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The Petrology of the Lost Creek stock and its relation to the Mount Powell batholith

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THE PETROLOGY OF THE LOST CREEK STOCK AND
ITS RELATION TO THE MOUNT POWELL BATHOLITH

by

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Chapter 1

INTRODUCTION

The Flint Creek Range of Montana is a complex of Precambrian to Tertiary sediments with metasedimentary rocks and granitic intrusions of Cretaceous to Tertiary age. Currently, a major study of the granitic intrusions is in progress.[1] The intrusions are the Philipsburg batholith, Mount Powell batholith, Royal stock and the Racetrack Creek "pluton." Adjacent to the southern contacts of these bodies are various small outliers. One of these, the Lost Creek stock, is the subject of this thesis.

This stock is four miles north of Anaconda in the southern portion of the Flint Creek Range (Fig. 1).

Previous Work

Few geological investigations have been published on the southern portion of the Flint Creek Range. The most recent by Be'la Csejtey, Jr. (1962) focused on the structure in the area of Lost Creek stock but the petrology of the stock was only briefly mentioned. In the period 1912 to

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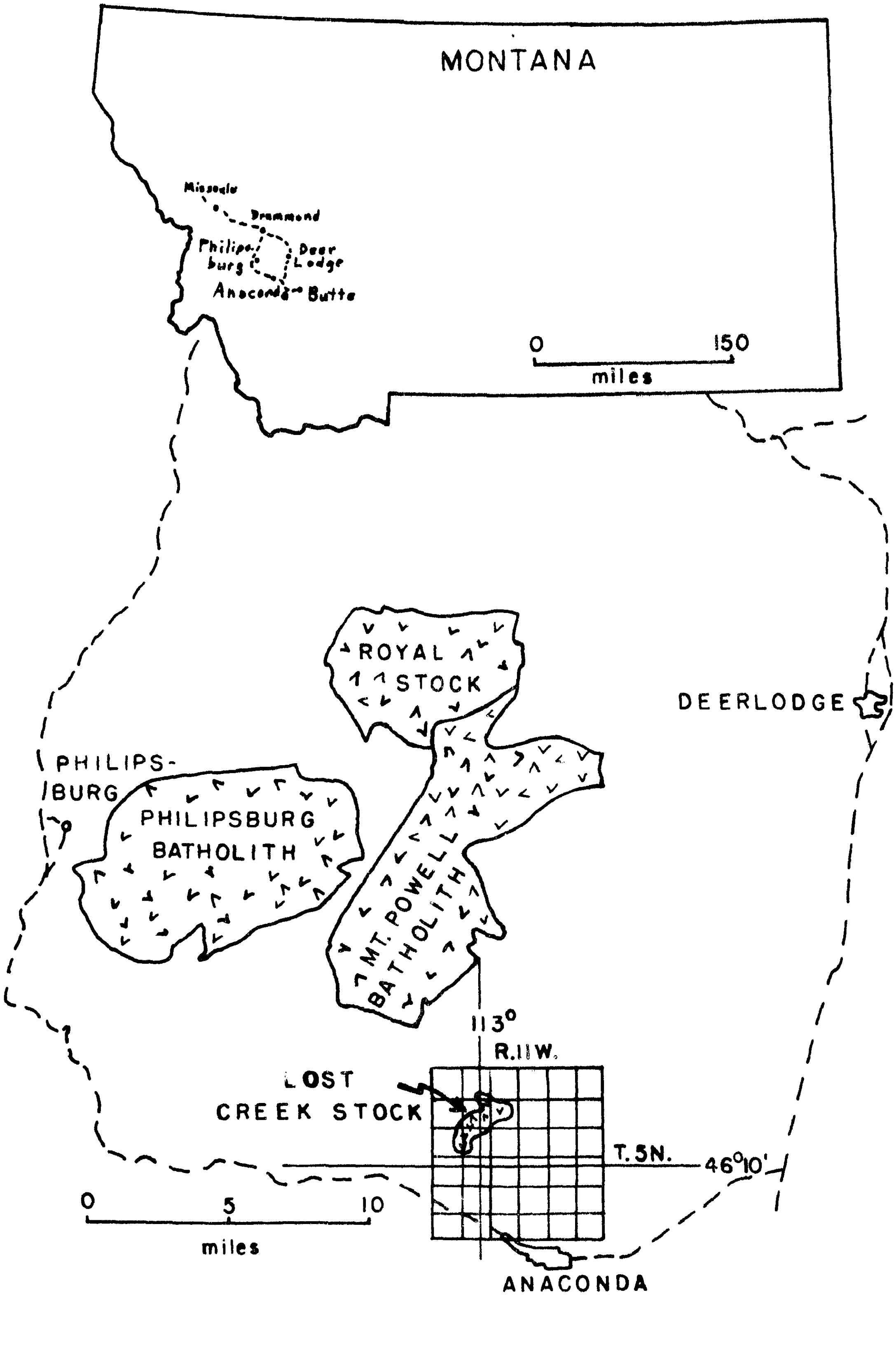
[1]This study is supported by National Science Foundation grant GA 1286 to A. J. Silverman and D. W. Hyndman.

FIGURE I. LOCATION MAP--LOST CREEK STOCK



1915 Calkins and Emmons (1915) mapped the Philipsburg area, including the area of the Lost Creek stock. Their correlations and stratigraphy are only slightly changed today.

Regional Geology

Western Montana is dominated by thrust plates, later normal faults and larger lineaments of regional extent. Configuration of these features led McMannis (1965) to generalize four major tectonic provinces for Montana (Fig. 2). The Flint Creek Range is located in the Batholithic province which is characterized by granitic plutons, reoccurring faults, and eastward wedging.

The stratigraphic column (Table 1) for the Flint Creek Range contains most of the units from upper Precambrian to Recent, except those of Ordovician, Silurian and Triassic age. Sedimentary units represented in the area of the Lost Creek stock are the Newland formation, Madison limestone, and Tertiary sedimentary rocks and volcanic rocks. The metamorphism and the major deformation of the above units occurred between late Cretaceous and Eocene time (Laramide orogeny). During the late Laramide, Precambrian to Cretaceous rocks were intruded by the granitic plutons which comprise the bulk of the Flint Creek Range today. The Philipsburg batholith has been dated as Middle Eocene (50 million years). All the granitic intrusions in the

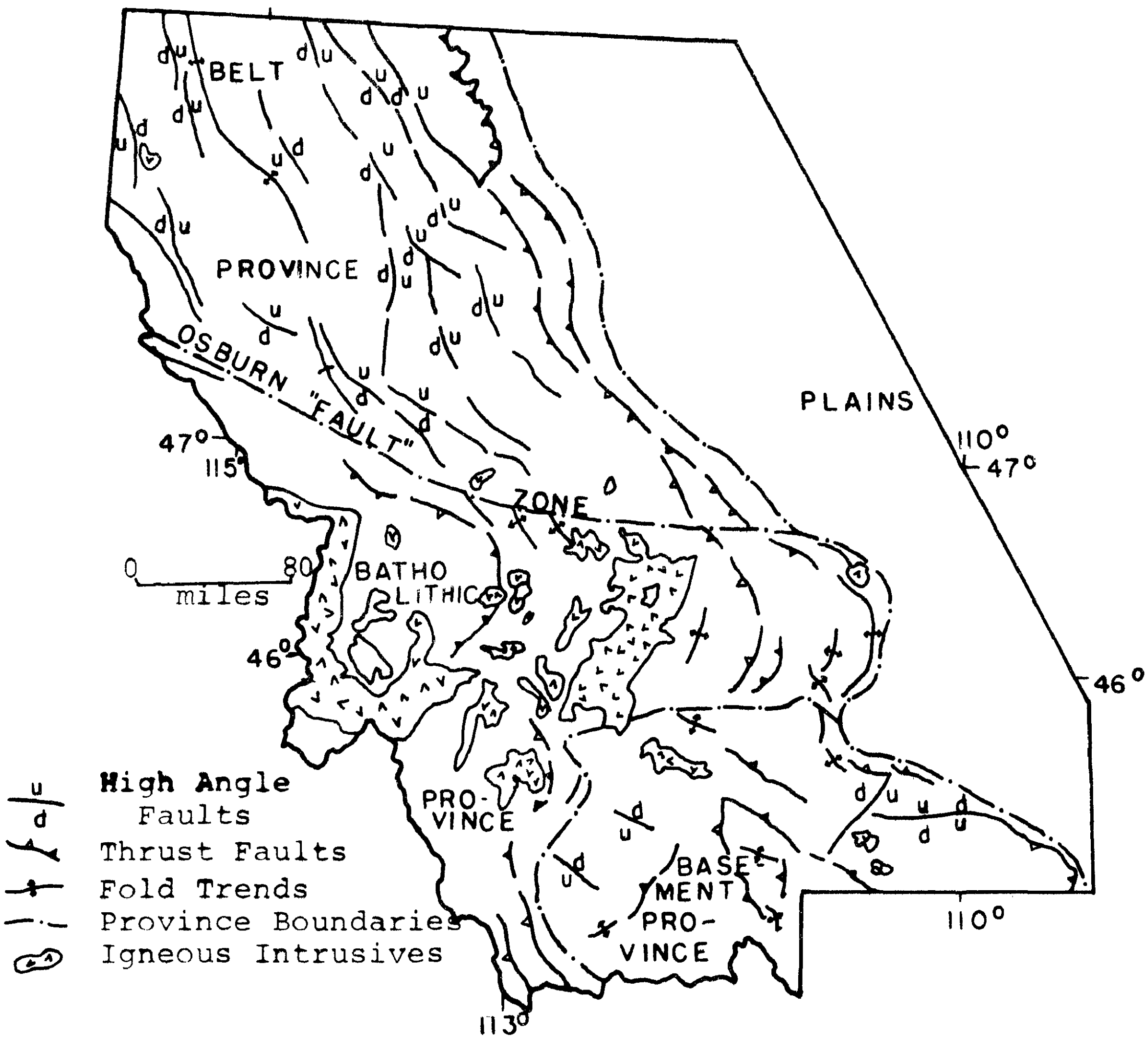


Figure 2. Generalized tectonic map of western Montana, showing major provinces. (Modified from McMannis, 1965).

Table 1. Stratigraphic Column of the Flint Creek Range. (Csejtey, 1963).

	SERIES	FORMATION	ORIGINAL LITHOLOGY	THICKNESS
TERTIARY			Gravels	800'
			Gravels	2500'
		Lowland Ck.	Volcanics	3000'
CRETA-CEOUS	Lower	Colorado Gr.	ss, siltstone, mud-stone, shale	2400'
		Kootenai Fm.	ss, siltstone, mud-stone, shale, lime-stone	1250'
JUR-RASIC	Middle & Upper	Jurassic Undiff.	calcareous silt-stone, shale, ss	200'
PER-MIAN		Permian Undiff.	carbonate, ss, chert, phosphate	175'
CARBO-NIFEROUS	Penn.	Quadrant Qtzt	quartzite	120'
		Amsden Fm.	siltstone, shale	200'
	?			
	Miss.	Madison Ls.	limestone	1000'
DEVO-NIAN	Upper	Jefferson Fm.	limestone, dolomite	850'
		Maywood Fm.	siltstone, ss	275'
CAMBRIAN	Upper			
	?			
	Middle	Red Lion Fm.	limestone	330'
		Hasmark Dolom.	dolomite	1100'
		Silver Hill Fm.	limestone, shale	330'
		Flathead Qtzt.	quartzite	160'
PRECAM-BRIAN	Belt	Missoula Gr.	shale, quartzite	1700-700'
		Newland Fm.	limestone, shale	?

Flint Creek Range are considered approximately comagmatic with the Philipsburg batholith (Csejtey, 1963).

The above activity has produced the complex geology seen in the Flint Creek Range today (Fig. 3). Figure 4 shows a general structure section of the Flint Creek Range.

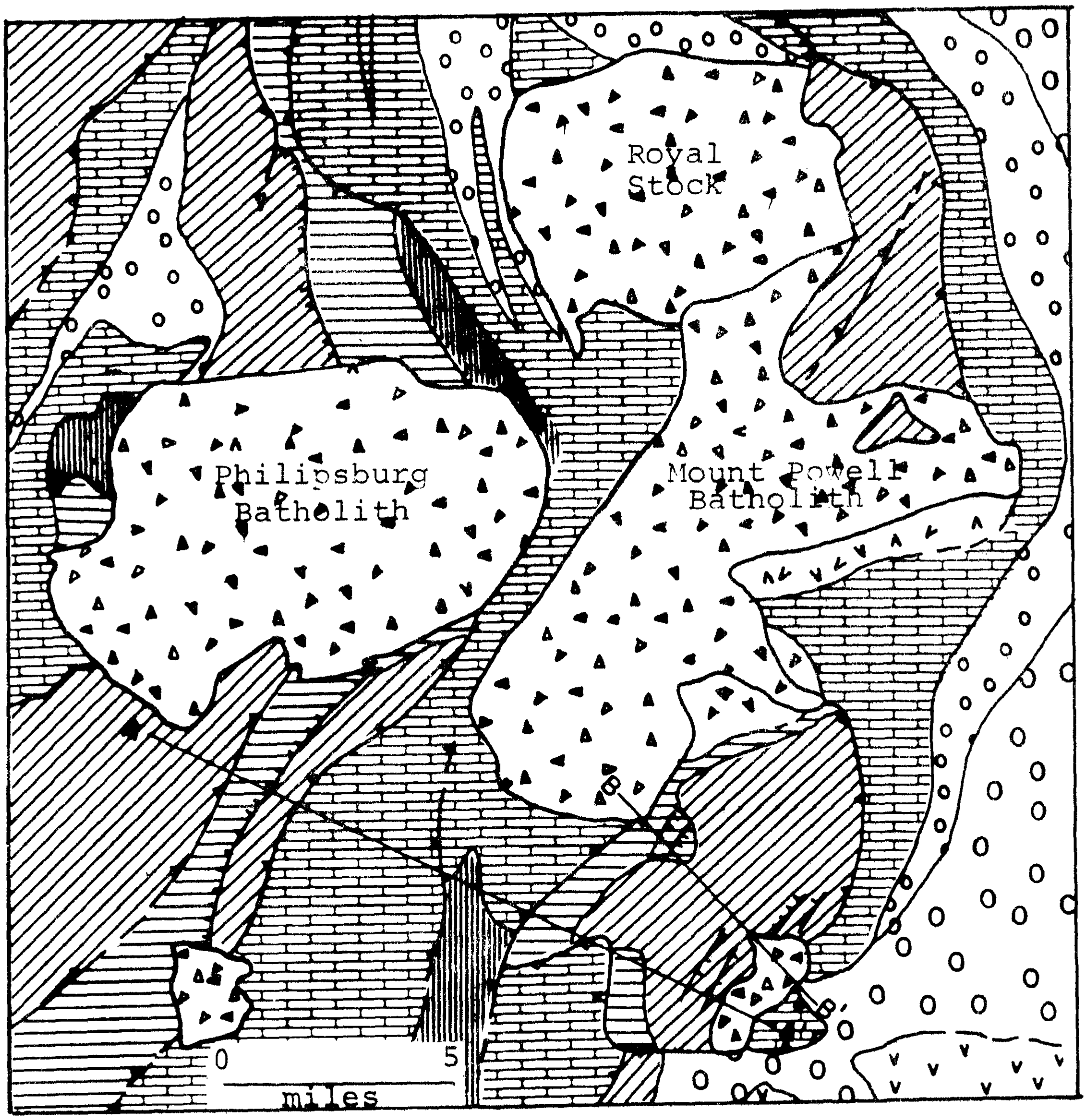


Figure 3. General geologic map of the area of the Flint Creek plutons. Simplified from Emmons and Calkins (1915), Csejtey (1962), McGill (1964), and Mutch (1964).

Sediments and Meta-sedimentary Rocks

- Tertiary
- Cretaceous
- Carboniferous
- Devonian
- Cambrian
- Precambrian (Belt)

Volcanics and Igneous Rocks

- Tertiary Volcanics
- Tertiary and Cretaceous Intrusives

- Thrust fault (teeth on plate)
- High angle fault (teeth on down-block)

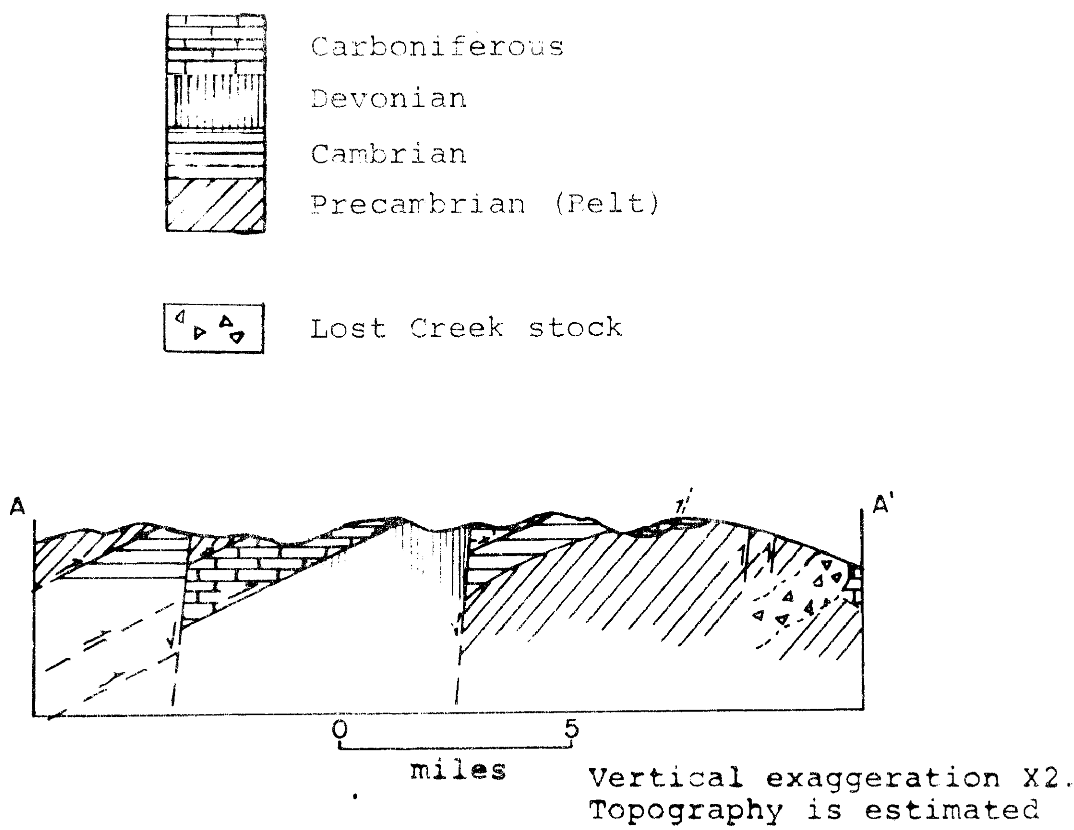


Figure 4. Generalized structure section of the Flint Creek Range constructed from Figure 3. For simplicity, folds are not shown.

Chapter 2

METHODS

Field

1:24,000 topographic coverage is available only east of the 113° meridian (Fig. 1) which cuts through the center of the Lost Creek stock. Initially pace and compass traverses were made and obvious land marks were located within the canyon. Sample locations could then be triangulated. Large aerial photographs (1 mile = 7 inches) were obtained and the locations were also plotted on these.

Outcrops were excellent in the deep northwest-southeast canyon cutting through the stock but generally poor on the higher elevations outside the canyon. Therefore collecting was not done on a grid system. Need and outcrop availability dictated the sample locations. Forty-seven samples were collected. All orientation data were collected with a brunton compass.

Laboratory

Each of the samples were cut into three pieces: a slab for staining, a slab for thin section and a piece for crushing. Fifty-two thin sections were prepared and 19 stained slabs were used in modal analysis.

Sodium cobaltinitrate and amaranth stains were used to aid in point counting potassium feldspar and plagioclase, respectively, and in estimating perthite percentages.

Universal stage measurements were made for anorthite content on several plagioclase grains, as a check on the flat stage bisectrix method which proved to be accurate and consistent with the Slemmons method (Appendix, p. 56). The universal stage was also used for 2V measurements on alkali feldspars. Composition of the alkali feldspar was found by measurement of n_y in oils checked to ±.001 on an Abbe type refractometer.

Some weathering and hydrothermal alteration products were identified with the X-ray diffractometer (Appendix, p. 57).

Chapter 3

PETROGRAPHY

Lost Creek Stock

Weathering and other alterations, plus variations in texture have produced a very inhomogeneous appearance in these rocks. Color varies from distinctly red in the upper and eastern reaches of the stock (Plate 1) to gray in the lower and western reaches, particularly in the Lost Creek Canyon area. Petrographically the rocks are similar despite their differences in appearance (Table 2). Anorthite content of the calcic plagioclase varies only a few percent. Albite content of the orthoclase/microcline, based on n_y, from five scattered samples was consistent. The only mineralogical variations were in the amount of perthite present, the textures of these perthites, and modal percentages.

Perthite. Perthite textures include all but the penetrating and interlocking types according to the classification of Alling (1938) (Fig. 5). Plates 2-4 show some of the perthite textures seen in the Lost Creek rocks. The texture shown in Plate 2 undoubtedly resulted from exsolution but textures as seen in Plates 3 and 4 could be

Plate 1. Red color displayed by upper portions of pluton. (In the vicinity of LC9-6). View is south toward the Anaconda Pintlar Range.

Table 2. Modal analyses of 19 Lost Creek stock samples (minimum of 1,010 counts per sample).

Sample	Quartz	Plag.	Potassic feldspar	Biotite	Perthite	An_{plag}	$Ab_{K-felds}$	Accessories	Ab/An_{rock}
LC2-1	39.5	31.4	23.0	6.1	7.0	30	--	Fluorite Apatite	3.4
LC3-1	33.6	29.8	30.0	6.6	3.9	31	28	Zircon Hematite	3.3
LC3-2A	32.1	32.3	33.0	2.6	3.0	31	28	Zircon	3.3
LC4-1	33.8	36.1	26.6	3.5	10.0	30	--	Zircon Apatite Hematite	3.5
LC4-2 (dike)	35.8	10.4	53.8	tr.	1.0	30	--	Sericite Muscovite	7.1
LC5-1	35.7	25.1	36.3	2.9	2.0	31	--	Muscovite Hematite Fluorite Sphene	3.6
LC5-2	40.6	21.9	33.5	4.0	1.0	29	--	Muscovite Hematite Chlorite	4.0
LC6-1	27.1	37.0	31.5	4.4	10.0	32	28	Sphene Zircon	2.6
LC7-2	28.6	44.0	22.8	4.6	5.0	28	28	Muscovite Sphene	3.3

Table 2--Continued

Sample	Quartz	Plag.	Potassic feldspar	Biotite	Perthite	An_{plag}	$Ab_{K\text{-}felds}$	Accessories	An/An_{rock}
LC7-3	19.6	54.7	8.8	16.9	5.0	30	--	Muscovite Zircon Fluorite Apatite	2.7
LC8-2	36.8	26.9	30.5	5.7	10.0	30	--	Muscovite Hematite	4.0
LC8-5	22.7	39.9	28.3	9.1	15.0	28	--	Sphene Chlorite Hematite Muscovite Pyrite	4.0
LC8-5A	29.0	40.3	27.7	3.0	12.0	30	--	Muscovite Hematite	4.0
LC9-1	31.4	32.1	30.5	6.0	20.0	31	28	Zircon Pyrite	4.2
LC9-2	29.1	28.2	37.1	5.6	15.0	30	--	Zircon Pyrite Muscovite Hematite	4.5
LC9-3	23.5	40.1	35.0	1.4	5.0	31	--	Apatite Zircon Hematite Pyrite Chlorite	3.3

Table 2--Continued

Sample	Quartz	Plag.	Potassic feldspar	Biotite	Perthite	An_{plag}	$Ab_{K\text{-}felds}$	Accessories	Ab/An_{rock}
LC9-4	33.3	27.9	35.6	3.2	20.0	31	--	Fluorite Sphene	4.6
LC9-5	30.1	33.3	31.3	5.3	15.0	30	--	Fluorite Hematite	4.0
LC9-6	36.3	31.8	27.0	4.9	15.0	30	28	Muscovite Pyrite Hematite	4.0

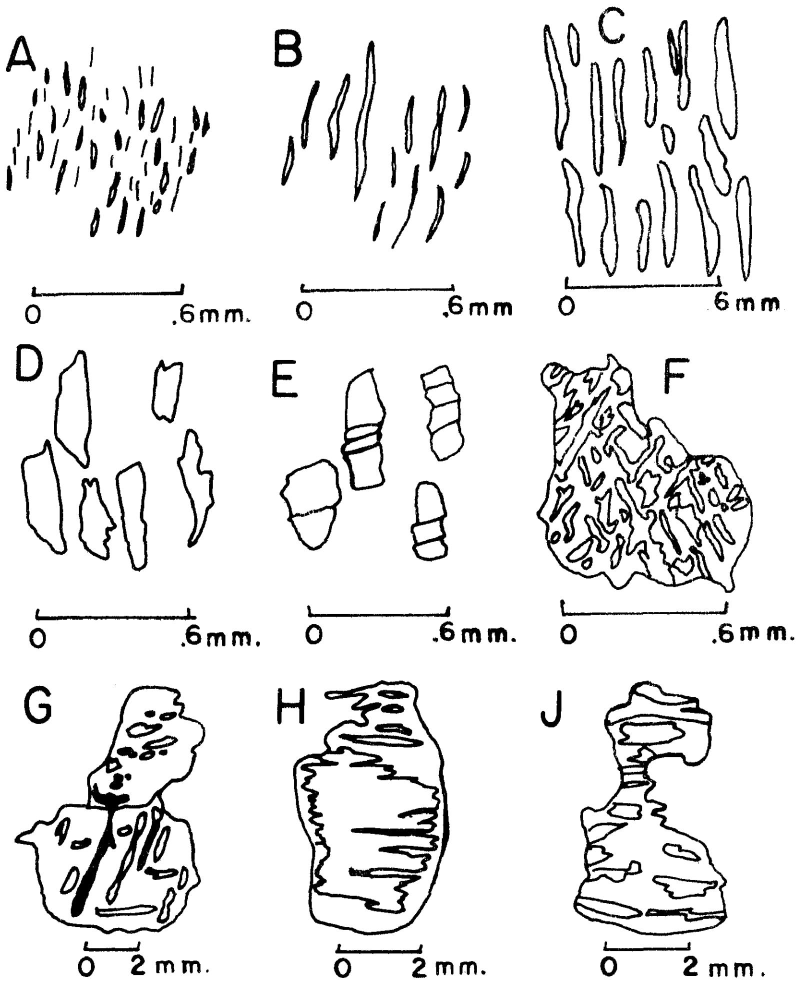


Figure 5. Perthitic types: A) Stringlets. B) Strings. C) Rods. D) Beads. E) Fractured beads. F) Penetrating film. G) Interpenetrating film. H and J) Replacing plume, soda orthoclase replacing albite-oligoclase. (Alling, 1938).

0 1mm

Plate 2. Exsolution perthite (LC8-5).

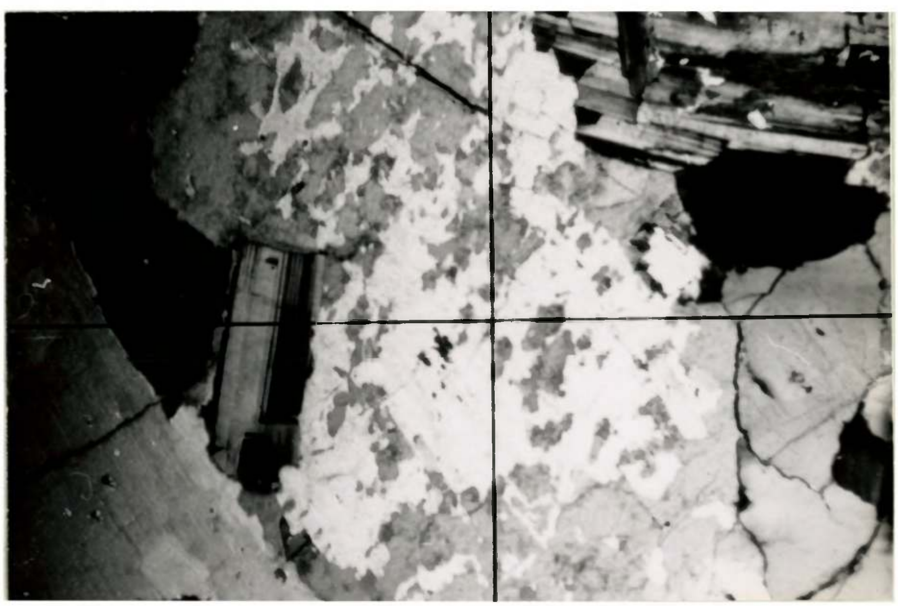


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Plate 3. Exsolution or replacement perthite (LC9-2).

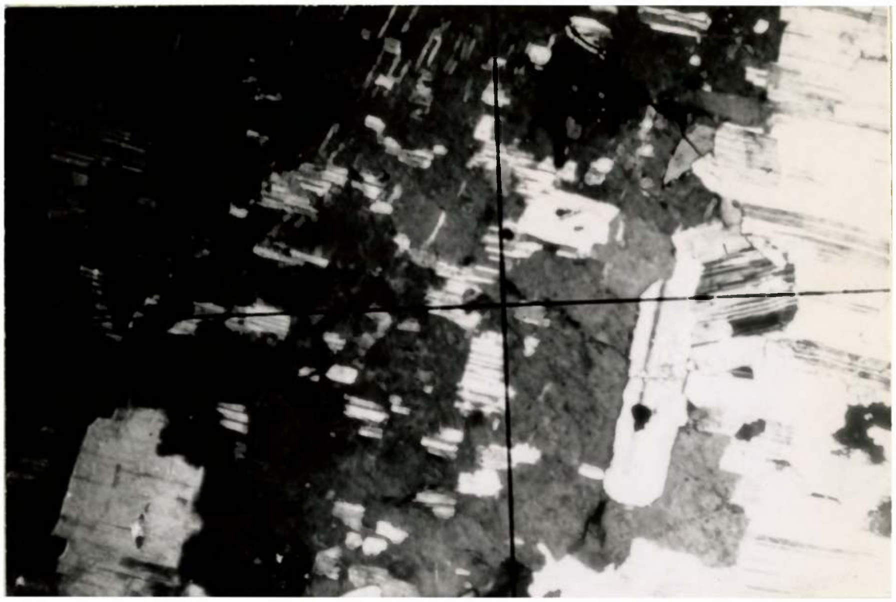

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Plate 4. Exsolution or replacement perthite (LC9-4).

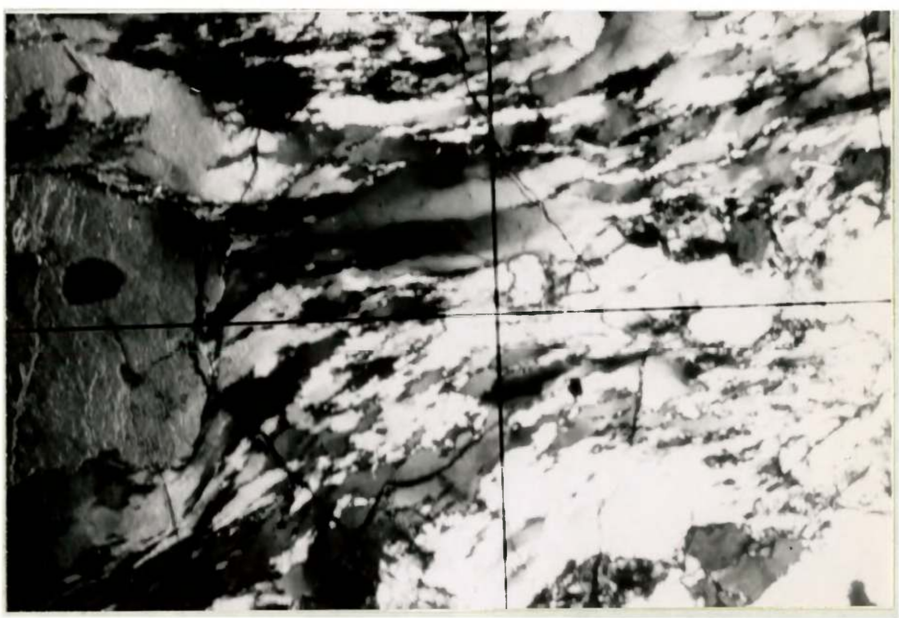

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Plate 5. Granulated granite. Quartz streaked out around a feldspar grain (LC5-2).

simultaneous (eutectic) crystallization or replacement of albite by potassium-rich residual fluids. However, the extinction positions from albite bleb to bleb do not match, suggesting exsolution progressing ultimately to a stage in which the feldspars could completely separate. All the albite in these rocks is considered to be formed by unmixing, but another possibility exists, the albite of Plates 3 and 4 could be replacing the potassic feldspar.

Quartz. Undulose extinction is very common and in the granulated and mylonitic samples the quartz appears streaked out (Plate 5). In these mylonitic rocks quartz streaks generally have uniform extinction. It is always anhedral.

Orthoclase/microcline. This is the designation chosen for the alkali feldspar. It does not appear to be entirely of one form or the other. Plaid twinning is present but commonly not well developed. A green variety in the northwestern portion of the pluton also appears to be an intermediate form.

$2V_x$ is determined to be 75-80° (Appendix, p. 56),[2] and the albite content determined by refractive index, is Ab_{28}, quite high for a microcline. The feldspar is taken to be an intermediate microcline (Figs. 6 and 7).

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[2]Five of the sixteen measurements gave a $2V_x$ of 60-66°. This bimodal occurrence of $2V_x$ probably indicates a structural change in the feldspars (Fig. 6).

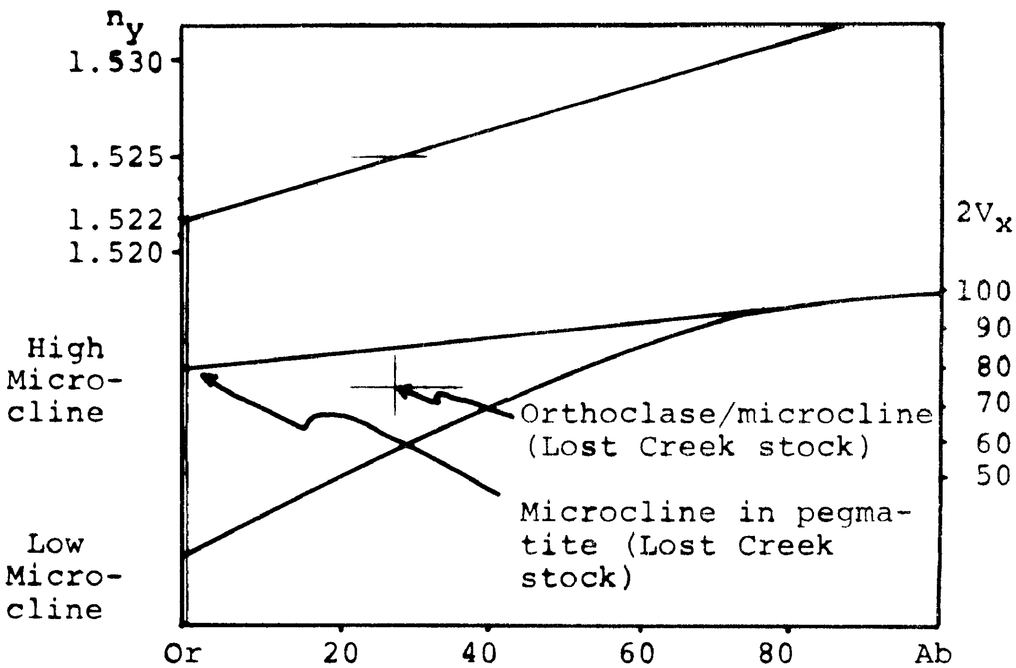

Figure 6. Index of refraction (n_y) and $2V_x$ of the microcline and orthoclase/microcline of the Lost Creek stock (modified from Troger, 1956).

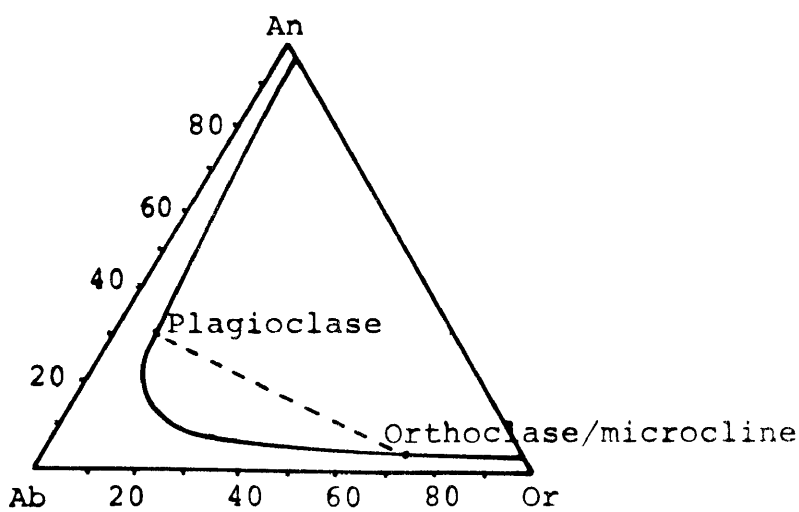

Figure 7. Coexisting feldspars (Lost Creek stock) (modified from Deer, Howie and Zussman, 1966).

The grains are anhedral except in one sample of dike rock (LC4-2) in which they are subhedral.

Plagioclase. An content is consistently about An_{30}, the range being An_{28-33}. Unlike the orthoclase/microcline or the exsolved albite, the plagioclase is euhedral to subhedral. In contrast to the plagiocalse of the Mount Powell batholith, the grains show no zoning. The only variation is in the amount of plagioclase present. The range is about 10.4% in a dike rock (LC4-2) to 53.8% (LC7-3) in a contact portion of the stock.

Biotite. Biotite is present in all samples except LC4-2 and is subhedral to anhedral. Pleochroism varies from Z = greenish black to reddish brown. X is light green to colorless. Biotite often shows some replacement by chlorite and is commonly associated with muscovite.

Accessory Minerals. Muscovite is associated with biotite (Plate 6). In samples LC7-2 and LC8-1 the muscovite is enclosed by quartz. Rarely does it occur in the plagioclase. Sericite is usually present in small amounts but alteration is slight. Chlorite is generally present, in most cases replacing biotite. Hematite or limonite occur as a stain, often on grain boundaries or as euhedral crystals in or around biotite. Magnetite is rarer, its occurrence is also associated with biotite. Pyrite is present in the

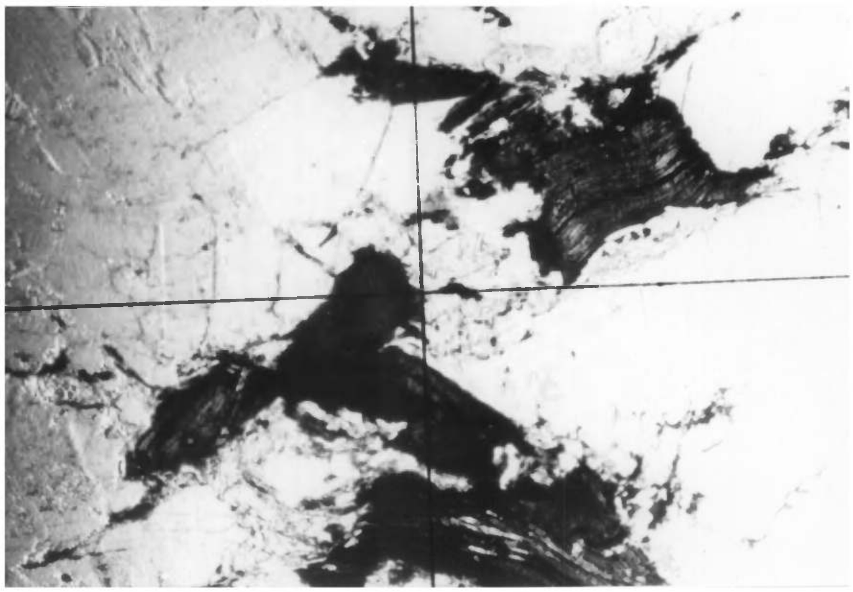

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Plate 6. Muscovite associated with biotite. Muscovite is the high relief material around the black biotite (LC8-1).

southern part of the pluton. Biotite or muscovite encloses euhedral pyrite grains. Fluorite appears in many thin sections as interstitial grains. It is also found in some of the metamorphic rocks around the pluton. Zircon, apatite, and sphene are nearly ubiquitous and all are euhedral. Epidote was found only in one thin section.

Paragenesis. Based on textural evidence from thin sections, a general sequence of crystallization is presented in Table 3. But much of the textural evidence is ambiguous, particularly that involving feldspars and perthites. Examination of Figure 14 (p. 42) reveals that plagioclase should crystallize first. Upon reaching the cotectic, plagioclase and quartz would crystallize. Upon reaching the ternary minimum the remaining orthoclase, plagioclase and quartz would crystallize.

Mount Powell Batholith

Mineralogy of the Lost Creek stock is very similar to this batholith. Comparison of Table 4 with Table 2 will reveal that the Lost Creek stock rocks average 5% more quartz, 5% more alkali feldspar and 10% less plagioclase.

Accessory minerals, both primary and deuteric, are less abundant. In the Mount Powell batholith, sphene, magnetite, zircon, apatite and ± muscovite are all commonly

Table 3. Mineral paragenesis suggested by textural relationships. Textural relations between quartz and feldspar suggest no sequence. Quartz before microcline is inferred from Figure 14.

Stage	Order	Mineral	Textural evidence
Primary	1	Zircon Sphene Hematite Magnetite	Euhedral and enclosed by all other minerals
	2	Plagioclase	Euhedral and enclosed by microcline, quartz and biotite
	3	Quartz	In part interstitial around both feldspars, but probably before orthoclase/microcline (Fig. 14, p. 42). Always anhedral
	4	Microcline	In part interstitial around both feldspars. Sometimes subhedral in dike rock
	5	Biotite	Interstitial around both feldspars and quartz. Subhedral to anhedral
Deuteric	6	Fluorite	Interstitial, anhedral
	7	Perthite	Stringlets to beads to replacement. Sometimes separate albite grains, but generally within microcline
	8	Muscovite Chlorite Hematite	All three usually associated with a corroded biotite grain. Muscovite in some cases in plagioclase. Epidote in one slide
Hydro-thermal	9	Sericite	In plagioclase
	10	Pyrite Sericite Bornite	Introduction by hydrothermal solutions. Anhedral to euhedral crystals

Table 4. Modal analyses of 23 Mount Powell batholith samples.[3]

Sample	Quartz	Plagioclase	K-spar	Biotite + Muscovite	An_{plag}	An/An_{rock}
H6-1	35.8	40.1	17.6	6.5	30	2.7
H6-2	40.2	33.2	20.7	5.9	34	2.4
H6-3	24.3	49.4	15.7	10.6	33	2.3
H7-4	24.3	51.2	16.8	7.7	33	2.3
H7-5	19.3	40.7	27.1	12.9	35	2.3
H7-9	30.9	39.8	18.8	10.5	30	2.5
H8-1	27.0	40.9	26.2	5.9	28	2.9
H8-2	29.2	47.5	19.5	3.8	33	2.3
H8-10	32.5	38.0	23.5	6.0	30	2.8
H8-11	31.4	45.1	15.3	8.2	26	3.2
H10-2	28.7	38.7	20.6	12.0	32	2.5
H10-4	30.4	36.9	19.3	13.4	30	2.8
H12-1	10.7	46.8	35.9	6.6	28	3.3
H12-2	17.2	55.5	21.6	5.7	30	2.7
H12-4	31.3	39.6	24.1	5.0	31	2.7
H12-9	36.6	41.8	15.0	6.6	33	2.3
H15-1	21.6	51.6	13.0	13.8	36	2.0
H15-12	35.9	47.8	16.8	9.5	31	2.5
H16-1	39.4	38.6	12.3	9.7	33	2.3
H16-3	28.9	45.8	18.2	7.1	29	2.8
H16-8	28.8	51.1	14.3	5.8	34	2.2
H16-12	42.3	40.3	10.6	6.8	34	2.1
H17-3	36.2	35.8	14.5	13.5	23	3.8

[3]Data compiled from Hyndman and Silverman, 1969, unpublished work, in conjunction with N.S.F. grant GA 1286 and Cheney, 1969, Senior Problem.

present as the primary suite, whereas chlorite, epidote, sericite and ± muscovite form the deuteric suite.

Also notable is the alkali feldspar. It is very similar to the orthoclase/microcline feldspar in the Lost Creek stock. A green variety occurs in the southeastern part of the batholith closest to the stock, and in the associated dikes (Fig. 9, p. 30). Plaid twinning is present but poorly developed.

Metamorphosed Diabasic Sills

There exists some enigmatic bodies of rock in the area. In the Lost Creek area these rocks are referred to as mafic sills, usually a diorite to diabasic rock (Calkins and Emmons, 1915; Csejtey, 1963). The Lost Creek stock is intrusive to these sills, just as the Mount Powell batholith is intrusive to the Racetrack Creek "pluton." Mineralogy for four locations sampled in the Lost Creek area is as follows:

Hornblende	60-70%
Plagioclase	20-30%
Biotite	Tr-5%
Quartz	0-5%
Magnetite	Tr-2%
Rutile	Tr
Apatite	Tr

Texture of three of the four samples was subophitic with euhedral to subhedral hornblende. Grain size is constant at 1 mm.

Here in the Lost Creek area these units do appear to be metamorphosed diabasic sills, but a little farther north the Racetrack Creek "pluton" appears to be a regional metamorphic amphibolite. Mineralogy for ten samples is as follows:[4]

Hornblende	20-40%	Range 10-75%
Plagioclase	20-55%	
Biotite	10%	Range 0-15%
Quartz	5-20%	
Magnetite	Tr-2%	
Sphene	1%	
Chlorite	0-15%	

Both plutons are intrusive to a mineralogically similar body. The diabasic sills in the Lost Creek canyon are, therefore, considered to be the southern most extent of the Racetrack Creek "pluton."

[4]Data compiled from Hyndman and Silverman, 1969, unpublished work, in conjunction with N.S.F. grant GA 1286.

Chapter 4

PETROLOGY

Considering the close geographical relation of the Lost Creek stock to the Mount Powell batholith and the similarity in mineralogy, one would suspect a possible genetic relationship between the two. For this reason a compositional diagram (Fig. 8) of a scattering of Mount Powell samples (Fig. 9) was constructed. Note that the bulk of the Mount Powell rocks lie in the granodiorite field, whereas the Lost Creek rocks are more felsic, monzogranite by Streckeisen's (1967) classification. This does suggest the possibility of a compositional relationship. There are two possibilities which would account for this compositional relationship.

1) The Lost Creek stock is a more felsic differentiate from the Mount Powell batholith.
2) The Lost Creek stock is a direct product of anatexis and represents a lower temperature melt or has assimilated less than the Mount Powell batholith.

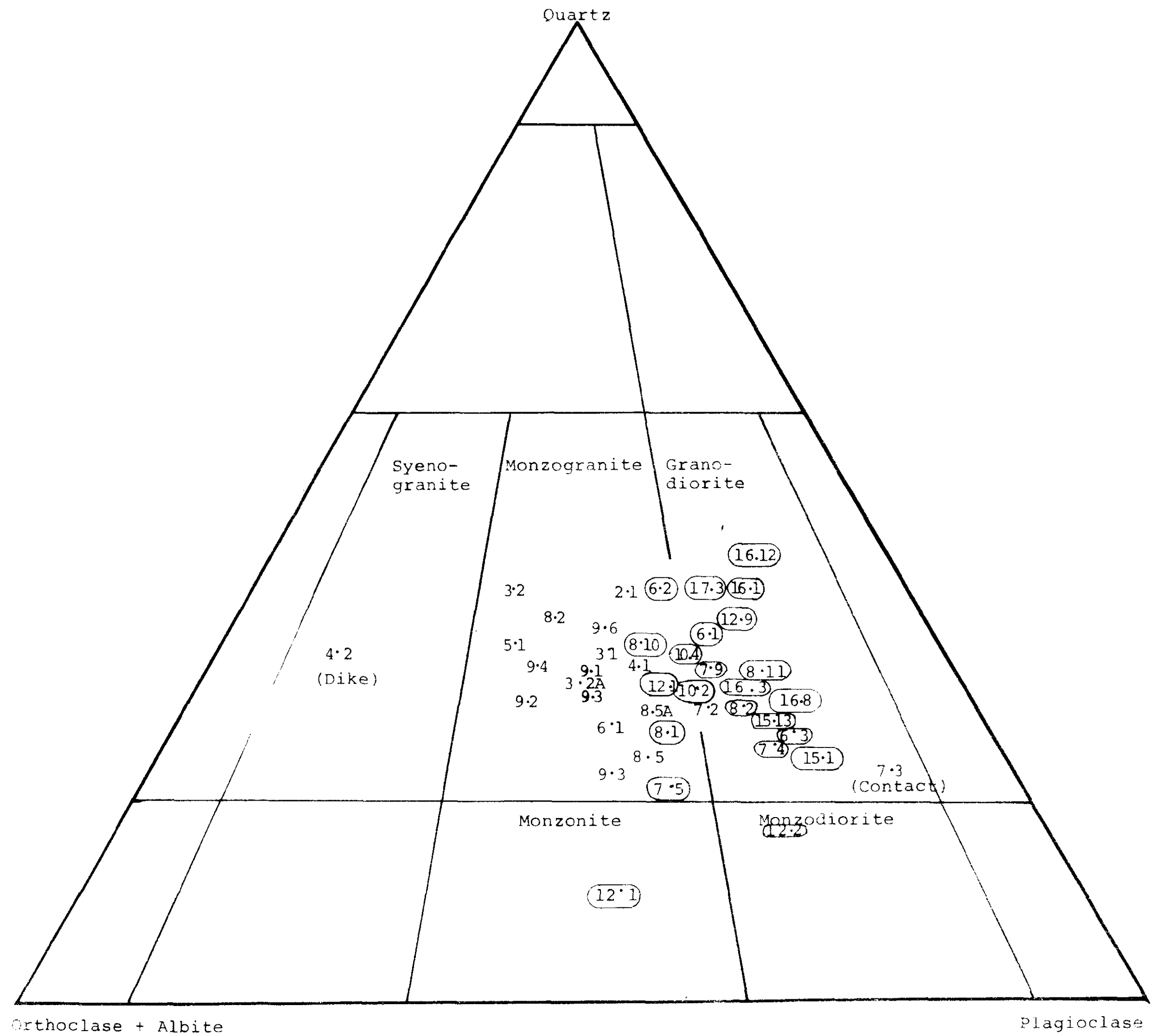
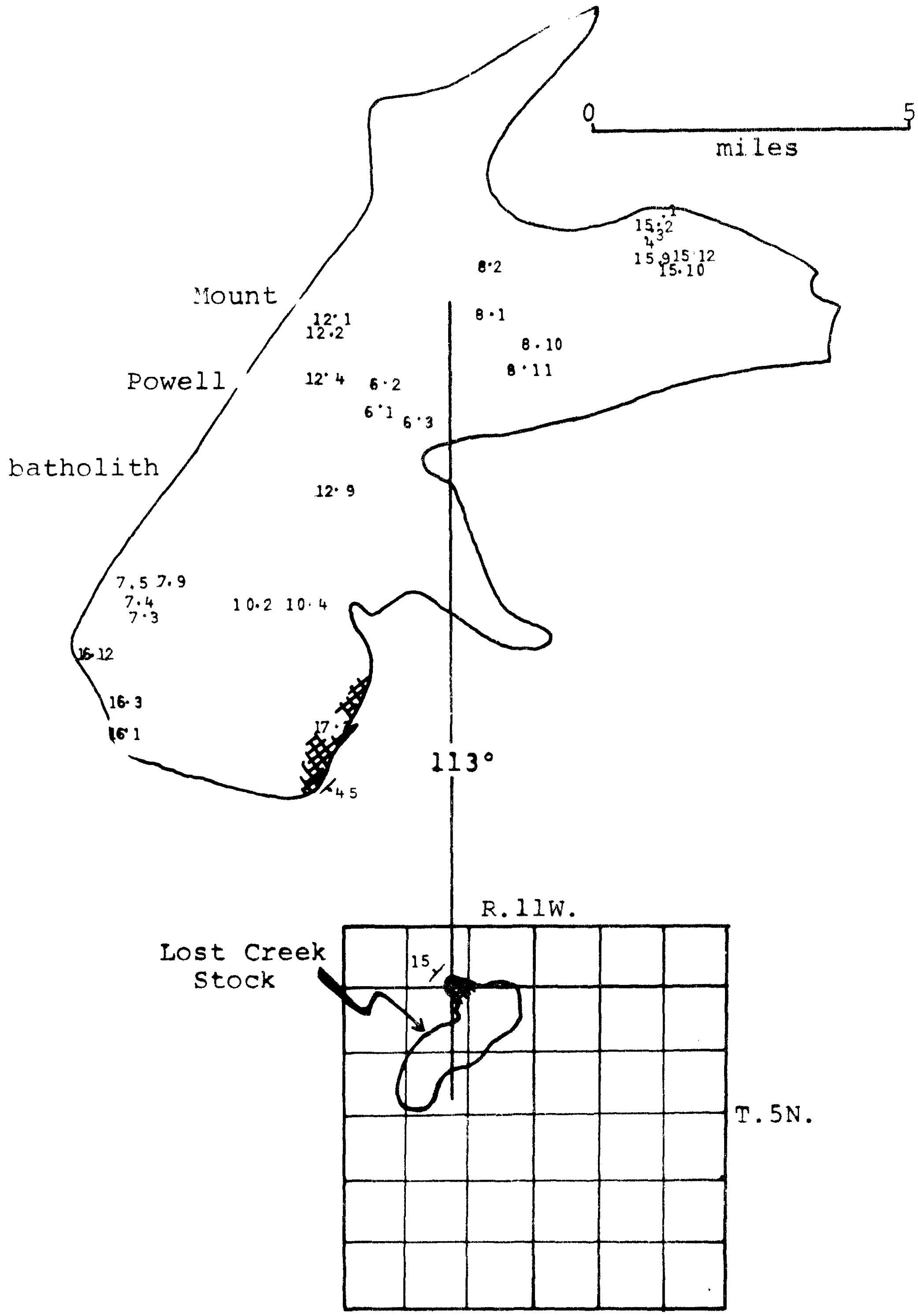


Figure 8. Compositional diagram after Streckeisen, 1967. 23 Mount Powell rocks. 19 Lost Creek rocks. (Mount Powell samples are circled).

Figure 9. Sample locations for the Mount Powell batholith. Cross-hatching shows areas of green orthoclase/microcline. Strike and dip of the intrusive contacts in the area of the green orthoclase/microcline is also shown.



To try to distinguish between these two possibilities the analyses were recalculated and plotted on an An-Ab-Or diagram (Fig. 10). Note that the Mount Powell distribution does define a crystallization path. Assuming H15-1 to be the original melt composition, the indicated crystallization path appears to be a disequilibrium fractional crystallization. The crystallization path curves very strongly toward the Or corner. The zoned plagioclase of the Mount Powell rocks also support disequilibrium, for the grains have increasingly more sodic rims. This means the melt became more sodic as crystallization continued. The equilibrium path would lie somewhat closer to the Ab corner.

The Lost Creek stock represents equilibrium crystallization after derivation of a small body of magma from the remaining Mount Powell magma. Because crystallization has proceeded from a granodiorite to a monzogranite, the magma loss by the Mount Powell magma body occurred late in its crystallization history.

Examination of the Lost Creek stock sample locations (Figs. 10 and 11) explains the variation of the Lost Creek composition. LC7-3 and LC7-2 are locations at the contact of the pluton with a limestone of the Newland formation in the Belt Supergroup. These probably acquired Ca from, and lost K to, the country rocks. LC5-2 and LC4-2 are the other extremity, presumably produced by differentiation. All other sample compositions lie between these two groups.

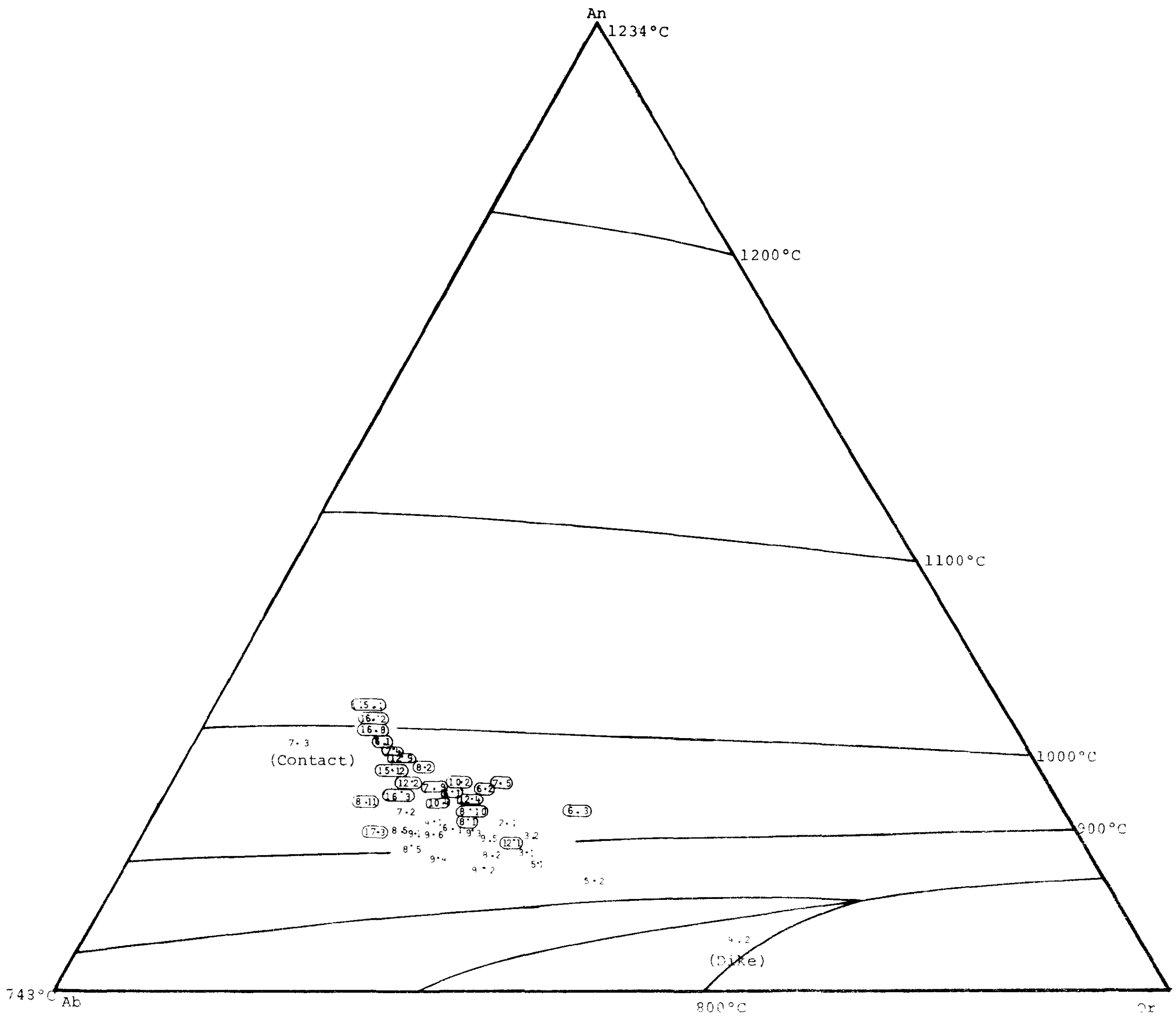


Figure 10. An-Ab-Or System at 5 kb. (Hyndman, 1970). Crystallization path of the Mount Powell magma. Note modifying of the Lost Creek stock composition due to limited assimilation and differentiation. Mount Powell samples are circled.

Figure 11. Lost Creek stock.

Road through Lost Creek canyon
Sample location
Foliation in granite
Bedding
Mylonitic veins
Thrust faults
Area of green orthoclase/microcline
Mylonitic zones
Tertiary
Madison limestone
Silicified Madison limestone
Precambrian (Belt)(Newland fm.)

The close proximity of the batholith and the stock plus the petrologic considerations are highly suggestive of a differentiation relationship. Inclination of the stock to the northwest in the direction of the Mount Powell batholith (Figs. 9 and 18) is also suggestive, perhaps even of a direct connection. Further evidence is the green orthoclase/microcline occurring in both plutons including the associated pegmatites.

The pegmatites of the Lost Creek pluton contain a high microcline of essentially no albite content (Fig. 6). Because green microcline exists in both the pegmatites and the pluton proper, it is evident that these pegmatites were generated from the pluton composition. The pegmatite modal estimate is Q = 30%, Ab = 35%, and Or = 35% with some muscovite and fluorite present (Appendix, p. 58). This is close to the ratios given by Winkler (1967) for minimum melts produced at pressures greater than 2 kb with no anorthite in the system (Table 6, p. 41).

The presence of fluorite in the contact rocks, pegmatites and pluton, plus the presence of scapolite in some contact rocks, indicates a loss of the volatiles water, fluorine, and possibly CO_2 from the pluton. Volatiles appear to have concentrated in the outer portions of the pluton as shown by the aplite-pegmatite border zone.

In the northwestern portion of the stock this is very well displayed. Pegmatite-aplite complexes have formed, sometimes discernible as dikes parallel to the contact but generally as a parallel gradational zone along the contact. Assimilation is only locally important, for example in the area of LC7-3 (Fig. 11).

Chapter 5

ENVIRONMENT OF CRYSTALLIZATION

To establish the pressure-temperature conditions of crystallization, several methods are used, including (1) Barth's feldspar geothermometer, (2) Winkler's "minimum melt" curves, and (3) contact metamorphic assemblages. Comparison of the above with the granodiorite melting curve should establish the environment within acceptable limits.

Barth's Feldspar Geothermometer

This method is dependent on the partitioning of the albite molecule between alkali feldspar and plagioclase. The ratio $\frac{\text{mole \% Ab in K-spar}}{\text{mole \% Ab in plag.}} = K_d$ should then be constant for a particular temperature (Barth, 1956a). This value is .4 for the Lost Creek rocks and when plotted in Figure 12 indicates a minimum temperature of crystallization of about 680°C.[5] The slope of line a-a represents ordered feldspars. The dotted line was drawn by Barth to account for the gradational structural changes in the feldspars.

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[5] Temperatures by this method are accurate to ± 50°C.

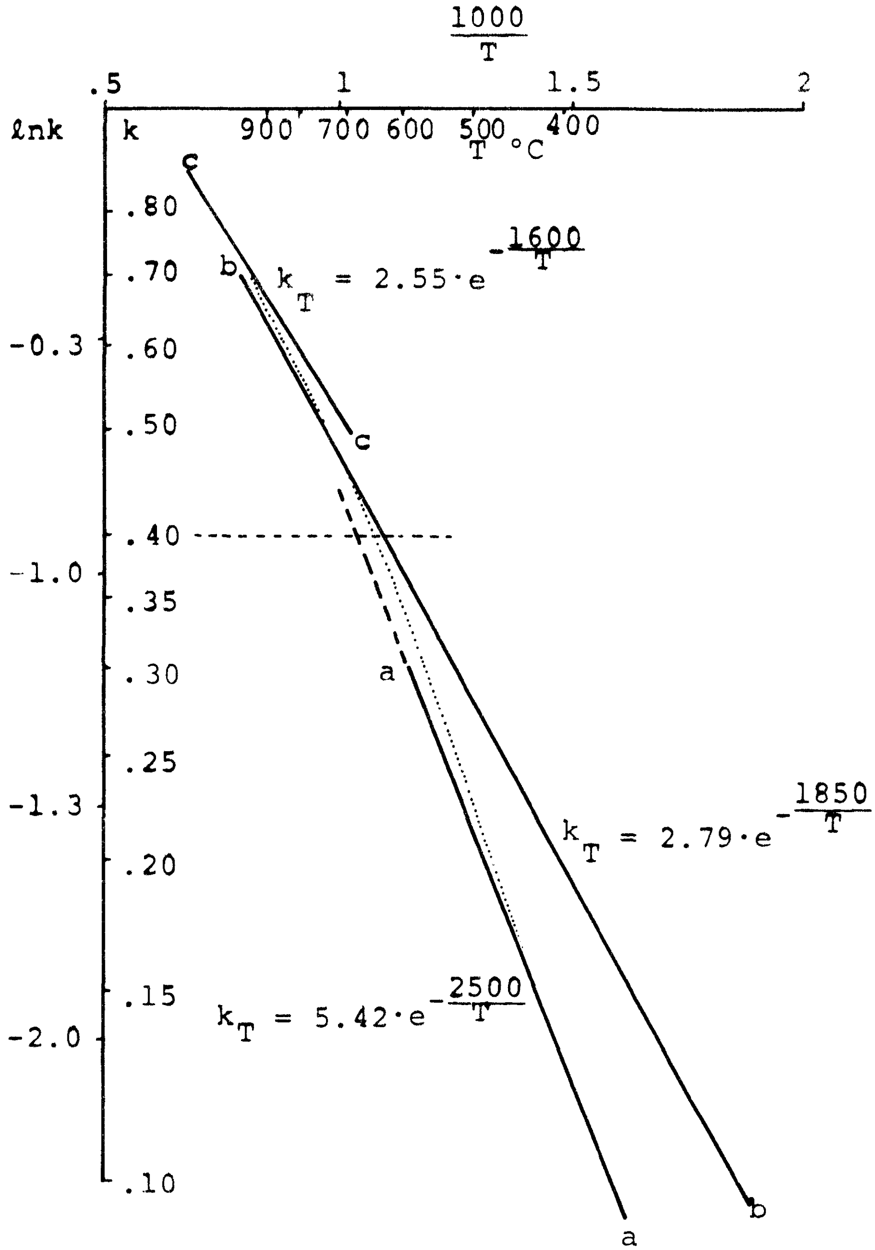

Figure 12. Relation between temperature and the ratio of distribution of albite between K-feldspar and plagioclase. Abscissa: the inverse of the absolute temperature. Ordinate: natural logarithms to the ratio of distribution (Barth, 1956a).

Barth produced Figure 13 to allow for these different structural states in the feldspars. Using Ab_{28} and An_{30} in Figure 13, a temperature of about 680°C is indicated.

There exist valid criticisms of this method but the Lost Creek stock lends itself to this method on two counts:

1) Equilibrium conditions were achieved as withnessed by distinct grain boundaries, no reaction rims, and no zoning in the feldspars.
2) The assimilation and differentiation have caused changes in the modal analysis without changing the K value. This means that although the feldspars may not be entirely ideal dilute solutions, they may approach this condition and are dependent on temperature for their composition.

Winkler's "Minimum Melt" Curves

The amount of An-component in a melt and the pressure have been found to change the temperature of crystallization and the composition of the beginning melt (Winkler, 1967). This "minimum melt" can be used to determine the pressure if the temperature is known.[6]

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[6]"Experimentally it is not possible, of course, to determine the exact composition of the minimum-temperature melt.... Notice that it has been set in quotation marks." This "minimum melt" composition is then 10 to 15° higher than the true beginning of melting and its composition is between the true beginning melt and that end of coexistence of three solid phases and melt (Winkler, 1967, p. 201).

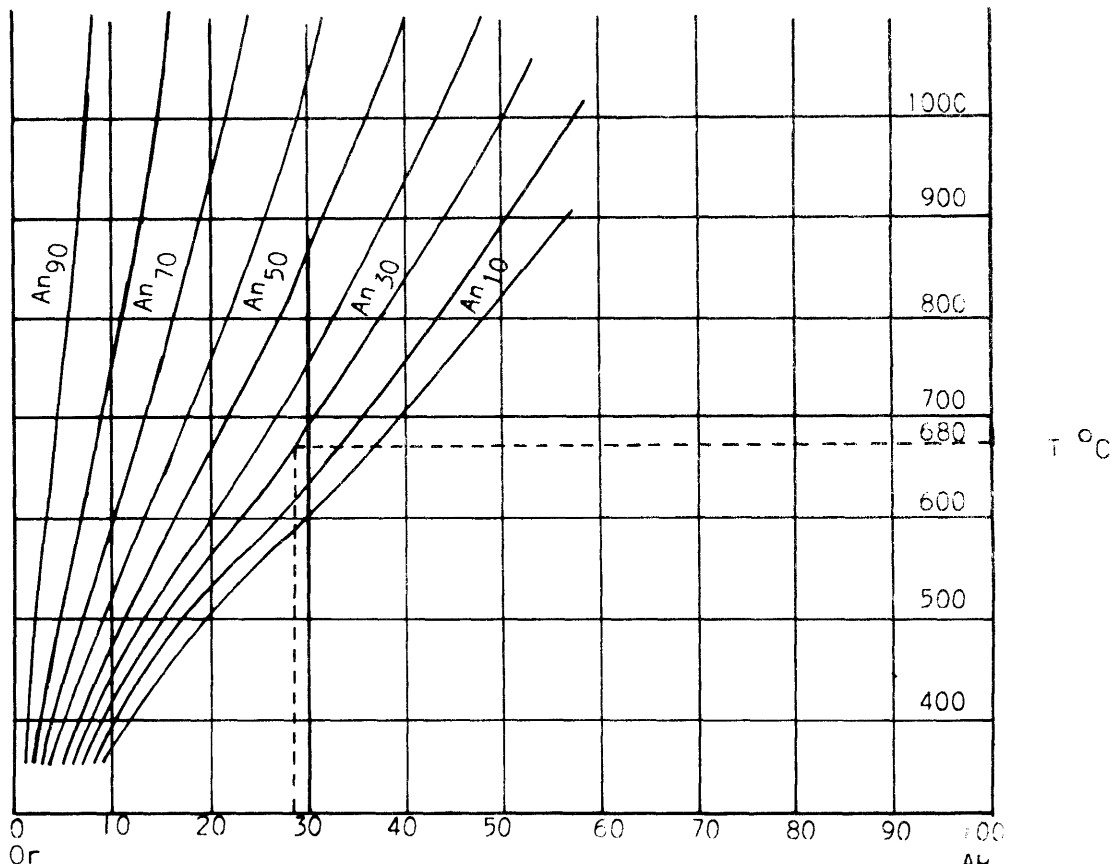


Figure 13. The co-existence of alkali feldspar and plagioclase. The curves indicate the equilibrium relation between the composition of the plagioclases and the composition of the alkali feldspars at various temperatures (Barth, 1956b).

The Ab/An ratios for the Lost Creek samples are consistently 3.4 (some minor problems existed in calculating this ratio, see Appendix, p. 57). By interpolation using Table 5, a 3.4 ratio indicates 695°C at 2 kilobars. The 3.4 trough is then plotted for 2 kilobars (Fig. 14). Table 6 shows the effect of pressure. Since the feldspars yield minimum temperatures of crystallization, the temperature already derived from Barth's method would suggest a pressure of about 3 kilobars (Table 6). The location of the trough thus defined is shown in Figure 14. This temperature and pressure are plotted with the granite melting curve (Fig. 15). Good correlation exists between the melting temperature of a water saturated granite and an environment of 3 kilobars at 680°C.

A temperature drop of 100°C at the contact of a pluton is a modest assumption, since this temperature drop could possibly range 200°-300°C (Jaeger, 1959). By subtracting the above 100°C from the granodiorite melting curve, and plotting these derived contact temperatures in Figure 15, a better method of estimating the pressure is established. The pressure indicated by the field defined by this curve and the high temperature diopside curve should be representative of the pressure at the time of emplacement (i.e., 2.8 kb or less).

Table 5. "Minimum melt" compositions at 2 kb with the associated Ab/An ratio. The 2.9 value is from Table 6. The 3.4 value is interpolated. From Winkler (1967).

Ab/An ratio	"Minimum melt" temperature °C	"Minimum melt" composition Q	Ab	Or
∞	670	34	40	26
7.8	675	40	38	22
5.2	685	41	30	29
3.8	695	43	21	36
3.4	695	43	20	36
2.5	695	44	19	37
2.9	695	44	19	37
1.8	705	45	15	40

Table 6. Effect of pressure on the composition and temperature of the "minimum melt." The 680° temperature is interpolated. From Winkler (1967).

P_{H_2O} kb	System with Ab/An = ∞ Q : Ab : Or	T in °C	System with Ab/An = 2.9 Q : Ab : Or	T in °C
.5	39 : 30 : 31	770		
2	35 : 40 : 25	670	44 : 19 : 37	695
3			41 : 22 : 36	680
4	31 : 46 : 23	655	39 : 25 : 36	670
5	27 : 50 : 23	650		
7			31 : 35 : 34	655
10	23 : 56 : 21	625		

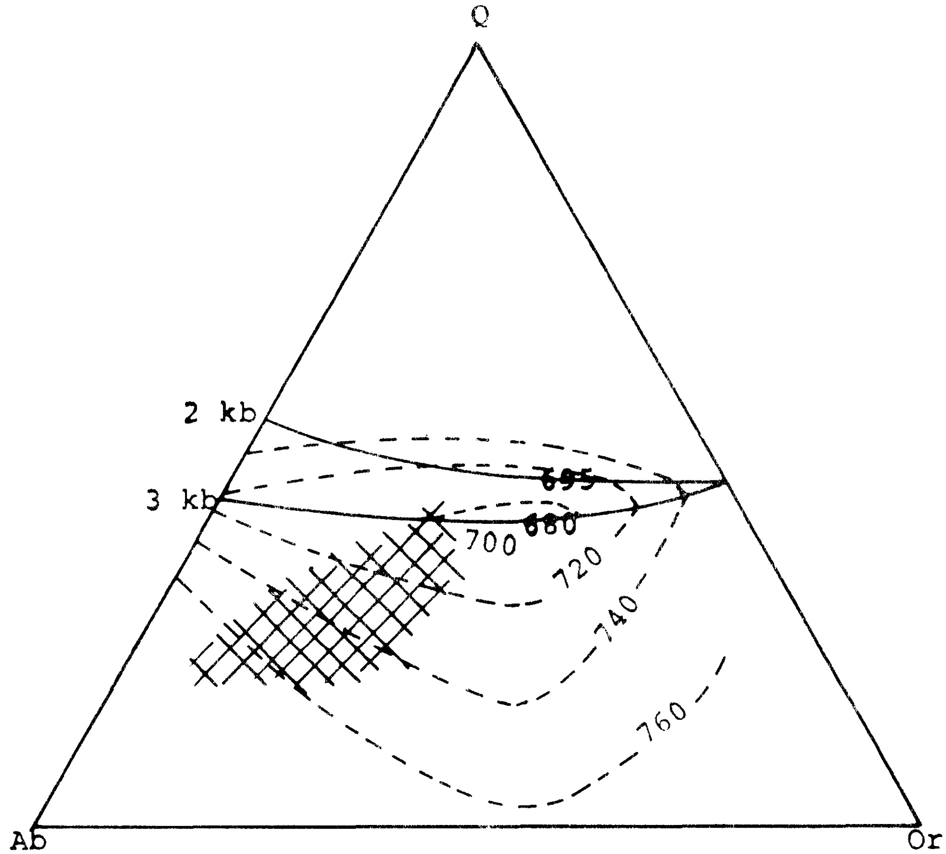


Figure 14. Location of the cotectic trough at Ab/An = 3.4 at 2 kb and 3 kb. The temperature of the "minimum melt" (Winkler, 1967) coincides closely with the minimum temperature of crystallization as determined by Barth's feldspar geothermometer. Contours are estimated using Tuttle and Bowen's 1958 data. Cross-hatched area is the composition of the Lost Creek stock samples projected onto the Q-Ab-Or plane.

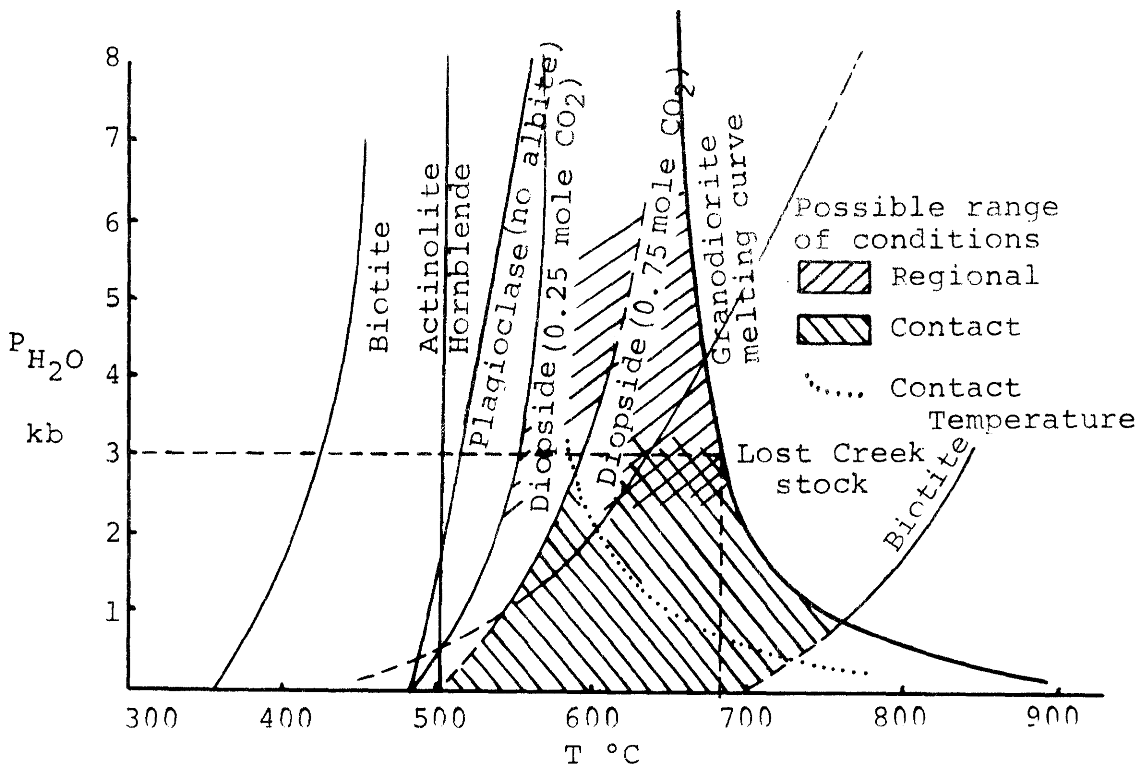


Figure 15. Stability fields of minerals in the country rock assemblages shown in Figure 16. Contact temperature curve is assumed to be 100°C less than the granodiorite melting curve.

Muscovite/orthoclase (Evans, 1965).

Biotite. The biotite stability curves are dependent on Mg content and P_{O_2}. The ratio $Fe^{+2}/Fe^{+2}+Mg = .5$ is used here and is consistent with biotites from granodiorite. P_{O_2} yields a ratio $Fe^{+3}/Fe^{+3}+Fe^{+2} = 1$ which is consistent with natural assemblages. (Wones and Eugster, 1965).

Diopside (Metz and Winkler, 1964).

Boundaries and accompanying data are drawn from Hyndman (1970).

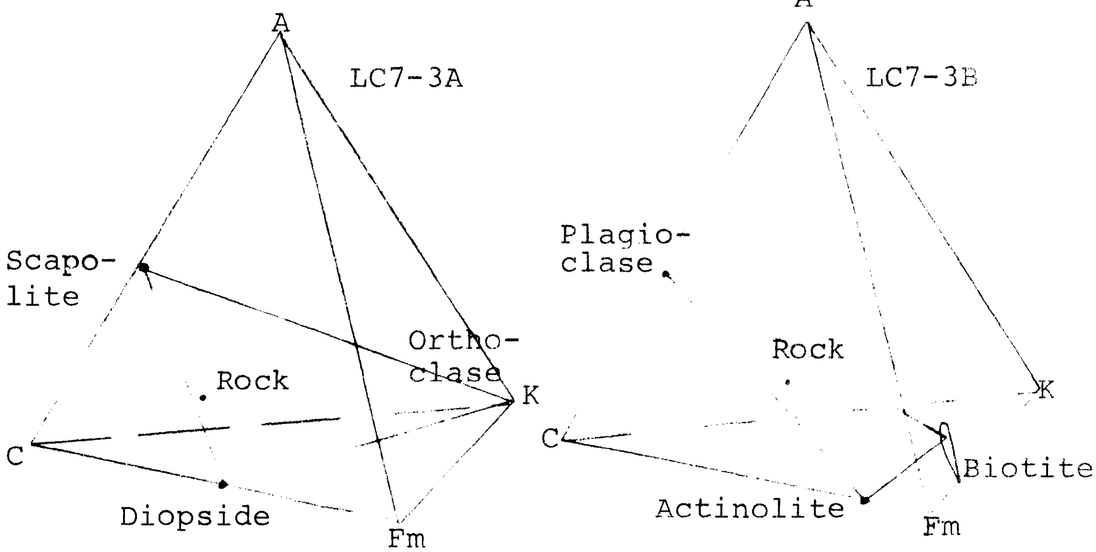
The Mount Powell samples have an Ab/An ratio consistently around 2.5. If the depth of burial for this pluton is assumed about the same as the Lost Creek stock, then using Table 6 the temperature indicated is also about 680°C. Probably the major influence in crystallization of the Lost Creek stock was a decrease in temperature. The Lost Creek stock plagioclase is not zoned, therefore, a rapid loss of pressure, which could also initiate crystallization, is not indicated.

Contact Metamorphic Assemblages

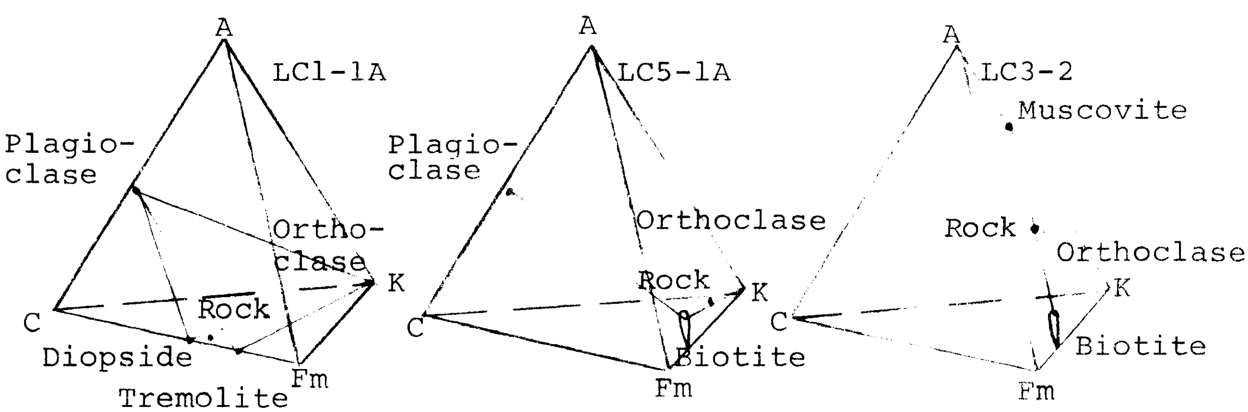
Contact metamorphism around Lost Creek stock is not very distinctive or diagnostic in terms of defining the environment. This stock was intruded into regional metamorphic rocks of the amphilolite facies. The regional metamorphic assemblage is shown in Figure 16b and the corresponding environment is indicated in Figure 15. Intrusion temperatures, allowing for loss of temperature at the contact, must have approached equilibrium with the regional assemblage. Therefore, the recognizable contact effects are absent or only locally developed. It may be that the intruded country rocks were dry after regional metamorphism and the contact metamorphism is restricted to localized areas where volatiles were allowed to escape from the magma. All rocks in the area showing contact effects contain scapolite and fluorite. Because scapolite and

Figure 16. Metamorphic Assemblages.

16a. Calc-silicate contact assemblages (+ quartz and fluorite).



16b. Regional assemblages (+ quartz).



fluorite are present, the concentration of volatiles was high. The diopside curve is taken to be the higher temperature curve because of its occurrence in calc-silicate rock derived from a limestone. Derivation of the calc-silicate rocks would involve liberation of large quantities of CO_2.

The contact metamorphic assemblages are shown in Figure 16a. Minerals which would indicate something of pressure are not present (i.e., andalusite, cordierite, or muscovite without alkali feldspar). These minerals would be expected to develop in a more pelitic rock, not in the calc-silicate rocks available here. Diopside formation is inhibited by the presence of CO_2. This limits the contact environment somewhat because the higher temperature curve would apply to the diopside in these contact rocks. Muscovite is not present in the contact rocks but its absence is probably due to compositional factors and does not have any temperature implications. Therefore, the range of conditions indicated in Figure 15 for the contact environment is necessarily large.

Chapter 6

ALTERATION

Hydrothermal

Alteration due to hydrothermal or supergene processes is limited. The altered and vein-like appearance of some areas within the pluton is due to shearing and mylonitization (Plates 7 and 8). However, some hydrothermal alteration has taken place in the southern portion of the pluton.

The country rock adjacent to the southeastern part of the stock is Madison limestone and it is completely silicified near the contact. Prospect shafts close to the granite contact in the country rock intersect a sheared biotite-chlorite-epidote vein trending 040E/40S laced with stringers of hematite and malachite. This vein does not appear in the granite. The greater amount of kaolinite, montmorillonite, and sericite, which occur in the sheared zone of the granite, may be related to this vein. The silicification around this vein and its occurrence in the Madison limestone suggest hydrothermal activity. Because alteration is slight within the pluton, and intense right up to the southeast contact outside of the stock, it is probable that the limestone produced an environment in which solutions from

Plate 7. Shearing and mylonitization caused the dark vein indicated. (In the vicinity of LC8-4).

Plate 8. Shearing and mylonitization. Note the dark areas in the outcrop. Orientation of these veins is approximately 040/40S, approximately parallel to the grassy slope. (In the vicinity of LC8-4).

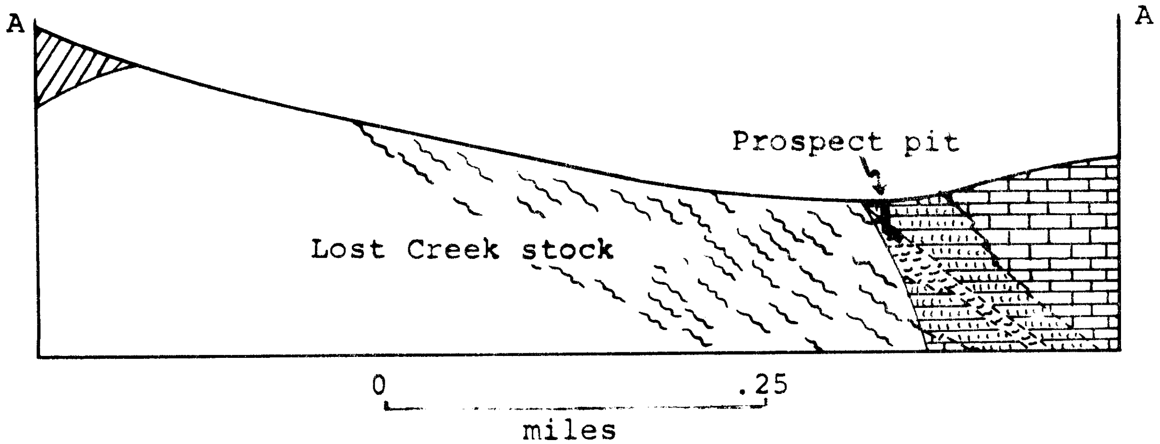
the pluton were localized and formed an implied silicate and sulfide assemblage. Figure 17 shows the structure section of this zone constructed from Figure 11.

Weathering

Lost Creek stock has a deceiving appearance (Plate 9). This red-streaked, altered looking granite is crumbly and grus piles exist wherever there is an outcrop, but in thin section it is very fresh rock. Very little alteration due to supergene activity has apparently taken place. X-ray patterns do reveal a small amount of kaolinite and chlorite (Appendix, p. 57). If intergranular solutions caused alteration producing clay on the grain boundaries, then continued weathering and expansion could produce the crumbly nature without great effect on the minerals.

Another possibility is that supergene alteration has oxidized some iron (presumably pyrite and biotite) and produced solutions which could percolate down through the pluton. Unsatisfied intergranular surface charges would then be satisfied by iron oxides and the rock would crumble.

Figure 17. Structure section from Figure 11. Structural relations of the hydrothermal alteration zone to the Madison limestone and the Lost Creek stock.



Topography is estimated.
No vertical exaggeration.

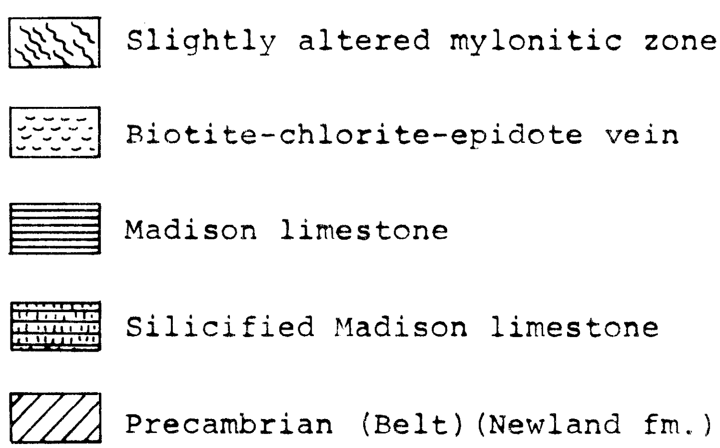


Plate 9. Inhomogeneous appearance of much of Lost Creek stock. (In the vicinity of LC7-1).

Chapter 7

STRUCTURE AND EMPLACEMENT

Previous workers (Csejtey, 1963; Mutch, 1964; McGill, 1964) in the Flint Creek Range recognized thrust faults as having a place in the structure, but in the Lost Creek area thrusting is a pervasive part of the structure, and is much more dominant than recorded for other parts of the Range.

Six thrusts were encountered in the metasedimentary rocks in the north canyon wall (Fig. 11). Orientation of the thrusts is in general 040/15N. The pluton contacts, in places, parallel the thrusts. In another case they will orient at a large angle to the thrusts, as evidenced in the vertical contacts exposed in the canyon walls. Very few xenoliths are found in the pluton. Emplacement is, therefore, believed to be by forceful injection in a "stairstep" manner (Fig. 18). Foliation within the pluton does not parallel the regional schistosity, but parallels the igneous contacts. Therefore, it is believed to be flow foliation. The foliation is steep on the southeast and shallow on the northwest (Figs. 11 and 18), in a general way suggesting intrusion from the west.

Granulated and mylonitic "veins" exist through the upper portion of the pluton. In general they are oriented 040°/40°S, parallel to the trace of the pluton and thrust faults but the dip is different than the foliation (center of Fig. 11, p. 33). This trend is not apparent in any faults in the metasediments. However, it must be noted that the hydrothermal vein did align with this orientation. These granulated and mylonitic zones represent internal movement of the pluton after or during late stages of consolidation. They are, therefore, not shear zones of regional extent.

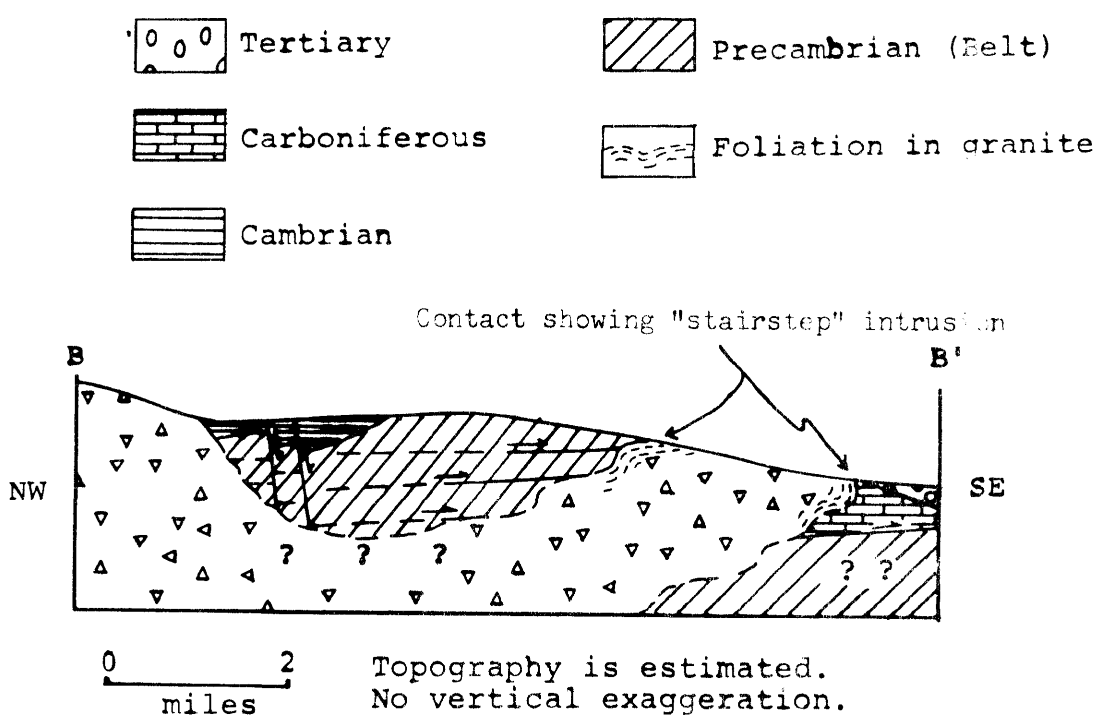


Figure 18. Structure section from Figure 3. "Stairstep" intrusion of the Lost Creek stock.

Chapter 8

CONCLUSIONS

The Lost Creek stock is related to the Mount Powell batholith through differentiation, the crystallization path of Mount Powell batholith rocks leading to the Lost Creek stock composition. Compositional variation of the Lost Creek stock suggests some minor assimilation and continued differentiation to modify the composition. Inclination of the Lost Creek stock in the direction of the Mount Powell batholith suggests a possible direct connection. Additional evidence for a genetic relationship is the green orthoclase/microcline which occurs in the southeast border of the Mount Powell batholith and in the northwest portion of the Lost Creek stock.

Pressure-temperature conditions at the time of crystallization were approximately 680°C at 3 kilobars (10 km). Pressure, however, could have been lower as approximated by the field defined by the diopside stability curve and the contact temperature curve.

Emplacement was by forceful injection along and cutting between thrust planes, in a "stairstep" manner, as can be seen in the vertical exposures within Lost Creek canyon.

APPENDIX

$2V_x$ of the Alkali Feldspar

2V measurements (Table 1A) were determined on a Zeiss research microscope with a mounted 3-axis universal stage.

Table 1A

Sample	$2V_x$	Sample	$2V_x$
LC2-1	77° 80° 76°	LC6-1	60° 60°
LC3-1	70° 75°	LC7-2	60°
LC3-2A	60° 66°	LC9-1	70° 76°
LC4-1	72° 75°	LC9-6	82° 78°

Note bimodal occurrence at 60° and 75-80°.

An Content of Plagioclase

Slemmon's (1962) method was used for a check on the An content of plagioclase found on the flat stage by the bisectrix method (Table 2A).

Table 2A

Sample	An-content	Sample	An content
LC2-1	An_{30} (Ambiguous)	LC6-1	An_{31} An_{32}
LC5-1	An_{32} An_{32}	LC9-6	An_{29} An_{30}

X-Ray Diffraction Patterns

LC10-2A. Montmorillinite was identified by expansion of the lattice from 14.6 Å to 16.7 Å upon glycolating the sample. Heating to 550°C for 2.5 hrs. destroyed the 7.1 Å peak. The 13.6 Å peak gained intensity suggesting the presence of chlorite.

LC10-1. Kaolinite was identified by heating to 550°C for 2.4 hrs. The 7.1 Å peak was destroyed; no 13.6 Å peak was present. A highly expandable montmorillinite was present. Glycolating the sample yielded an intense 16.9 Å peak.

LC5-2. Kaolinite was identified by the method above (LC10-1). A 10.0 Å peak is a mica presumably sericite.

Calculation of Ab/An Ratio

Rock must first be recalculated to 100% for quartz, orthoclase, albite and anorthite.

LC5-1	Q	Plag	Kspar	Per
	36.7	26.0 (An_{31})	37.3 (Ab_{28})	2.0

$$\text{Kspar} - \text{Per} = \text{Ortho}$$
$$27.3 - 2 = 35.3$$

$$Q = 36.7 \qquad = 36.7$$
$$An = .31\ (26.0) + .03\ (2) \qquad \simeq 8.1$$
$$Ab = .69\ (26.0) + .28\ (35.3) + .97\ (2) \qquad = 29.7$$
$$74.5$$

$$\text{Ortho} = 100 - 74.5 \qquad = 25.5$$

$$Ab/An = \frac{29.7}{8.1} = 3.6$$

The problem is in accounting for the perthite which is present up to 20.0%. This has probably been counted in the orthoclase counts, therefore when calculating the Ab/An ratio it should be subtracted from orthoclase. However, such high percentages as in the southern portion of the stock probably were not included in orthoclase counts. This means a higher Ab/An. Therefore the apparent higher Ab/An for the southern portion is not real, but is a consequence of the correction for the presence of perthite.

Modal Estimate of Lost Creek Pegmatite

Seven traverses were made across a 15 x 12 inch area on the pegmatite dike. Each inch equaled one count. 105 counts were obtained yielding the following proportions:

$$\begin{array}{ccccccc} \text{Total} & = & \text{Q} & & \text{Or} & & \text{Ab} \\ \frac{105}{100} & = & \frac{31}{30} & = & \frac{37}{35} & = & \frac{37}{35} \end{array}$$

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