figure 14, are characteristic of layers containing amphilboles and biotite. These are not extensive, but clearly are associated with contact metamorphic rocks. Foliation of amphiboles and biotite are common.

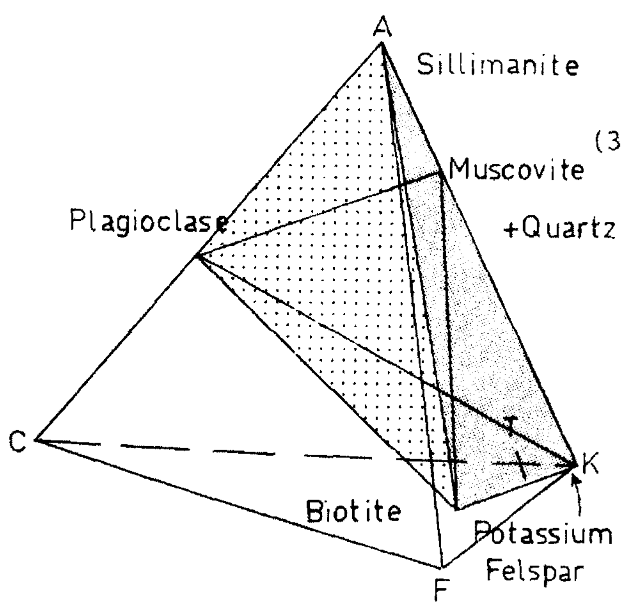
Assemblage (3) is found in fine-grained, white and black, biotite-quartz gneisses occurring in inclusions of metamorphic rock within the granite. These generally contain



(1) plagioclase (scapolite)-diopside±potassium feldspar ±quartz (14 samples)
Also:
a. diopside-phlogopite-potassium feldspar-quartz (2 samples)
b. diopside-potassium feldspar-quartz (1 sample)

(2) hornblende-biotite-diopside-potassium feldspar-quartz (2 samples)
Also:
hornblende-diopside-potassium feldspar-scapolite-quartz (1 sample)





(3) biotite-muscovite-potassium feldspar-quartz±sillimanite±plagioclase (8 samples)

Also associated with contact metamorphic rocks:
a. tremolite-scapolite-potassium feldspar-quartz (1 sample)
b. tremolite-plagioclase-biotite-quartz (1 sample)

Figure 13. Contact zone metamorphic assemblages. T = bulk composition.

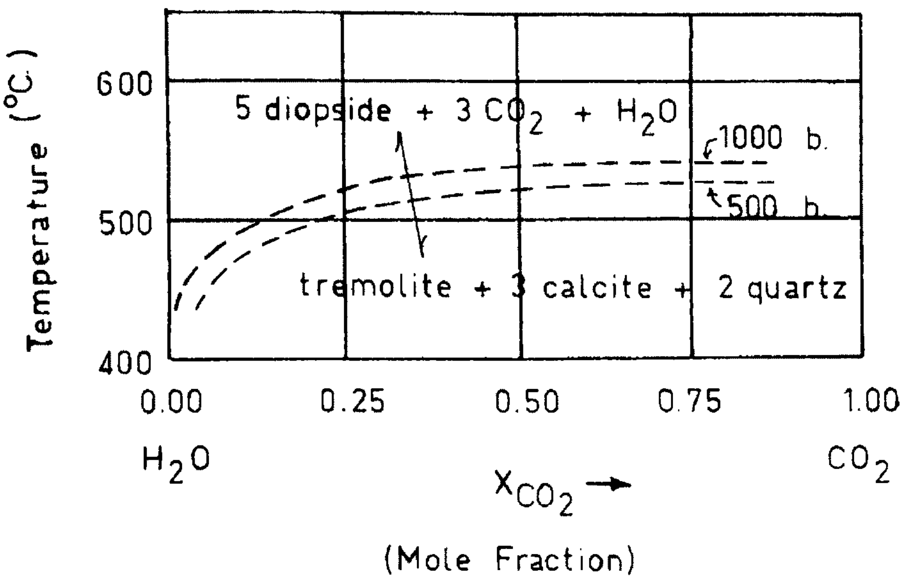


Figure 14. Equilibrium curves for the stated reaction at 500 and 1000 bars pressure, after Winkler, 1967 (Metz, 1964). The equilibrium is dependent on the composition of the CO_2-H_2O fluid phase.

sillimanite, and except for minor plagioclase, contain no calcium-bearing phases. Although the rocks commonly appear foliated in hand specimen, and the gneissic bands in several samples show small scale (wave length of 2 cm.) folded patterns, no good preferred orientation can be observed in thin section. Crystallographic axes of biotite and quartz show no preferred orientation, so the folds observed in hand specimen must be the result of pre-metamorphic folding event.

Sillimanite and biotite tend to be segregated into pelitic zones, one or two small biotite grains wide and are separated by quartz-rich layers of the same thickness. They form a branching, yet flattened, pattern.

In several samples, sillimanite muscovite, potassium feldspar are found in apparent equilibrium. A thin section from one of these samples was stained for potassium feldspar, and shows a segregation of potassium feldspar from sillimanite; but thin sections from other samples, which were not stained, showed either a similar segregation or equal distribution of grains. Some of the muscovite occurs in irregular grains and is probably a retrogressive phase, but the majority appears fresh, and therefore stable.

Evans and Guidotti (1966) report the coexistence of sillimanite, muscovite, and potassium feldspar in the presence of plagioclase and quartz in western Maine. The assemblage forms in the vicinity of the isograd, found in sillimanite grade rocks, where a muscovite and sillimanite stability field is replaced by a potassium feldspar and sillimanite stability field. The stability can be explained if sodium is considered as an extra component, and is dependent on the amount of this element in the muscovite, potassium feldspar, and plagioclase. The assemblage is probably extended over larger areas in western Maine by what Evans and Guidotti believe is P_{H_2O} less than P_{total}. Dehydration of the muscovite would cause an increase in P_{H_2O}, assuming a closed rock system, and tend to counter the reaction causing the breakdown of the muscovite, and maintain the isograd conditions over a wider temperature range. The sillimanite bearing rocks in the contact zone of the Willow Creek stock were probably water saturated during the crystallization of the magma, and by the argument of Evans and Guidotti, could have only formed over a narrow temperature range.

The verification of the sillimanite-potassium feldspar-muscovite stability in the Willow Creek area is possibly on theoretical grounds involving variable Na-content in orthoclase and muscovite and therefore an additional component, but is beyond the scope of this report.

Mineralogical data for the contact zone is listed in Table 4.

TABLE 4. Mineralogical Data. Contact Zone.

Mineral	Notes	Range of Modes by Assemblage in Fig. 13 (visual est.) (1)	(2)	(3)
biotite phlogopite	1. in calc-silicate rocks, X = clear to pale brown, Y & Z = light brown; 2. in pelitic and quartzitic rocks, X = light brown, Y & Z = dark olive brown	0-5	5-20	3-30
calcite	found in veins and stringers	0-5	--	--
diopside	colorless, subhedral to granular crystals	30-60	10-20	--
hornblende	pleochroic, X = colorless, Y = olive green, Z = green	--	5-30	--
tremolite	colorless, found in additional assemblages associated with contact metamorphic rocks	--	--	--
muscovite		--	--	tr-10
plagioclase	An_{24}-An_{40}*, in assemblage (3) values are grouped, An_{24}-An_{28}	10-50	--	0-20
scapolite	Me_{65}-Me_{75}**, Δ=0.028-0.032	0-30	--	--
potassium feldspar		0-20	30-60	tr-30
quartz		0-30	10-30	40-80
sillimanite		--	--	0-10
ACCESSORY MINERALS:				
apatite		--	--	tr
fluorite		tr	--	--
hematite		tr	tr	tr
opaques		--	--	tr-1
sphene		tr-1	tr	tr

* Plagioclase compositions were determined on a universal stage using the curves of Slemmons (1962), and by the flat-stage bisetrix method using the curves of Moorhouse (1959).

** Scapolite compositions were determined using birefringence measurements from thin sections and reading the composition from the curve of Deer, Howie, and Zussman (1963), v. 4, Figure 101. The birefringence of a scapolite-rich rock can be easily determined by finding adjacent quartz and scapolite grains giving flash figures. The thickenss of the slide may be determined from the quartz interference colors.

The following criteria may be used in separating the contact metamorphic events from purely regional metamorphism.

(1) The contact metamorphism is accompanied by a reduction in the CO_2 content of the mineral phases. This is expressed in the calc-silicate rocks by a lack of calcite and a reduction in the amount of scapolite. Only minor amounts of calcite are found in alteration zones and veins, and as the contact metamorphic effects decrease, the amount of calcite increases up to as much as 40% in the diopside zone.

(2) Calc-silicate rocks in the contact zone have a tendency to be unfoliated, coarse-grained, commonly with subhedral diopside crystals, and well-twinned plagiocalse.

(3) Hornblende is a common amphibole, which is not present in the regional metamorphic rocks.

A change in the relative concentrations of H_2O and CO_2 in the contact zone can be used to explain several features of the contact metamorphism. The reaction

$$\text{tremolite} + 3\ \text{calcite} + 2\ \text{quartz} \rightleftarrows 5\ \text{diopside} + 3\ CO_2 + H_2O$$

is affected by the composition of the fluid phase, as is shown in Figure 14. A higher X_{H_2O} (mole fraction H_2O) allows diopside to remain stable at lower temperatures, at the expense of tremolite. A great deal of H_2O was probably added to the contact metamorphic rocks in the Willow Creek from the crystallizing granite magma. This would have lowered the X_{CO_2} and favored the crystallization of diopside. Hornblende would then have replaced tremolite as the stable amphibole. The higher X_{CO_2} would have facilitated all of these reactions and allowed the development of coarse-grained textures.

Scapolite

Scapolite is a common mineral in the metamorphosed Wallace formation. Hietanen (1967) studied scapolite in the Belt series in central Idaho and Nold (1968) described scapolite in the Wallace formation in the Lolo Pass area in west central Montana.

In the Willow Creek area, scapolite is found as euhedral to subhedral crystals and as poikilitic balls, measuring up to 5 mm. in diameter, typically with inclusions of quartz and phlogopite. In most cases the scapolite appears to superimpose itself over the former sedimentary layering. Other minerals have not been differentiated into groups or bodies to the same extent as scapolite, a factor which allows the preservation of many sedimentary features. The scapolite appears to have formed simultaneously with other metamorphic textures and mineralogies. The mode of occurrence -- large crystals and balls -- of scapolite can be attributed to a low potential for nucleation of the scapolite molecule and a high mobility of the scapolite components.

The best recent summary of the literature on scapolite is by Shaw (1960a,1960b). He points out that most of the explanations of the origin of scapolite involve the introduction of chlorine by regional or contact pneumatoytic metasomatism in metamorphic terranes. Hietanen (1967) believes that scapolite in the Wallace formation of central Idaho forms from the isochemical metamorphism of an original saline and carbonate-bearing sediment.

The scapolite compositions in the Willow Creek area range from Me_{50} to Me_{75}, so the chloride requirements of the scapolite structure are low. Since the original sediment was carbonate-bearing, and the scapolite appears to be an integral part of the regional metamorphic textures, the scapolite components were probably derived from the original sediment, without the necessity of pneumatolytic transport of chloride from the granite.

Also, in several cases in the contact zone, plagioclase appeared to be replacing scapolite. This would imply the existance of scapolite before the intrusion of the stock.

Environment of Metamorphism

Metamorphic rocks of the Wallace formation similar to those found in the Willow Creek area have been described by

Hietanen (1967) and Nold (1968). Nold defined:

> (1) a biotite zone with biotite, chlorite, actinolite, calcite, potassium feldspar and muscovite as the major minerals,
>
> (2) a plagioclase zone with scapolite and plagioclase, diopside and hornblende, and
>
> (3) a sillimanite zone with diopside, hornblende, and plagioclase, but no calcite.

Work in this thesis closely correlates with this metamorphic scheme. Metamorphism described by Hietanen in central Idaho, although classified into different zonal patterns, also appears to correlate with the metamorphism in the Willow Creek area.

A larger study of the metamorphism in the Southern Sapphire Mountains, especially in the area to the south and southwest of the Willow Creek area, would be quite useful. Metamorphic rocks of the Wallace formation similar to those found in Willow Creek can be mapped at least as far south as the Skalkaho Road and west to Skalkaho Pass (Fig. 1).

All of this metamorphism is part of a large body of metamorphic rocks, spatially related to the Idaho batholith. Two ages of metamorphism are generally recognized in the literature:

> (1) a Precambrian metamorphism (Fryklund, 1964; Hobbs et al., 1965; Eckelman and Kulp, 1967; Reid and Greenwood, 1968), and
>
> (2) a Mesozoic metamorphism (Hamilton, 1963; Nold, 1968).

If the magma for the Idaho batholith resulted from anatexis of the Belt sediments and basement in this area, it would have presumably resulted from a Mesozoic metamorphic stage.

The Willow Creek stock has been intruded at high enough pressures to have been reasonably close to the stability conditions of the regional metamorphic terrane. If the regional metamorphism is Mesozoic in age, then the Willow Creek stock could have been intruded at the same time or shortly after the formation of the regional metamorphic assemblages. The validity of such an idea is dependent upon the age of the regional metamorphism.

Nold (1968) found that isograds mapped in the northeastern border zone of the Idaho batholith intersected the batholith, showing that the metamorphism in that area was a product of regional burial, rather than a contact zone created by a high geothermal gradient around the batholith. The identification of a contact zone around the Willow Creek stock, and the separation of contact metamorphic assemblages from a regional metamorphic terrane brings one to the same conclusion.

Most of the major examples of contact metamorphism in the literature involve hornfelsic assemblages in low pressure environments. This results in the fallacy of equating contact metamorphism with low pressure metamorphism.

Contact metamorphism under high pressures is probably quite common, and can result in coarse-grained rocks quite unlike the typical hornfels.

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