PETROLOGY, STRUCTURE AND METAMORPHISM OF A CONCORDANT GRANODIORITE GNEISS IN THE GRENVILLE PROVINCE OF SOUTHEASTERN ONTARIO

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ABSTRACT OF THE THESIS

Petrology, Structure and Metamorphism of a Concordant Granodiorite Gneiss in the Grenville Province of Southeastern Ontario

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The Cross Lake Granodiorite Gneiss in the Grenville Province of Southeastern Ontario is a conformable, compositionally layered, lenticular body twenty miles long and five miles wide, associated with amphibolite, paragneiss and marble. The metamorphic grade of the country rock increases from west to east regionally and a major emphasis of this study has been to determine the effect of regional metamorphism on the Cross Lake Gneiss.

The average composition of the gneiss is 54% plagioclase (average An 27), 7% K-feldspar, 24% quartz, 12% biotite, 0-2% hornblende, 0-2% muscovite, 0-2% epidote and 0-1% calcite. Crystallization from a melt is indicated by the presence of partially aligned, subhedral plagioclase, Carlsbad twins, zoned plagioclase, evidence of chilled contacts and schlieren-like mafic inclusions of country rock.

The effect of the regional metamorphic gradient on the gneiss is indicated by several textural and mineralogical changes from west to east. To the west, much of the original character of the rock is retained, whereas to the

east, there is nearly complete recrystallization. To the west, the mineral assemblage is epidote, muscovite, traces of calcite and partly sericitized plagioclase with relatively albitic rims interpreted as resulting from depleted anorthite. This assemblage indicates that the western part of the Cross Lake Gneiss has been subjected to a low grade of metamorphism and equilibrium was not reached. The tendency for formation of albite suggests upper greenschist to lower amphibolite facies conditions.

To the east, there is evidence of metamorphism to middle amphibolite grade. Hornblende formed, but muscovite did not. Plagioclase recrystallized and became slightly less ordered, but the composition remained essentially the same (An 25-35)--a stable range for this environment. K-feldspar also recrystallized, expelling most of the Ab held in solution since original crystallization; by contrast, this was still retained to the west. K/Rb ratios in the gneiss decrease to the east, indicating increased tolerance for Rb.

The Cross Lake Gneiss consists of two northeasterly trending belts having the form of an elongate domal structure. All parts of the gneiss are well foliated and the foliation is generally concordant with contacts and compositional layering. Biotite has a segregated, knotted texture to the west, but is evenly disseminated to the east. The difference is probably related to increased metamorphism and/or shearing to the east.

The K-poor plutons, such as the Cross Lake Gneiss, and the Elzevir and Weslemkoon Plutons to the west and northwest, all appear to be older than the K-rich plutons of Southeastern Ontario. The Elzevir and Weslemkoon Plutons have intruded, for the most part, after the culmination of regional metamorphism and have superimposed contact metamorphic aureoles on the already metamorphosed country which they cross-cut. The Cross Lake Gneiss, however, intruded before the regional metamorphism and therefore predates these other plutons.

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INTRODUCTION

Purpose of Study

The plutonic rocks of Southeastern Ontario may be divided into two major groups: the older, potassium-poor, and the younger, potassium-rich. One type of the former cross-cuts country rock and is exemplified by the Elzevir and Weslemkoon Batholiths (Lumbers, 1967). The other is similar to the Cross Lake Gneiss which is a conformable, somewhat heterogeneous, metasedimentary-appearing lenticular body. One of the basic problems of this study is to establish the origin and nature of the Cross Lake Gneiss.

Other workers in the area (Smith, 1958; Hounslow and Moore, 1967; Moore, 1967) have shown that a steep regional metamorphic gradient existed in the vicinity of the Cross Lake Gneiss. Another major aspect of this study is to determine the effect and relationship of this gradient to the Cross Lake Gneiss.

Acknowledgments

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Geography

The Cross Lake Gneiss occurs in three northeast trending belts which occupy approximately 100 square miles in Clarendon, Palmerston, Lavant, Barry and Dalhousie Townships in Southeastern Ontario, Canada (Figure 1). The area lies about 10 miles north of the town of Sharbot Lake and 25 miles west of Perth. The third and southernmost belt of gneiss (not studied here in detail) continues westward and is called the Northbrook Gneiss, which forms the northern border of the much-studied Clare River Syncline.

Cross Lake is 10 miles long and cuts across the two northern gneiss belts, and Clarendon Lake (approximately 11 miles long) occupies much of the southern of the two belts. Well over 50 miles of washed outcrop are exposed on the shorelines. The gneiss outcrops form resistant ridges trending northeast, whereas much of the interlayered metavolcanic septa forms low ground characterized by beaver swamps. Such swamps are, however, not lacking in the gneiss area. Much of the area is well traversed by dirt roads, paths and lake shore, although this is less true of the northern belt.

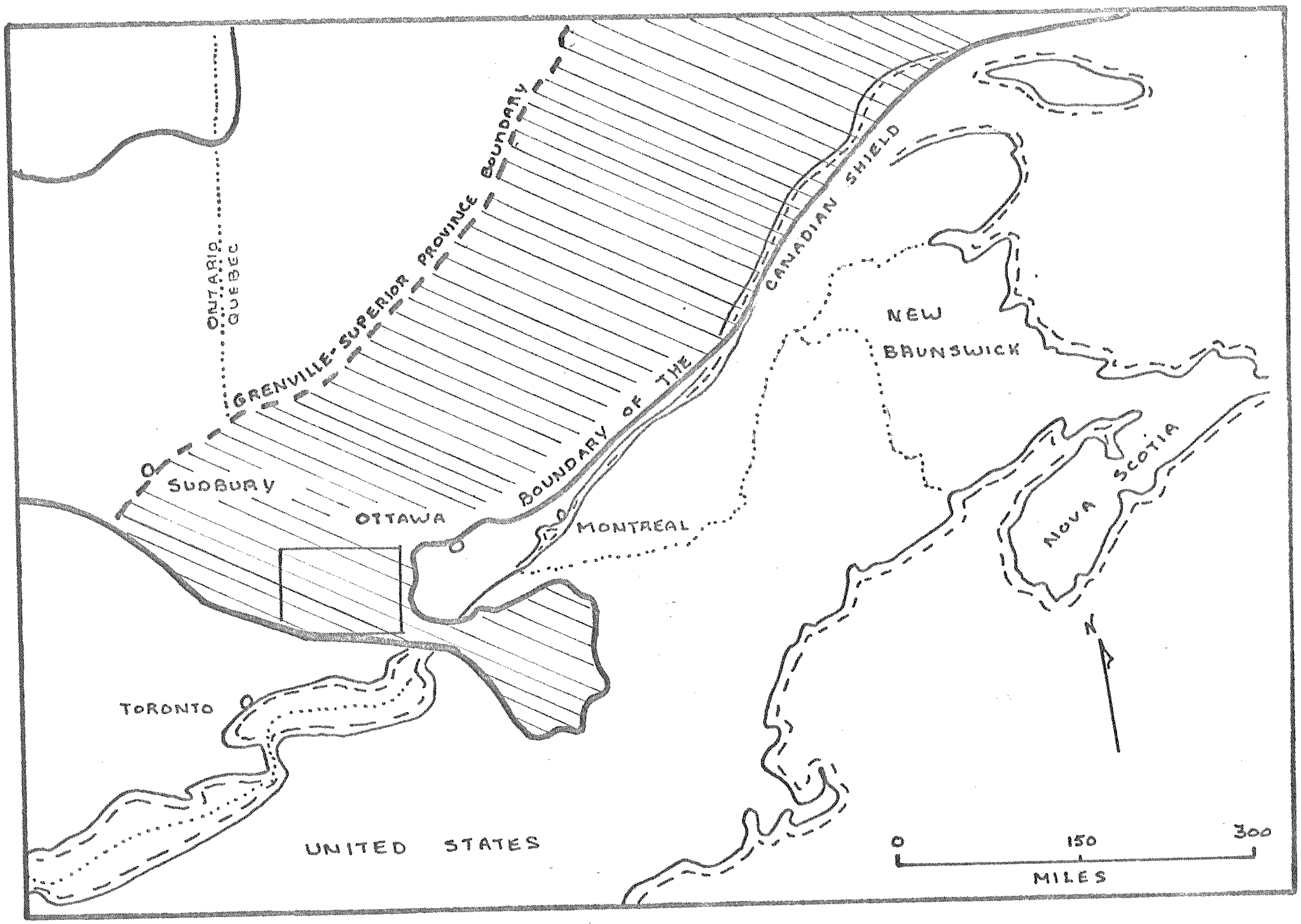


Figure 1. Index map showing location of the Cross Lake Gneiss within the Grenville Province of Southeastern Ontario.

Regional Geology

Lumbers (1967) has compiled an excellent review and evaluation of the many works dealing with the Southern Ontario area, and a summary chart of studies concerned with the plutonic rocks is given in Table 1. The works most important to the immediate area are by Adams and Barlow (1910), Miller and Knight (1914), Wilson (1925), Kay (1942a, b), Hewitt (1956) and Smith (1958). Current studies have been or are being carried out by Smith (1965), Lumbers (1967), Moore (1967), Wynne-Edwards (1967a, b, c), Smith, Vogel and Spence (in press) and K. Sethuramen (in progress).

The Grenville Province, in the southeastern part of the Canadian Shield, trends northeasterly for over 1,000 miles. It contains rocks of many ages, including the 'Grenville Group', all of which have been subjected to the 'Grenville Orogeny' (Wynne-Edwards, 1967b, p. 1). Because of this orogeny, these rocks carry K/Ar radiometric dates of 950 ± 150 m.y. All of the rocks in the Grenville Province are highly metamorphosed except for those of the Hastings 'Basin' near Madoc.

The Bancroft-Madoc area occurs in Southeastern Ontario and contains the only unquestioned metavolcanic sequence and greenschist facies metamorphism of the Grenville Province (Lumbers, 1967; Moore, 1967; Wynne-Edwards, 1967). Hewitt (1956) divided the area on the basis of structure into the 'Hastings Basin' and the 'Kaladar-

TABLE 1. Studies of Certain Plutons in the Madoc-Bancroft Area (from Lumbers, 1967)

Pluton	Townships	References
	Trondhjemite and Sodic Granite Group	
Cross Lake gneiss	Kaladar, Kennebec, Barrie, Clarendon	Harding (1944); Meen (1944); Bain (1960); Smith (1958); Lumbers (unpublished)
Elzevir Trondhjemite-Granodiorite	Elzevir, Kaladar, Grimsthorpe, Anglesea	Meen (1944); Ingham and Keevil (1951); Bain (1960)
Canniff pluton	Grimsthorpe, Anglesea	Meen (1944)
Grimsthorpe Trondhjemite	Tudor, Grimsthorpe	Lumbers (unpublished)
Wadsworth Trondhjemite	Tudor, Limerick	Lumbers (unpublished)
Bessemer Trondhjemite	Dungannon, Mayo	Giblin (1960)
Boulter Trondhjemite	Mayo, Carlow, Raglan	Hewitt (1954, 1955)
Trondhjemite stocks	northwestern Limerick	Lumbers (unpublished)
Weslemkoon Trondhjemite-Granodiorite	Grimsthorpe, Cashel, Mayo, Ashby, Denbigh, Effingham, Abinger	Hewitt and James (1956); Evans (1964); Hodgson (1965); Lumbers (unpublished)
Deloro Granite	Madoc, Marmora	Saha (1959)
	Potassic Syenite and Monzonite Group	
Syenite	Anglesea	Meen (1944); Ingham and Keevil (1951)
Mount Moriah Syenite	Grimsthorpe, Elzevir, Tudor	Meen (1944); Lumbers (unpublished)
Gawley Creek	Madoc, Marmora, Lake	Laakso (in press); Hewitt (1966); Lumbers (unpublished)
Chandos Lake Complex	Chandos	Saha (1959); Shaw (1962)
	Quartz Monzonite Group	
Addington gneiss	Kennebec, Kaladar, Elzevir	Ambrose and Burns (1956); Bain (1960)
Copeway	Lake	Laakso (in press)
Methuen Quartz Monzonite	Methuen, Chandos, Wollaston	Hewitt (1961, 1962a); Laakso (in press)
Wollaston Quartz Monzonite	Wollaston	Saha (1959); Hewitt (1962a)
McArthurs Mills Quartz Monzonite	Mayo, Ashby	Hewitt and James (1956); Evans (1964)

Dalhousie Trough'. The 'Hastings Basin' is that area bounded to the west by the Methuen Pluton, to the north by the Hastings Highlands and to the east by the Weslemkoon and Elzevir Plutons; later studies by Lumbers (1967), however, showed that this area is neither a structural nor a stratigraphic basin, but a series of arches and domes separated by a series of narrow synclinal belts. Most of the plutons are in structural domes whereas the marble-rich sequences are northeasterly trending synclinoria.

The Cross Lake Gneiss lies directly to the east of the 'Hastings Basin' and to the north of the eastern extension of the 'Kaladar-Dalhousie Trough'. To the southeast of the Cross Lake Gneiss are the plutons, metasediments and granite gneisses that underlie the Frontenac Axis and the Grenville Lowlands of New York State. This region of Southeastern Ontario appears, then, to be divided into three major study areas: the Bancroft-Madoc area, studied most recently by Lumbers, the Frontenac Axis to the southeast, investigated by Wynne-Edwards and the somewhat poorly defined middle zone which includes the Cross Lake, Northbrook and Tichborne Gneisses.

The Cross Lake Gneiss lies immediately north of the eastern extension of the Clare River Syncline (Ambrose and Burns, 1956), a well-studied strip of metasediments and metavolcanics. A similar, more northerly strip includes metavolcanics, metasediments and metaconglomerates, and extends from Madoc northeasterly through Ompah (Smith,

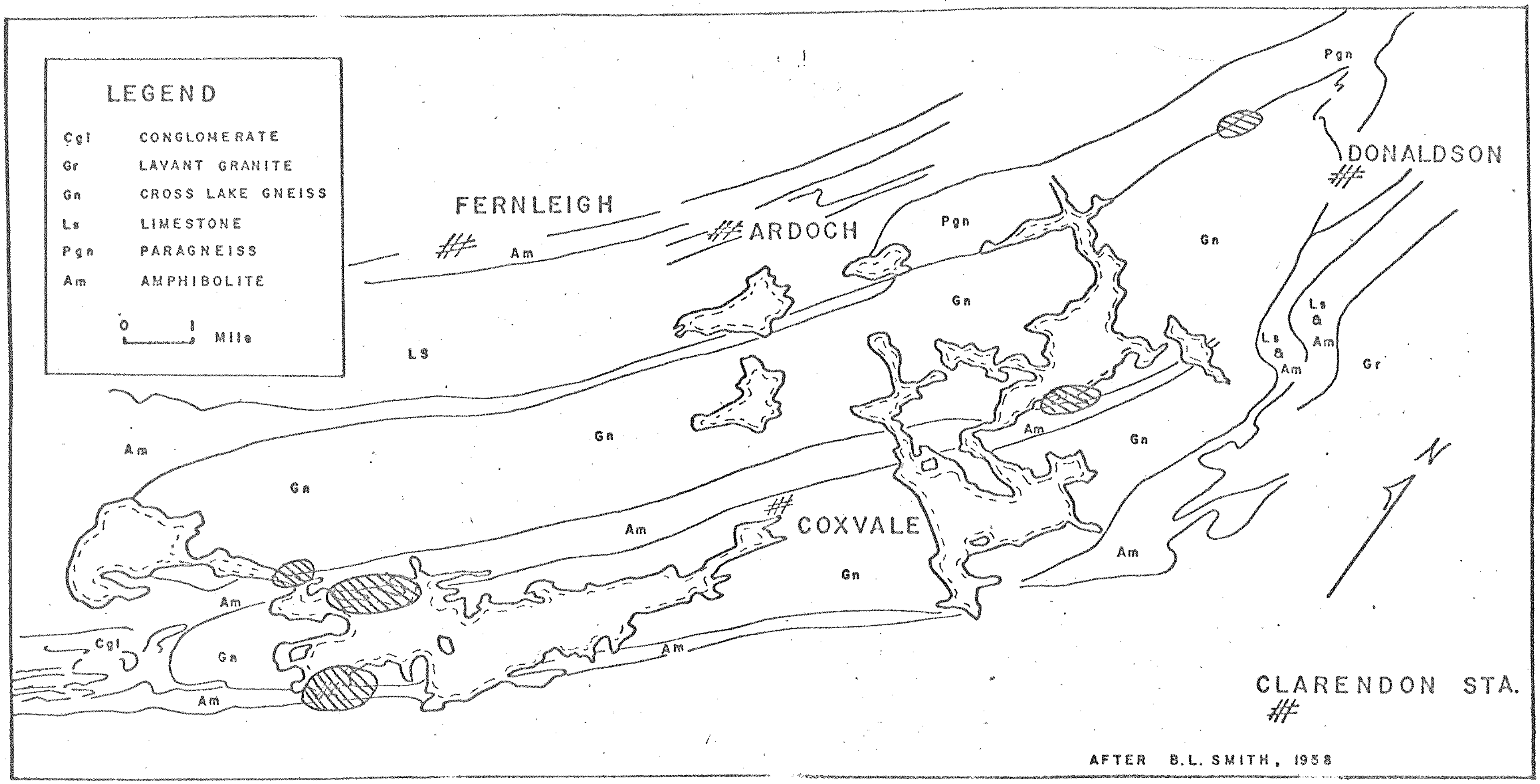


Figure 2. General geology of the Cross Lake Gneiss region. Well exposed contacts of gneiss with country rock are circled.

TABLE 2. Sequence of Precambrian Rocks in the Bancroft-Madoc Area (from Lumbers, 1967).

PROTEROZOIC	PLUTONIC ROCKS	QUARTZ MONZONITE GROUP	Quartz monzonite stocks and batholiths containg some granodiorite, potassic granite, and granite pegmatite. Main members of group are McArthurs Mills, Wollaston, Methuen, Ridge, Copeway and Addington masses. Both syntectonic and posttectonic bodies of these rocks present.
			INTRUSIVE CONTACT
		NEPHELINE SYENITE GROUP	Nepheline and alkalic syenites in Methuen and Denbigh townships. Age of group relative to plutonic rock groups below uncertain, but group is probably older than most of the rocks of the quartz monzonite group.
			INTRUSIVE CONTACT (?)
		POTASSIC SYENITE AND MONZONITE	Potassic syenite and monzonite stocks containing minor quartz monzonite and granodiorite. Some of these rocks could be younger than rocks of the quartz monzonite and nepheline syenite groups. Main members of group are Chandos Lake, Mt. Moriah, and Gawley Creek stocks.
			INTRUSIVE CONTACT (?)
		LATE GABBRO AND DIORITE GROUP	Gabbro and diorite stocks containing potassic syenite phases. Some of these stocks may be contemporaneous with potassic syenite and monzonite stocks. Main members of group are Umfraville, Wollaston Lake, and Boulter Gabbros.
			INTRUSIVE CONTACT (?)
		MAFIC SILLS AND DIKES	Altered gabbro and diorite sills and dikes concentrated locally in the region. Multiple ages probably present; most of these rocks appear to be older than the quartz monzonite group and some are younger than the biotite diorite series.
			INTRUSIVE CONTACT
		BIOTITE DIORITE SERIES — contemporaneous (?): Trondhjemite and Sodic Granite Group	Trondhjemite and granodiorite stocks and batholiths containing minor sodic granite and dikes of granite pegmatite. Sodic granite stocks. Main members of group are Weslemkoon, Elzevir, Cross Lake, Deloro, Wadsworth, Bessemer, and Boulter masses.
		BIOTITE DIORITE SERIES — contemporaneous (?): Diorite Group	Gabbroic to tonalitic stocks containing late trondhjemite and granodiarite phases. Main members of group are Lingham Lake, Tudor, Thanet, Jocko Lake, and Mellard Lake - Raglan Hills stocks.
			INTRUSIVE CONTACT
		BIOTITE DIORITE SERIES: Albite Granite and Syenite Group	Albite granite and syenite stocks containing some gabbro, diorite, trondhjemite, and granodiorite. Includes small metagabbro and metadiorite sill-like bodies. Main members of group are Glanmire, Beaver Creek, and Wendsley Lake stocks
			INTRUSIVE CONTACT

PROTEROZOIC — METASEDIMENTS AND METAVOLCANICS	Central and Western Section	Southeastern Section
	MAYO GROUP Lasswade Marble: carbonate metasediments Apsley Formation: carbonate-poor metasediments and calcareous metasandstone and metasiltstone. Dungannon Formation: carbonate metasediments; minor carbonate-poor metasediments and calcareous metasandstone and metasiltstone. (Locally interfingers with upper part of Tudor metavolcanics and other formations of the Hermon group).	TWEED GROUP (undivided) Carbonate metasediments; minor calcareous metasandstone and metasiltstone, mafic metavolcanics, and metaconglomerate. (May in part be equivalent to the Dungannon formation).
	HERMON GROUP Burnt Lake Formation: felsic and mafic metavolcanics, minor metasediments. Turriff Metavolcanics: felsic and mafic metavolcanics, minor iron formation. Vansickle Formation: metasediments and minor felsic and mafic metavolcanics, metaconglomerate. Oak Lake Formation: felsic and some mafic metavolcanics; minor metasediments Tudor Metavolcanics: mafic and minor felsic metavolcanics; rare iron formation and carbonate metasediments.	KALADAR GROUP (undivided) (May in part be equivalent to Skootamatta formation) felsic and mafic metavolcanics, carbonate-poor metasediments; minor carbonate metasediments, calcareous metasandstone and metasiltstone, and metaconglomerate. Skootamatta Formation: metaconglomerate, mafic and felsic metavolcanics, carbonate-poor and carbonate metasediments. (Probably equivalent to all but lowest part of Oak Lake formation) Tudor Metavolcanics: mafic and minor felsic metavolcanics; rare carbonate metasediments

granodiorites (including the Cross Lake Gneiss) and sodic granite and diorite. The younger plutons include late gabbros and diorites, K-syenites and monzonites, nepheline syenites and quartz monzonites. This classification is exclusive of the Frontenac Axis to the east; however, Wynne-Edwards (personal communication) maintains that the divisions and relative chronologies appear to hold to the southeast also. In summary, the Cross Lake Gneiss has been grouped with the older granodiorites of the K-poor biotite diorite series, and the Lavant and Elphin Granites with the younger K-rich rocks.

Figure 3 shows a recently compiled map of the general isograd distribution of Southeastern Ontario. Lumbers (1967) states that the greenschist facies and upper amphibolite facies in the Bancroft-Madoc Area occurred in two different stages: 1310 ± 15 and 1125 ± 25 m.y. ago. Upper amphibolite facies metamorphism coincided with the emplacement of the late K-rich plutonic rocks (1125 ± 25 m.y.) and intense deformation. Major northeasterly folding patterns were established before this. This sequence does not agree with much of the data collected from the Cross Lake Area, and these discrepancies are the subject of part of this paper.

Metamorphic grade rises to the northeast along the strike of a pelitic schist contained in the younger unconformable belt (Smith, 1958; Moore, 1967). The metamorphic facies change from the greenschist facies in the east to middle amphibolite in the west. The sillimanite isograd occurs near Ardoch.

Wynne-Edwards has done much work on the higher grade (upper amphibolite to pyroxene granulite facies) regionally metamorphosed rocks of the Frontenac Axis to the southeast of the Cross Lake Gneiss. He has shown that the grade decreases from the Clear Lake Anticline (granulite facies) northwestward toward the Bancroft-Madoc area and to the southeast across the St. Lawrence River. Near Tichborne, gneisses appear to be lithological equivalents of the Cross Lake Gneiss subjected to granulite facies conditions. Wynne-Edwards has discussed these only briefly (1967c, p. 81) and further, more detailed comparisons would be of interest.

In summary, recent study and compilation have shown that the regional metamorphic isograds in the Southeastern Ontario region form a continuous pattern of highs and lows. The Cross Lake Gneiss falls within the boundaries of the amphibilite facies as shown on the map.

Mineralogical analyses of Cross Lake Gneiss indicate that it falls within the granodiorite or quartz diorite field of the diagram by Streckeisen (1967, p. 160). Mean modal and partial chemical analyses are very similar to those of rocks collected at Coxvale (Wynne-Edwards, 1967c, p. 266), Tichborne (Wynne-Edwards, 1967c), from the conglomerate to the west (Walton, Hills and Hansen, 1964) and from the Weslemkoon Pluton (Lumbers, 1967). Chemical analyses and modes are compared in Table 3.

TABLE 3. Comparison of Modes and Chemical Analyses of Gray Gneisses from Southeastern Ontario

	Cross Lake Gneiss: North Belt		Weslemkoon Batholith Lumbers (1967)		Cross Lake Gneiss (Coxvale)	Gray Gneiss: Tichborne	Pebble; Kaladar Walton, et al. (1964)
	West	East	Trondhjemite	Granodiorite	Wynne-Edwards (1967)		
			Modes (Volume Percent)				
Plagioclase	53	56	69	53	45	50	48
An%	28	28	23	25	22	25	
K-feldspar	6	5	0.2	9	13	12	12
Quartz	24	23	20	26	31	26	33
Biotite	13	13	10	12	9	5	7
Hornblende	-	2	-	-	-	Tr	-
Hypersthene	-	-	-	-	-	5	-
Muscovite	4	-	-	-	-	-	-
Epidote	0.6	0.4	-	-	0.9	-	2
Calcite	0.5	-	-	-	-	-	-
			Chemical Analyses (Weight Percent)				
SiO_2			65.3	69.8	67.8	10.9	71.4
Al_2O_3			17.1	15.9	15.8	15.2	14.2
Fe_2O_5+FeO			3.2	2.9	3.2	2.6	2.0
MgO			1.92	1.43	1.2	1.3	0.98
CaO	2.8	3.0	2.53	2.59	2.75	2.4	3.16
Na_2O			5.07	4.43	4.90	3.7	4.1
K_2O	2.2	2.2	2.06	2.51	2.75	2.3	3.3
H_2O			0.53	0.35	0.69	0.65	0.45
MnO			0.03	0.05	0.06	0.05	0.07
			Trace Elements (ppm)				
Ba					500	390	
Sr	752	911			430	290	
Rb	57	76			47	36	
Ca/Sr	30	26					
K/Rb	339	231					

the southern belt. Fine-grained amphibolite occurs in continuous bands that appear to increase in number with nearness to the middle amphibolite septum (Figures 4a, b). Swarms of discontinuous mafic pods are rare.

Three major K-rich intrusives have invaded the coarse gray gneiss of the southern belt (see Figure 5). The first, to the far west, is predominantly K-feldspar-rich pegmatite. Coarse gray gneiss is minor in all outcrops. The second intrusive, in the Mid-Clarendon Lake area, is mostly dense pink, buff-weathering aplite. This aplite cross-cuts preexisting fine-grained gray gneiss. Coarse gray gneiss is absent. The third, to the east along the eastern bank of southern Cross Lake, is again pegmatitic; however, surrounding the pegmatite, rocks within the circled area on Figure 5 are an intricate mixture of fine to medium-grained aplite, coarse gray gneiss and pegmatite (see Figure 6). Outcrops between these three aplite-rich areas consist of typical coarse gray and fine gray gneiss.

The southern belt is also characterized by numerous swarms of discontinuous fine-grained amphibolite pods (see Figure 7) and a general lack of continuous mafic bands (except in certain parts to the east). There is no increase in the density of pod swarms toward either of the major amphibolite septa.

The average modal composition of the coarse gray gneiss is 54% plagioclase, 7% K-feldspar, 24% quartz, 12% biotite, 0-2% hornblende, 0-2% muscovite, 0-2% epidote and

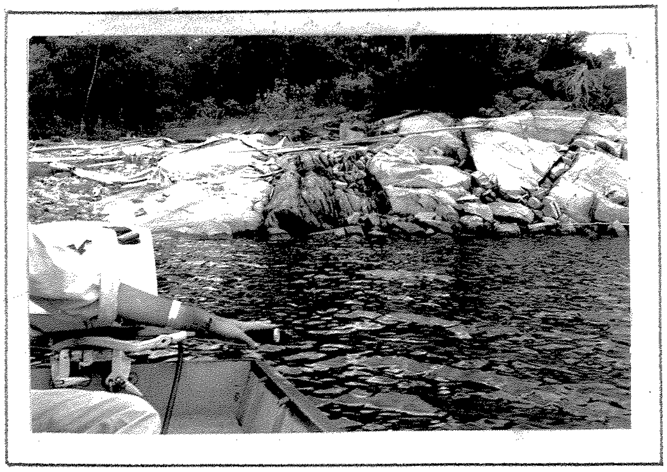


Figure 4a . Continuous mafic bands parallel to the foliation of the coarse gray gneiss(northern gneiss belt).

Figure 4b. Mafic band within the Cross Lake Gneiss(northern gneiss belt).

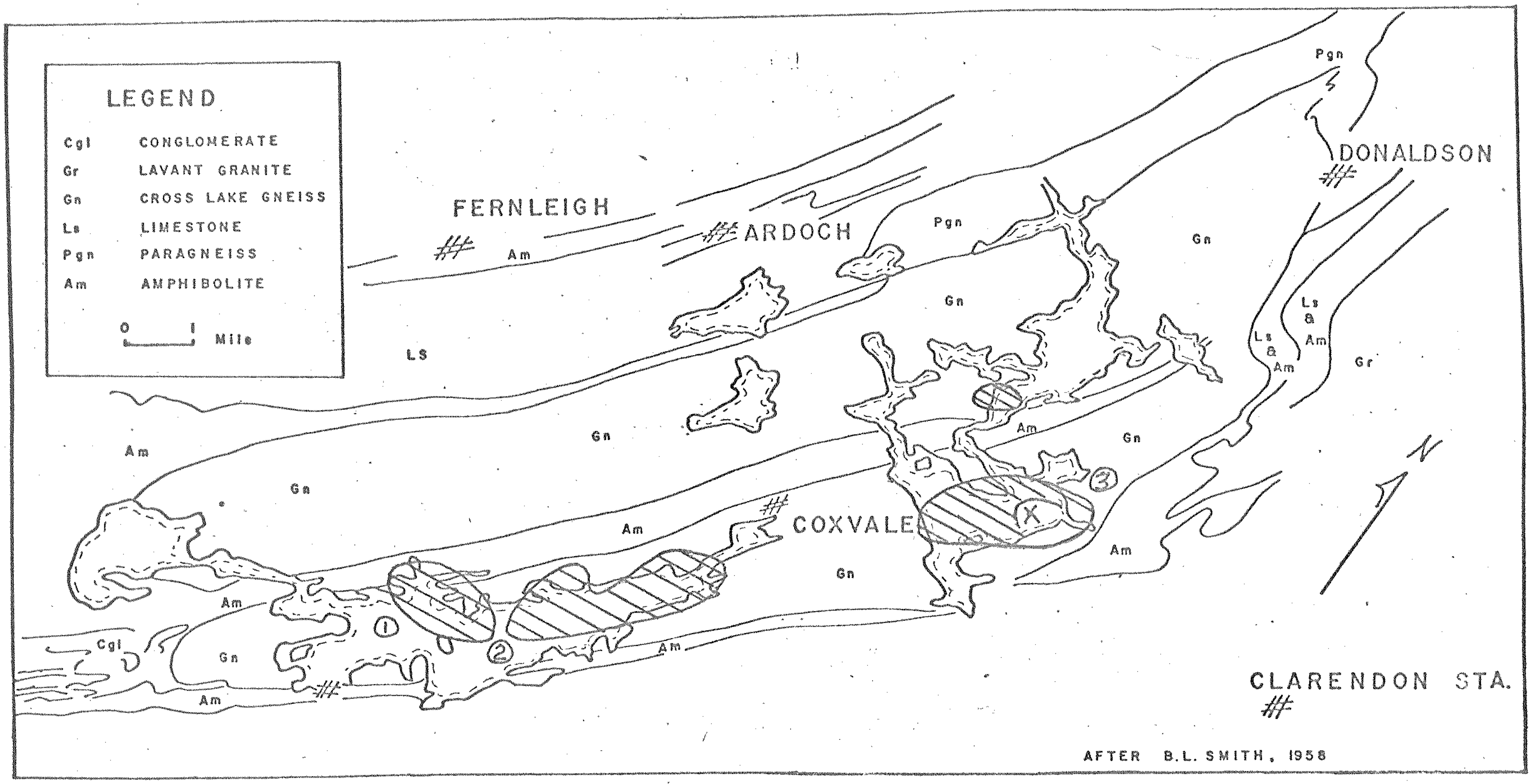


Figure 5. Distribution of K-rich intrusive bodies. 1) mostly pegmatite; 2) mostly aplite and fine-grained gray gneiss; 3) pegmatite(X), aplite and coarse gray gneiss.

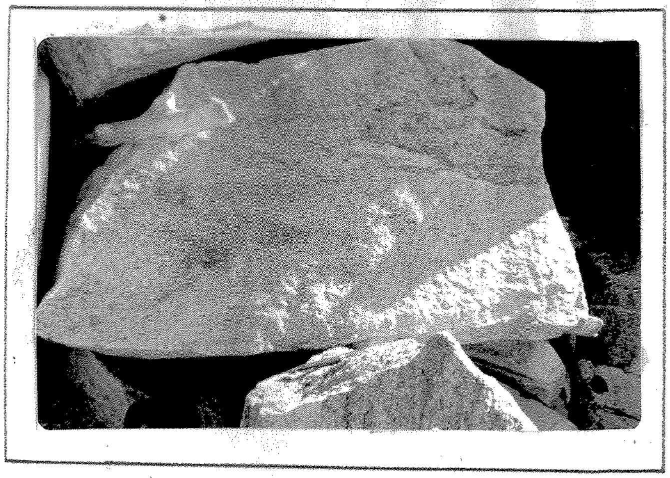


Figure 6. Complex interfingering of aplite(light) with coarse gray gneiss(gray) partially controlled by foliation

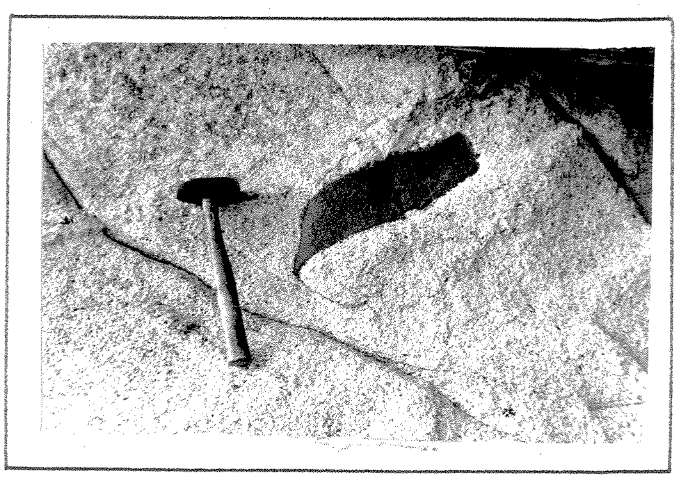


Figure 7a . Small fine-grained mafic pod in the coarse gray gneiss(southern gneiss belt).

Figure 7b. Swarms of small mafic pods oriented parallel to the foliation of the coarse gray gneiss(southern gneiss belt).

Figure 7c. Mafic pods parallel to the foliation of the gneiss(southern gneiss belt).

traces of calcite (Table 4a). The composition of the plagioclase ranges from An 18 to An 36, with a mean value of An 27. Reference to Figures 14 and 15 will clarify the following. Modal analyses were made using the point counting method of Chayes (1956). A few thin sections were stained and recounted with a non-significant change in results.

The only significant modal difference between the two belts is the higher K-feldspar content of the southern belt. This is probably related to the influx of major K-rich intrusives.

Modal composition of the coarse gray gneiss, the fine gray gneiss and aplite are plotted on the K-feldspar-Albite-Quartz ternary diagram (Figure 8). Adjustments have been made for Ab in K-feldspar. All values for the coarse gray gneiss fall within a strikingly restricted area. Four similar plots of samples collected east and west of Coxvale and from the northern and southern belts show no further patterns. The mean of three modal analyses of the fine-grained gneiss also falls within this restricted area. The mean of three aplite analyses (two from the southern belt, one from the northern) plots within the range typical of granite.

Contacts between Cross Lake Gneiss and country rock show what may prove to be the chilled textures characteristic of some igneous plutons. To the northeast of the northern half of Cross Lake, fine-grained paragneiss is

TABLE 4a. Average Modes of Cross Lake Gneiss from the Northern and Southern Belts

Mineral	Northern Belt (15 samples)		Southern Belt (24 samples)	
	Mean	Range	Mean	Range
Plagioclase	55	47-62	52	41-61
K-feldspar	5	.2-14	8	.4-19
Quartz	24	19-30	25	17-32
Biotite	12	7-18	11	5-19
Hornblende	1	0-7	Tr	0-3
Muscovite	1	0-8	.6	0-12
Epidote	.5	0-2	.4	0-2
Sphene	Tr	0-2	Tr	0-1
Apatite	Tr		Tr	0-1
Zircon	Tr		Tr	0-1
Calcite	Tr	0-2	Tr	0-2

TABLE 4b. Average Modes West and East of Coxvale in the Northern Gneiss Belt

Mineral	West (6 samples)		West (9 samples)	
	Mean	Range	Mean	Range
Plagioclase	53	47-56	56	50-62
K-feldspar	6	.4-14	5	.2-13
Quartz	24	20-30	23	19-30
Biotite	13	10-15	12	7-18
Hornblende	-	-	2	0-7
Muscovite	4	0-8	-	-
Epidote	.6	0.2	.4	0-2
Sphene	.4	0-2	2	0-8
Calcite	.5	0-2	-	-
Ab Rims	6 samples		1 sample	

TABLE 4c. Average Modes of Coarse Gray Gneiss Collected within Intrusive Areas (Southern Gneiss Belt)

Mineral	Intrusive Area 1# (3 samples)		Intrusive Area 2# (3 samples)		Intrusive Area 3# (3 samples)	
	Mean	Range	Mean	Range	Mean	Range
Plagioclase	48	45-53	54	50-59	56	53-60
K-feldspar	15	9-19	7	5-10	5	.6-13
Quartz	25	22-27	25	21-29	27	23-31
Biotite	9	8-11	12	7-18	10	5-14
Hornblende	Tr	0-.4	-	-	-	-
Muscovite	Tr	0-.4	1	0-3	.8	0-2
Epidote	1	.4-2	Tr	0-.2	Tr	0-.2
Sphene	.8	.4-1	Tr	0-.4	Tr	0-.2
Calcite	-	-	-	-	-	-
Ab Rims	2 samples		1 sample		2 samples	

TABLE 4d. Average Modes of Coarse Gray Gneiss Collected Outside of K-rich Intrusive Areas (Southern Gneiss Belt)

Mineral	West (6 samples)		Coxvale (7 samples)		East (5 samples)	
	Mean	Range	Mean	Range	Mean	Range
Plagioclase	48	41-53	55	51-58	55	50-61
K-feldspar	10	7-15	6	.4-13	7	2-13
Quartz	23	17-27	25	21-32	22	21-23
Biotite	12	7-19	13	8-16	12	11-12
Hornblende	-	-	-	-	2	.6-3
Muscovite	6	1-12	-	-	-	-
Epidote	Tr	0-.4	-	-	-	-
Sphene	Tr	0-.4	-	-	-	-
Calcite	.6	0-2	-	-	-	-
Ab Rims	6 samples		3 samples		none	

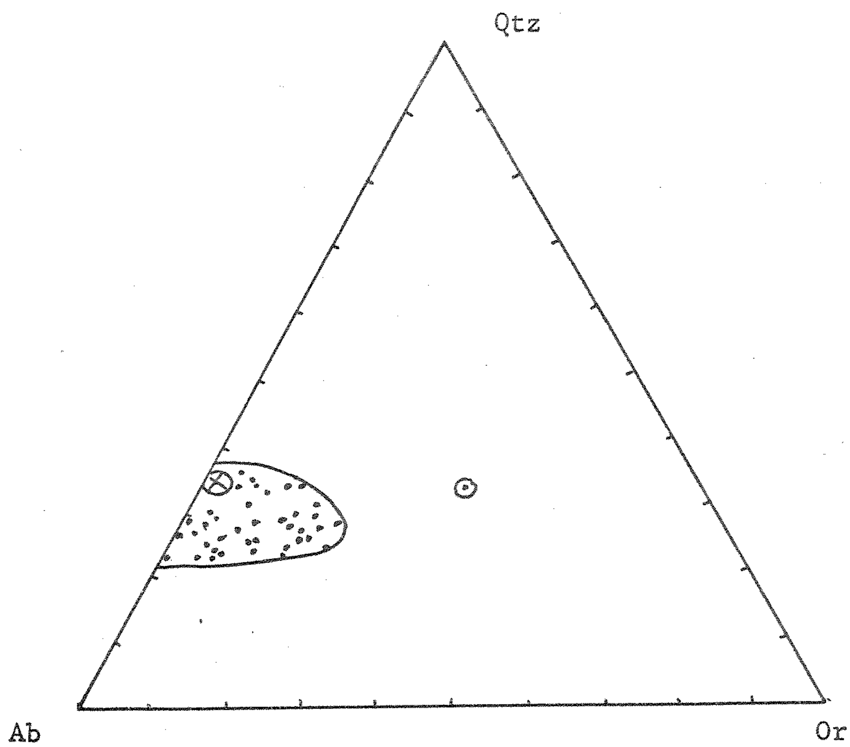


Figure 8. Ternary diagram of Qtz - Ab - Or modal values for the coarse gray gneiss(•), fine gray gneiss(⊗) and aplite(⊙).

in contact with a fine-grained equivalent of the Cross Lake Gneiss. The exact contact is covered but marked by a shallow depression. The fine-grained gneiss extends for approximately 100 feet before becoming coarse grained. This is an excellent, accessible area in which to study contact relations.

Several excellently exposed contacts between amphibolite and coarse gray gneiss occur on the lake edges (see Figure 2). There is commonly a zone of very fine-grained gneiss at the contact and other zones occur within the amphibolite. Although these may be interpreted as chilled textures, as this material is also interlayered with the amphibolite within the bulk of the septum, it may be acidic volcanic rock which was interbedded with the mafic material previous to the intrusion of the Cross Lake Gneiss.

In spite of metamorphism, subhedral plagioclase, zoning and Carlesbad twinning occur in many samples, suggesting that total recrystallization has not occurred, and that a chilled zone, if present, should still be recognizable.

Changes in modal composition and texture from west to east are important because they are directly related to the regional metamorphism. Segregated, elongated knots of biotite and quartz characterize the coarse gray gneiss to the west of Coxvale. The knots of biotite tend to weather, leaving a pitted, shredded surface (Figures 9a, b). To the east of Coxvale, mafic minerals and quartz are well

Figure 9a. Handsample of coarse gray gneiss collected west of Coxvale. Biotite and quartz are segregated into knots.

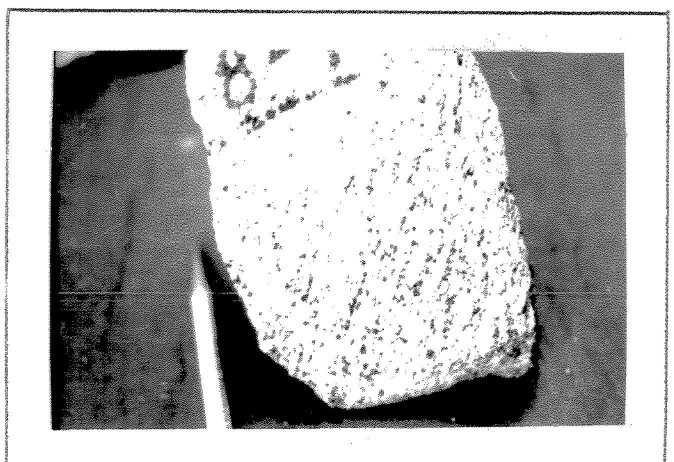


Figure 9b. Handsample of coarse gray gneiss collected east of Coxvale. Biotite is evenly disseminated throughout.

disseminated and the resulting surface weathers much more evenly.

Variations in west-to-east trends are most obvious in the northern belt. Textural and modal patterns in the southern belt are often disrupted by aplite intrusions. For example, the characteristic coarse gneiss texture just mentioned is totally obliterated in all three aplite areas; instead, finer-grained gray gneiss and fine-grained aplite and pegmatite are dominant. Trends in muscovite, hornblende and plagioclase composition are also changed radically.

Modes of the northern belt (Table 4b), however, show that, west of Coxvale, muscovite and calcite are present in samples and that east of Coxvale, hornblende appears to the exclusion of muscovite and calcite; biotite is constant in amount throughout the belt. Modes of the southern belt (Table 4c), excluding aplite-affected areas, divide the belt into a western, muscovite-bearing area, a central barren zone and an eastern hornblende-bearing zone. Figure 14 illustrates this striking pattern.

Fine-Grained Gray Gneiss

Fine-grained gray well-foliated gneiss is commonly interlayered with the coarse gray gneiss and may compose more than half of the outcrop. The modal composition of the fine gneiss (average of three samples) consists of plagioclase (62%, An 26), K-feldspar (1%), quartz (24%)

and biotite (15%). The plagioclase is subhedral to the west, anhedral to the east and non-antiperthitic. The presence of Carlesbad twinning and zoning indicates crystallization from a melt. No muscovite or hornblende was found. Therefore, the fine-grained gray gneiss differs from the coarse gray gneiss only in its much finer texture and slightly higher biotite content. Modes of the three analyses plotted on Figure 8 fall within the range of the coarse gray gneiss.

Figures 10a and 10b show two outcrops where the fine gray gneiss appears to cut off the foliation of the coarse gray gneiss. It is possible that the fine gray gneiss intruded slightly later and is a fine-grained equivalent of the coarse gneiss.

General Mineral Textures of the Coarse Gray Gneiss

Mineral textures of the coarse gray gneiss vary from west to east in response to the changes in the regional metamorphism. The general texture is granitoid and interlocking except in samples collected from the west of Coxvale in which plagioclase is subhedral. In all samples, biotite and about one-third of the quartz are elongated and oriented to form the strong foliation and lineation. All samples collected have been examined under the binocular microscope. Two hundred were chosen for thin-section study and, of these, 50 were given detailed optical and X-ray analysis.

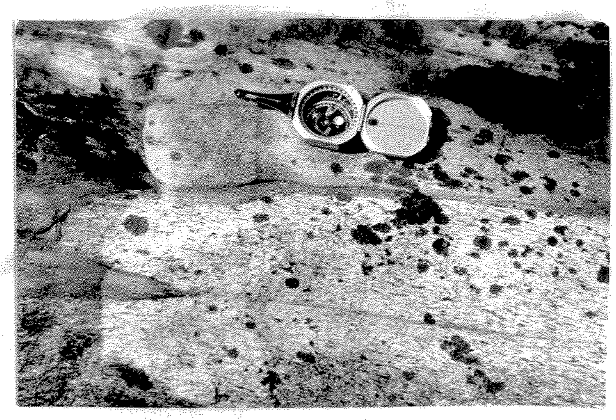


Figure 10a. Nonconcordant contact and foliation relationship between coarse gray gneiss(light) and fine gray gneiss(dark). Foliations are indicated by short black line.

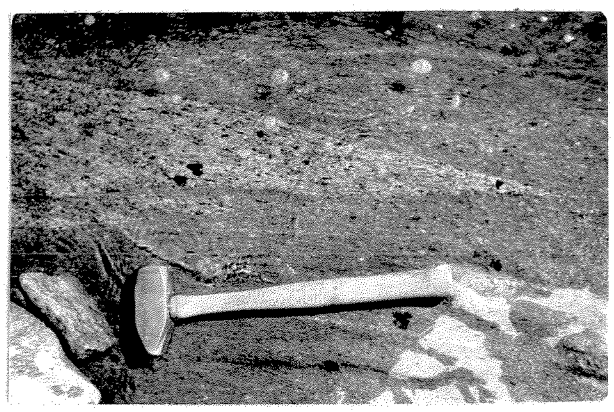


Figure 10b. Nonconcordant contact relationship between coarse gray and fine gray gneiss.

The muscovite in the samples to the west shows the development of secondary foliation. When it is associated with biotite, it either grows in optical continuity along the long axis of the biotite grain (Figure 11a) or forms sheaves radiating from a point on the side of the biotite crystal (Figure 11b). When grown in continuity with biotite, it is, of course, oriented parallel to the foliation. It may occur also in subhedral to euhedral grains isolated from biotite. In these cases, the muscovite is commonly oriented at a high angle (60^{o}-90^{o}) to the biotite foliation (Figure 11c). These isolated muscovite grains often form poikiloblasts around medium-grained quartz, microcline and plagioclase (Figure 11d), indicating late crystallization. When muscovite is absent from a sample, there is no evidence of a trend subnormal to foliation.

Hornblende occurs in most samples to the east of Coxvale. It is also occasionally found within aplite areas to the west of Coxvale (Figure 14). The hornblende is monoclinic, optically negative, and pleochroic green (or blue-green) to buff or greenish-brown. It occurs as subhedral to anhedral grains and is usually associated with biotite. Hornblende is totally absent from any samples containing muscovite or rimmed plagioclase.

Calcite occurs interstitially in trace amounts in most samples which contain muscovite to the west of Coxvale. It is not associated with any particular mineral and is often found in the irregular spaces between

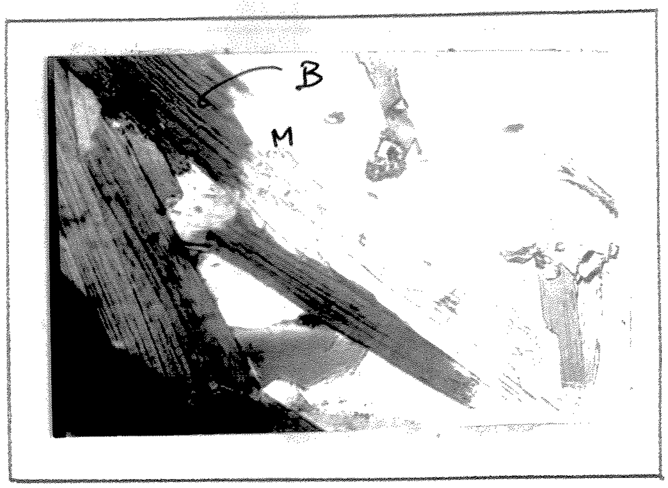


Figure 11a. Photomicrograph showing relationship of muscovite to biotite(crossed nicols).

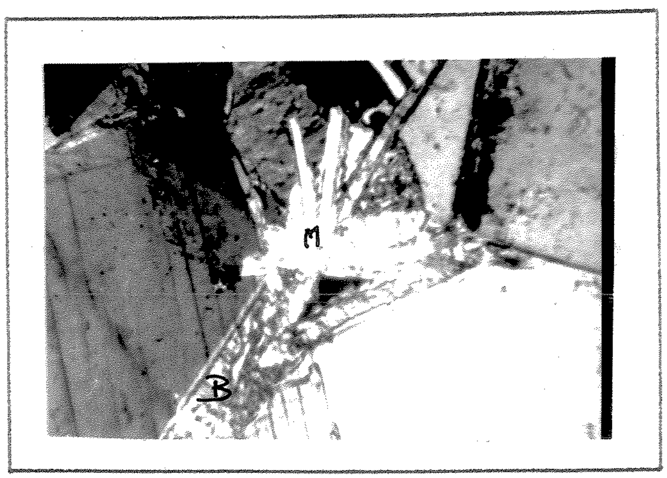


Figure 11b. Photomicrograph showing relationship of muscovite to biotite(crossed nicols).

interlocking quartz, plagioclase and K-feldspar.

Plagioclase in the Coarse Gray Gneiss

Plagioclase is a sensitive indicator of metamorphic grade and such features as types of twinning, structural state, composition, morphology, zoning and alteration may be used to establish changes from west to east in the Cross Lake Gneiss.

The composition of the plagioclase was determined by the Tsuboi method (Tsuboi, 1923, 1934) and by the use of a revised dispersion chart based on the α'_{001} curve (Morse, 1968). Ten grains were studied in each of 50 samples. Figure 15 shows the general distribution of plagioclase composition within the coarse gray gneiss. It is evident that there is no west-to-east trend. All variations appear to relate to bulk compositional changes caused by the aplite and pegmatite intrusions. Most plagioclase in the northern belt is relatively Ca-rich. Eighteen of 20 samples have compositions of An 27 or greater. In the southern belt, plagioclase from coarse gneiss unrelated to aplite bodies is significantly more calcic (An 28) than that of gneiss within aplite areas (An 25). Wynne-Edwards (1967, p. 262, and personal communication) noted that a similar association of less calcic plagioclase with higher modal K-feldspar existed in Tichborne granodiorite gneiss near contacts. He interprets the association as a chemical adjustment of the gneiss to the more hydrous, K- and Na-rich country rock with which it is in contact.

To the west, many features of the plagioclase indicate that they crystallized from a melt. West of Coxvale, they are subhedral in shape; to the east, however, the grains are anhedral and interlocking (see Figures 15 and 12a, b). The change in texture coincides with the approximate disappearance of muscovite, albitic rims, segregated biotite knots and the appearance of hornblende. Apparently in this eastern area the plagioclase recrystallized, producing a mosaic of interlocking plagioclase, quartz, and microcline grains. To the west, where the grains are subhedral, those grains with slightly longer axes appear to be subaligned with the strong biotite foliation. This suggests that the plagioclase was somewhat aligned by original flow.

Carlesbad twins in combination with subhedral texture indicate that the grains crystallized from a melt. Twin determinations were made of four or five grains in each of 15 thin-sections selected from the various sectors of the two gneiss belts. All determinations were made by the five-axis universal stage method described by Emmons (1943) and by the use of the composition charts originally plotted by Emmons and revised in part by Vogel (1964). The plagioclase grains are uniformly well twinned in all samples. The grains twin most commonly according to the albite law; however, grains with Carlesbad twins occur in samples from eastern and western parts of both gneiss

Figure 12a. Photomicrograph showing subhedral shape of plagioclase in gneiss west of Coxvale(crossed nicols).

Figure 12b. Photomicrograph showing anhedral shape of plagioclase in gneiss east of Coxvale(crossed nicols).

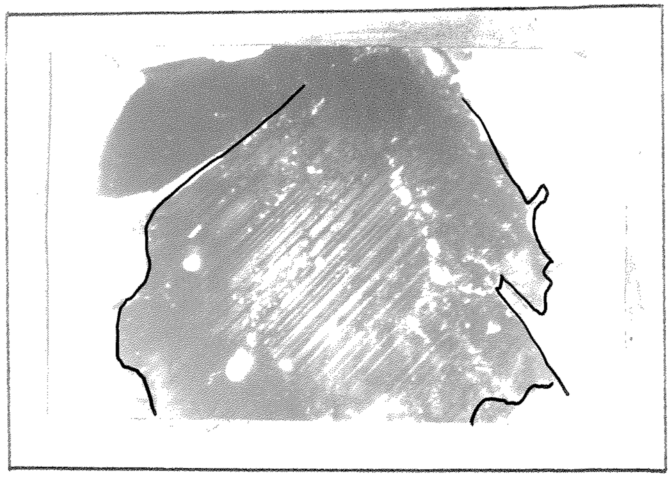


Figure 13a. Photomicrograph of compositional zoning in plagioclase(crossed nicols).

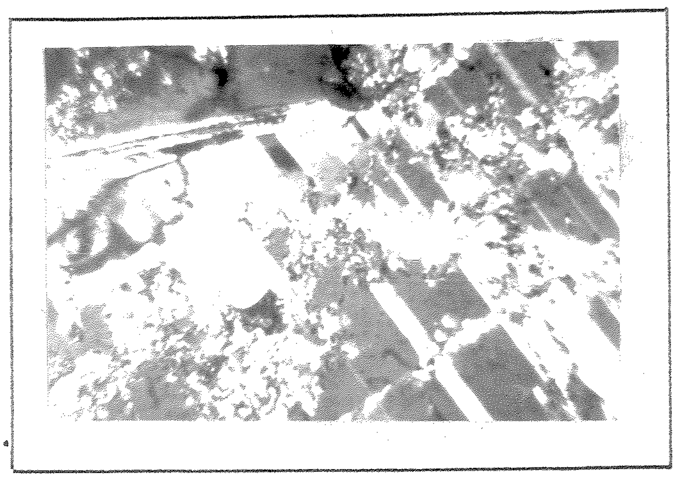


Figure 13b. Photomicrograph of albitic rim on plagioclase grain(crossed nicols).

of muscovite-bearing samples collected from the west. Little is found in plagioclase to the east. This fine-grained material selectively replaced the plagioclase along twin planes and in the cores of the more strongly zoned crystals and may be a metamorphic effect.

In summary, the textures of the plagioclase indicate crystallization from a melt and these are still preserved in the western area. An increase in metamorphic grade from west to east is shown by assemblages of muscovite, calcite, plagioclase with albitic rims and subhedral shape to the west and of hornblende and anhedral plagioclase to the east.

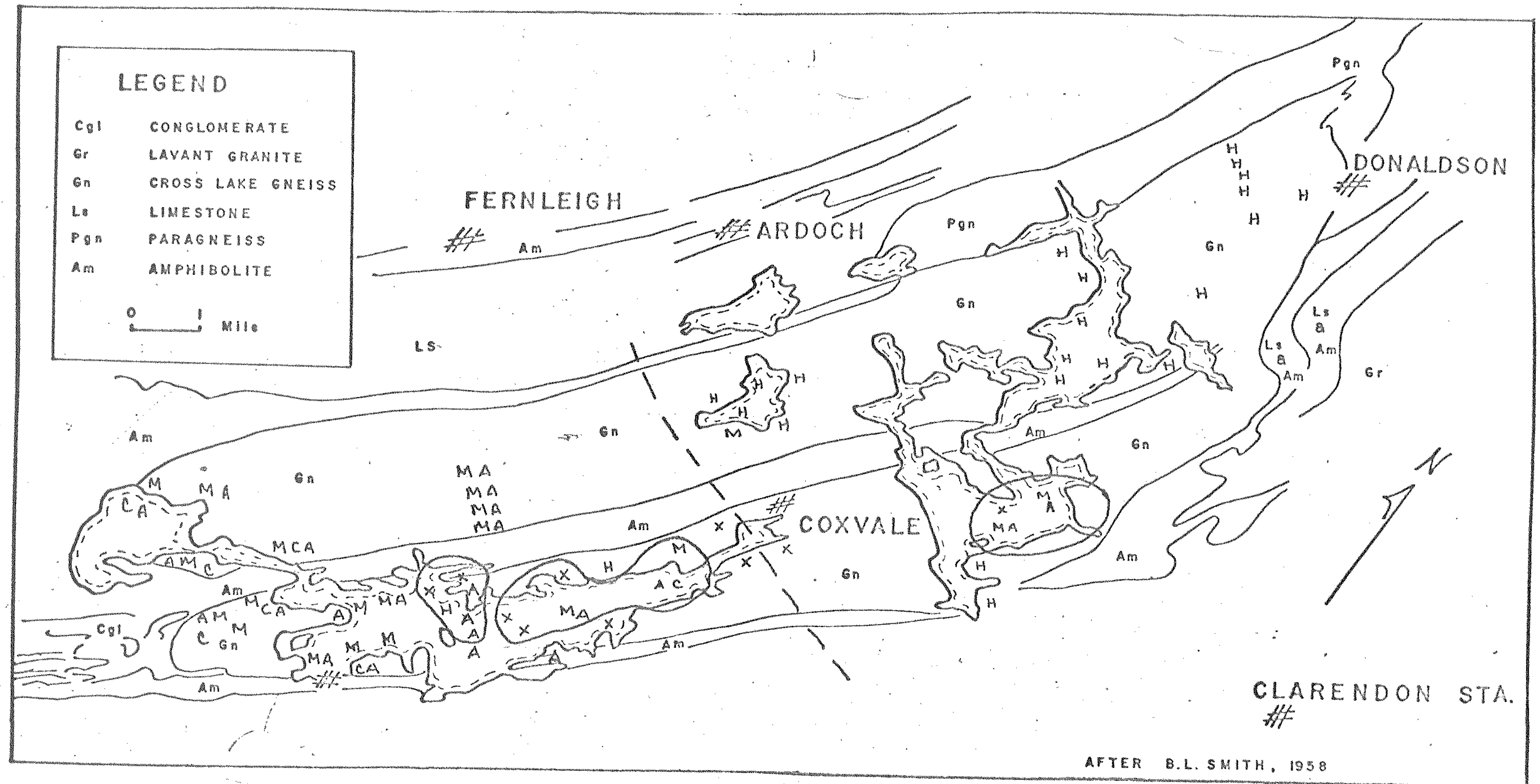


Figure 14. Distribution of muscovite(M), hornblende(H), calcite(C) and albitic rims on plagioclase (A). Samples lacking these are marked X. Aplite areas are circled and the dashed line approximates the division between rocks with muscovite and those with hornblende.

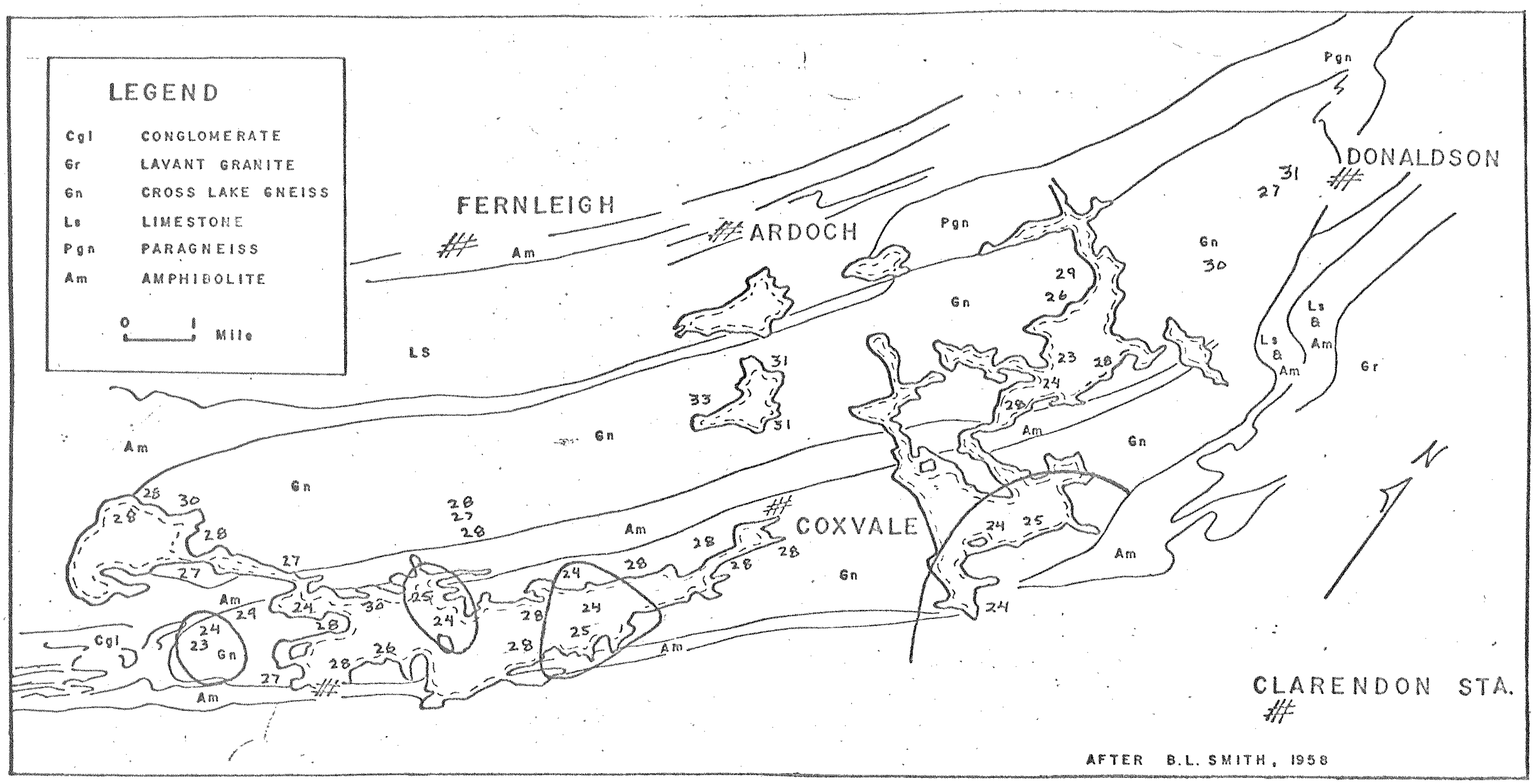


Figure 15. Distribution of plagioclase composition(An%). Areas with plagioclase of low An% are circled and coincide with intrusive areas.

DISTRIBUTION OF SELECTED CATIONS OF THE COARSE GRAY GNEISS

Introduction

The distribution of certain light elements (especially Na, Ca, K, Si, Al) and trace elements (Rb, Sr, Ba, Cs, Tl) can be used to interpret processes of sedimentation, regional metamorphism and fractional crystallization. Variations of these elements in the whole rock and in coexisting minerals of the Cross Lake Gneiss further document the west-to-east change in metamorphism.

The ability of an ion to substitute in a crystal lattice was originally thought to depend only on ion size and charge (Goldschmidt, 1937); however, it became evident that the many exceptions to this rule could only be explained by considering other factors, such as electronegativity (Fyfe, 1951; Shaw, 1953; Ringwood, 1955). Recently, Nockolds (1966) devised a bonding energy function which combines radius, charge and electronegativity. The bonding energy of a bond A-B (Pauling, 1960) is represented by:

$$\text{bonding energy}_{A-B} = \text{covalent energy}_{A-B} + \text{ionic resonance energy}_{A-B}$$

where ionic resonance is equal to $26(\Delta)^2$ and Δ is the electronegativity difference of A and B. Covalent energies are unknown for many elements; therefore it is necessary to use a formula devised for finding bonding energies for simple covalent gaseous molecules (Sanderson, 1960). The bonding energy of X-O bonds (a hypothetical 'molecule') is given by:

$$\text{Bonding energy}_{x-o} = \frac{11.8(S_m + 5.5)}{R} - 5.6 + \frac{26.5\Delta^2}{R}$$

where S_m is the stability ratio of the 'molecule'$_{x-o}$, Δ is the electronegativity difference between the metal, X, and oxygen, and R is the bond length. The bonding energy$_{x-o}$ is an approximation of bonding energies of common metals bonded to oxygen for bond lengths found in six-fold coordination. Bonding energy values should be used as relative values only, as absolute bonding energies will vary with the coordination and probably with different environments having the same coordination. The relative total bonding energies (RTBE) are the values that should be used to interpret cation distribution. These and other pertinent data for cations mantioned in this paper are given in Table 5, and a summary of expected substitution patterns is given in Table 6. Nockolds offers two new rules to explain cation substitution:

a. When two cations of the same valency are capable of substitution in a crystal lattice, the one having

TABLE 5. Bonding Energies of X-O Bonds (after Nockolds, 1966)

Bond, X-O	Effective r_x (Å)	R_{x-o} (Å)	Covalent Bonding Energy (Kcals per mol)	Ionic Resonance Bonding Energy (Kcals per mol)	Total Single Valence Bonding Energy	% Ionic Resonance Bonding Energy	% Ionic Character from E_o-E_x	Relative Total Bonding Energy
Ca-O	1.13	2.40	34	66	100	(66)	(77)	200
Sr-O	1.27	2.56	31	65	96	(68)	(79)	191
Ba-O	1.46	2.76	28	62	90	(69)	(80)	180
Na-O	1.09	2.40	31	69	100	(69)	(79)	100
K-O	1.43	2.77	25	65	90	(72)	(82)	90
Rb-O	1.56	2.90	23	62	85	(73)	(82)	85

TABLE 6. Substitution Possibilities for Ca and K (Compiled from Nockolds, 1966)

Cation	RTBE	Bond Length	Cation	Coupled RTBE		Bond Length	Comments
Ca^{++} (Allowable Radius Range: 0.96-1.30Å)							
Ca^{++}	200	2.40	Ca^{++}	CaAl	500	2.40	Divalent Sr and univalent Na (coupled RTBE) substitute for Ca easily.
Sr^{++}	191	2.56	Na^{+}	NaSi	480	2.40	
Mn^{++}	174	2.18	Cu^{+}	CuSi	460	2.08	Ba^{++} and K^{+} (coupled RTBE) may substitute for Ca^{++} under conditions of increased tolerance (i.e., higher temperatures).
Cd^{++}	156	2.25	Ag^{+}	AgSi	450	2.31	
Sn^{++}	152	2.27					
Hg^{++}	140	2.25					
Ba^{++}	180	2.76	K^{+}	KSi	470	2.77	
K^{+} (Allowable Radius Ranges: 1.21-1.64Å)							
K^{+}	90	2.77	K^{+}	KSi	470	2.77	Sr and Ba have greater RTBE than K; they should thus enter a suitable crystal lattice more easily than K (Sr more easily than Ba); however, bond lengths of K-O and Ba-O are equal; Sr-O is much less. Plagioclase, which takes Sr (not Ba) easily, crystallizes throughout the fractionation series. Thus Ba concentrates in the K-feldspars, and is rare in plagioclase.
Rb^{+}	85	2.90	Sr^{++}	SrAl	490	2.56	
Tl^{+}	74	2.62	Ba^{++}	BaAl	480	2.76	
Ag^{+}	71	2.31	Pb^{++}	PbAl	440	2.42	
Na^{+}	100	2.40	Ca^{++}	CaAl	500	2.40	During crystallization, sequence of entry into K-feldspar is: Ba, Sr, Ca. Thus, Ba decreases more rapidly than Sr (Ba/Sr decreases with increasing fractionation) and Sr enters more easily than Ca(Ca/Sr ratio increase)(Heier and Taylor, p. 303, 1959). Both Na and Ca should be preferred to K, if "tolerance" is great enough.

the greater relative total bonding energy will be incorporated preferentially.

b. When two cations of different valency, involving coupled substitution, are capable of substitution in a crystal lattice, that substitution will take place preferentially whose sum of relative total bonding energies is the greater. (Nockolds, 1966, p. 272)

It is assumed throughout that these elements are substituting in mineral lattices coexisting in a system of constant bulk composition and with adequate supply of any element concerned.

The distribution of elements within the Cross Lake Gneiss will be a result of (a) original crystallization and fractionation of the granodiorite magma, (b) redistribution during recrystallization by later regional metamorphism, and (c) introduction of material by hydrothermal solutions. In the following discussion, an attempt will be made to separate these three.

Distribution of CaO and K_2O

The distribution of CaO and K_2O was studied to determine if there is a west-to-east variation. CaO and K_2O contents of 50 samples were determined by heavy absorber X-ray fluorescence methods revised from those of Rose *et al*. (1962).

CaO in the coarse gray gneiss is distributed between plagioclase, hornblende, epidote and K-feldspar. The coincidence of bulk CaO and plagioclase composition patterns suggests that most of the CaO is in the plagioclase. K_2O

is distributed between K-feldspar, biotite, muscovite and plagioclase. Most is in the K-feldspar and the biotite. Because of this dual partitioning, trends in K_2O content are complicated. CaO/K_2O ratios and weight percent CaO and K_2O are plotted on Figures 16, 17 and 18. Reference to these maps and to those showing distribution of plagioclase composition, aplite intrusion, muscovite, biotite and hornblende should clarify the following discussion.

Bulk CaO and K_2O are constant from west to east and all changes in mineral assemblage occur within this framework. Most variations are related to the three aplite areas. The western part of the northern belt averages CaO: 2.8%, K_2O: 2.2%, and the eastern part averages CaO: 3.0%, K_2O: 2.2%. The northern belt contains more CaO (average 3.2%) than the southern belt (2.3%), and within the southern belt, CaO is lower in gneisses directly related to the late intrusives. K_2O content varies inversely with CaO. Neither K_2O nor CaO vary with nearness to mafic septa.

High CaO content coincides with the more calcic plagioclase; low CaO content coincides with aplite areas and less calcic plagioclase. Therefore, plagioclase composition is controlled only by rock composition and not by any change in metamorphic conditions.

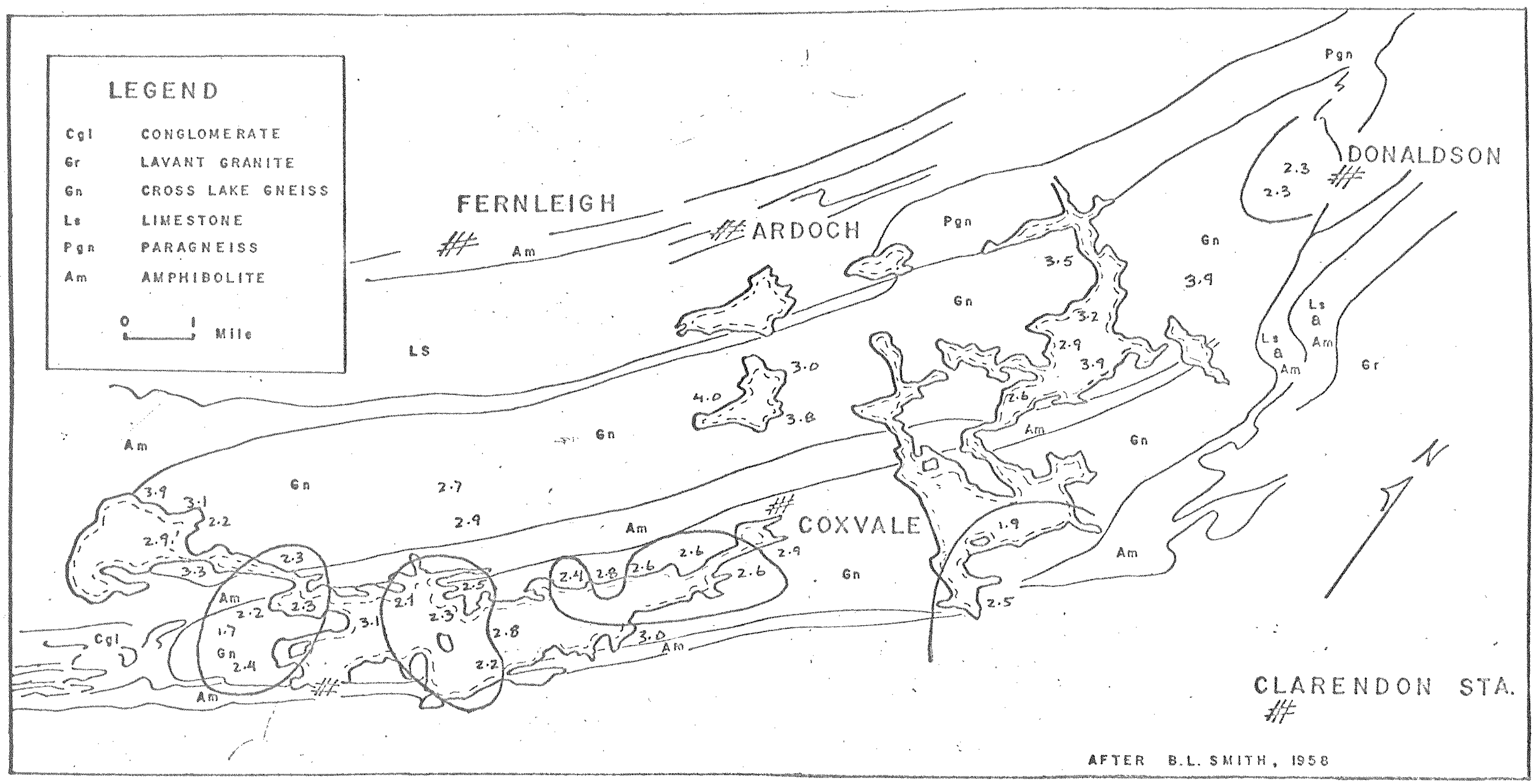


Figure 16. Distribution of weight percent CaO in the Cross Lake Gneiss. Areas of low CaO content are circled.

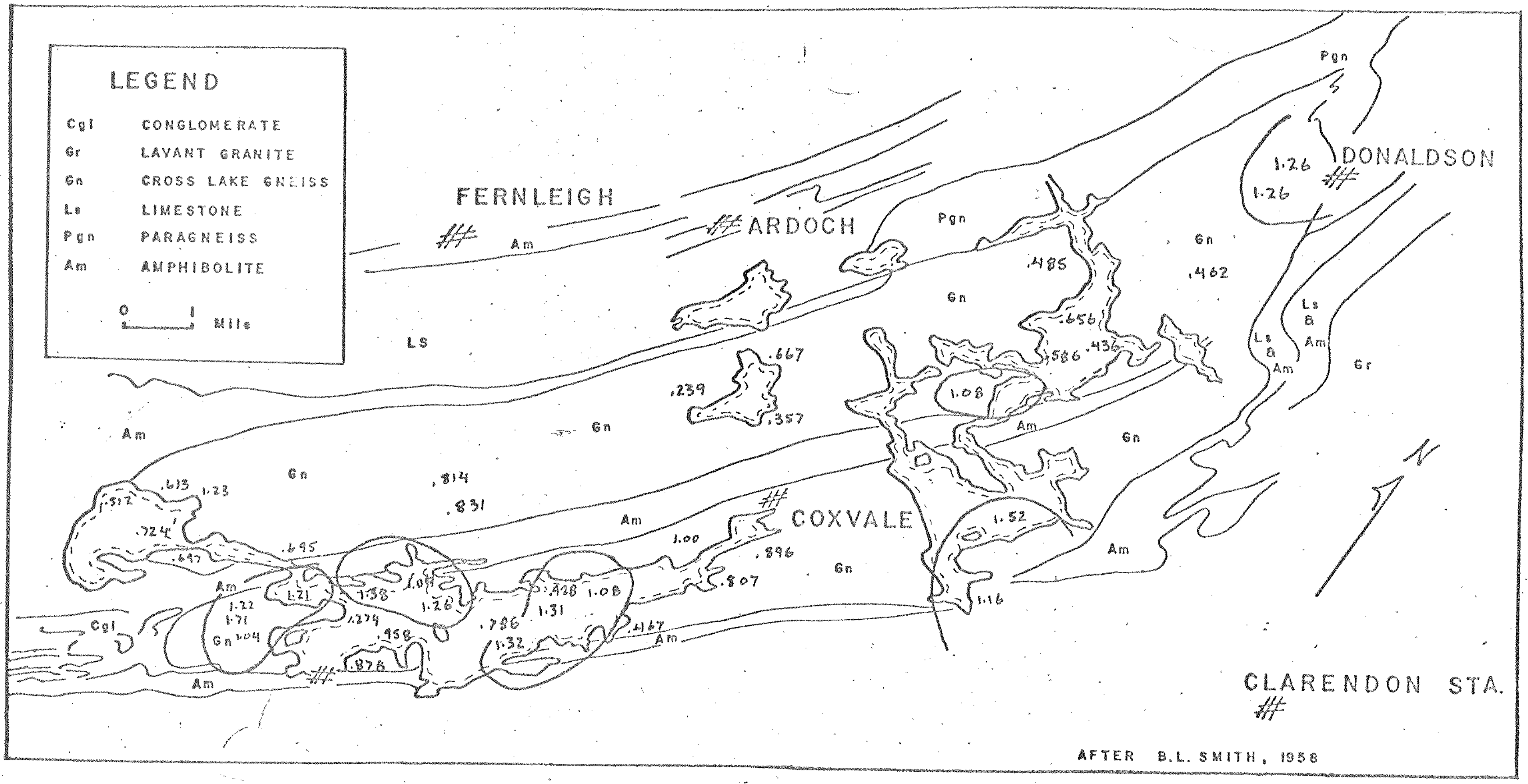


Figure 18. Distribution of K_2O/CaO ratios. Areas of high ratio(high K_2O) are circled.

<u>Distribution of Sr and Rb</u>

Sr (RTBE: 191, coupled RTBE: 490, Bond length: 2.56) may substitute for Ca (RTBE: 200, coupled RTBE: 500, Bond length: 2.40) in plagioclase and for K (RTBE: 90, coupled RTBE: 470, Bond length: 2.77) in the coexisting microcline (see Table 6). There will be no simple relationship because of its ability to substitute for two major elements and because of its intermediate bond energy and size; however, since plagioclase greatly dominates microcline in the gneiss, any pattern of Sr distribution will probably coincide with that of plagioclase. Sr does not enter the crystal lattice of the micas to any major extent (Taylor, 1965, p. 154). Ca/Sr ratios increase (Sr decreases faster) with decreasing amounts of Ca and Sr. In other words, feldspar should contain progressively less Sr relative to Ca with increasing fractionation. Therefore, whole rock and coexisting feldspar Ca/Sr ratio variation should be an indication of melt fractionation (Heier and Taylor, 1959b, p. 298).

Rb has a lower relative total bonding energy (RTBE: 85, coupled RTBE: 460, Bond length: 2.90) than K and may substitute for it, although never more easily than K itself. The difference in bonding energy becomes effective only in the very late stage of fractionation when Rb becomes slightly concentrated in the late fractions. Many authors have tried to use rock K/Rb ratios to interpret order of intrusion within a sequence of genetically related rocks (Tauson and Stavrov, 1957; Taylor, 1965, p. 145; Reynolds et al., 1967). Rb prefers the K position in micas by a factor of two or more over that in K-feldspars (Taylor, 1965). In the Cross Lake Gneiss, biotite is present in amounts up to 15% and K-feldspar in amounts up to 14%. Therefore the bulk of the Rb should be in the biotite. As the Rb is distributed between two minerals, patterns representing fractionation or changes in metamorphism may be indistinct.

Sr and Rb contents of 50 samples were determined by X-ray fluorescence using an arsenic internal standard and a revision of the method of Hower (1959). Sr and Rb contents and ratios are plotted on Figures 19-22.

Sr content is significantly higher in rocks of the northern gneiss belt (average, 836 ppm) than in the southern belt (average 642 ppm). This coincides with the higher CaO content in the northern belt and is to be expected due to the coherence of Sr to Ca in the plagioclase lattice and is not related to metamorphism. High and low Sr contents coincide with high and low CaO contents within each of the gneiss belts.

There is no significant difference in Ca/Sr between northern (average 27.7) and southern gneiss belts (average 30.9). The areas of high and low Ca/Sr ratios that do exist do not correlate with nearness to aplite areas; however, higher Ca/Sr ratios (lower Sr content) in rocks near mafic septa may represent assimilation of Sr-poor host

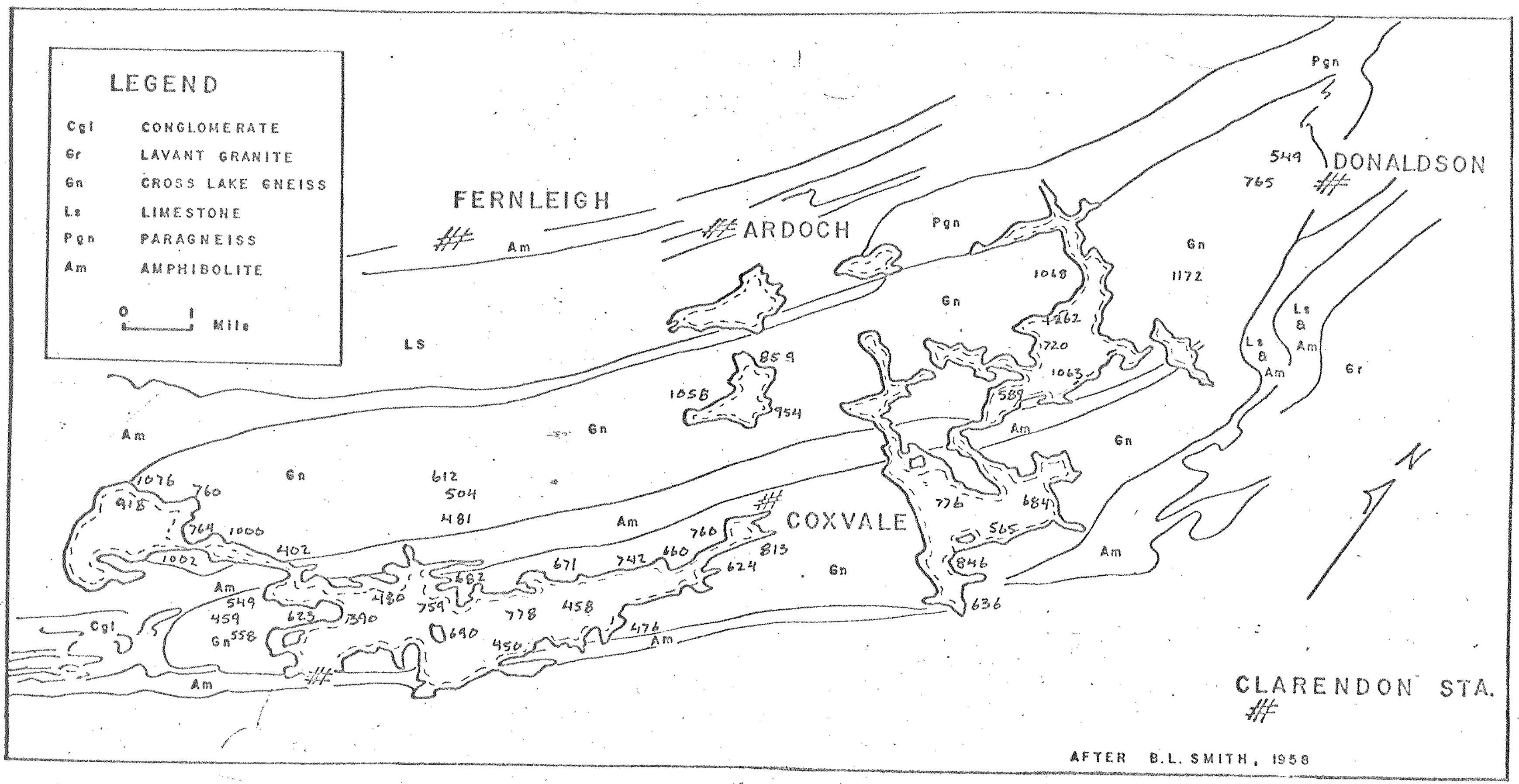


Figure 19. Distribution of Sr(ppm) in the Cross Lake Gneiss.

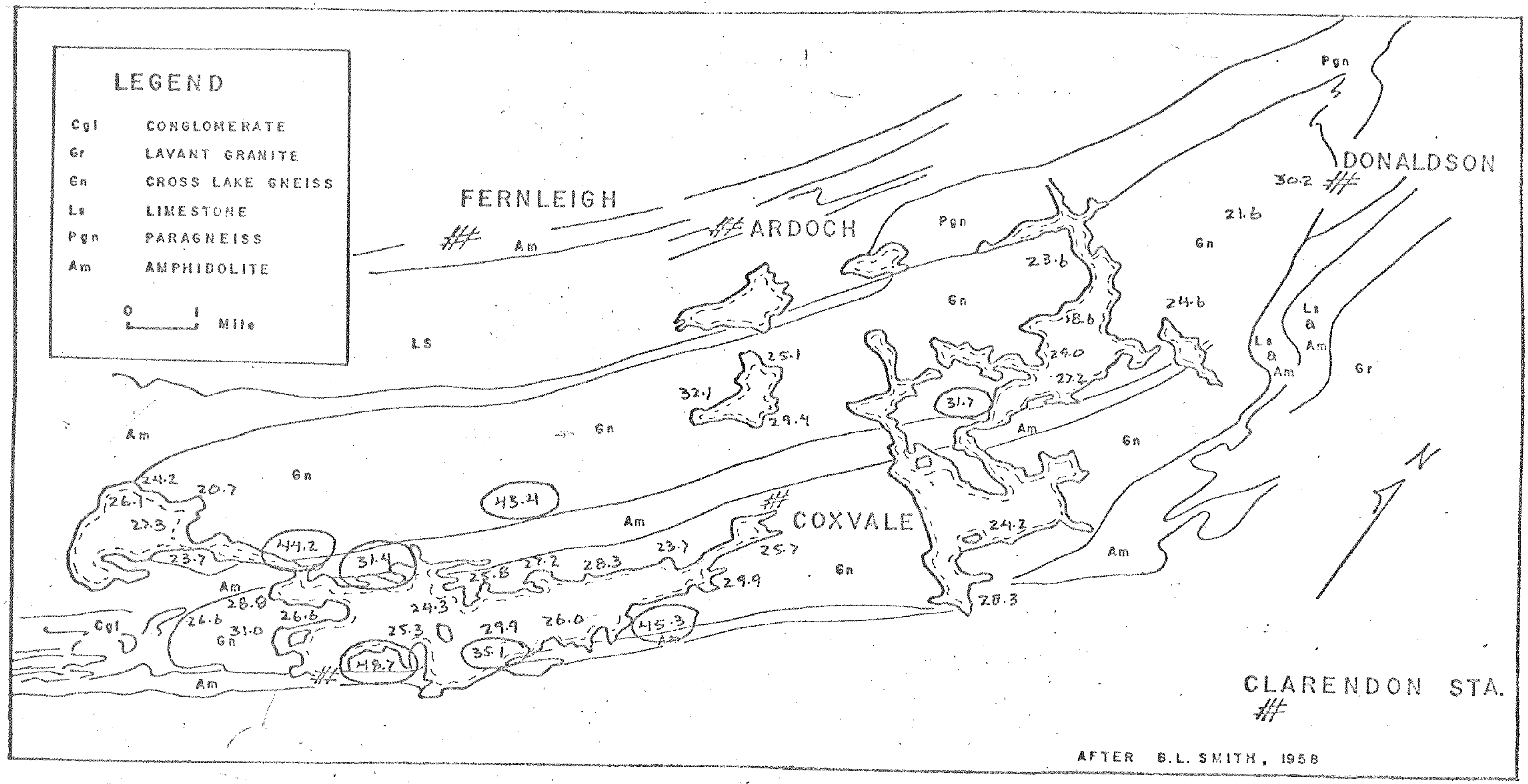


Figure 20. Distribution of Ca/Sr ratios in the Cross Lake Gneiss. High ratios(low Sr) in samples near contacts(circled) may represent assimilation.

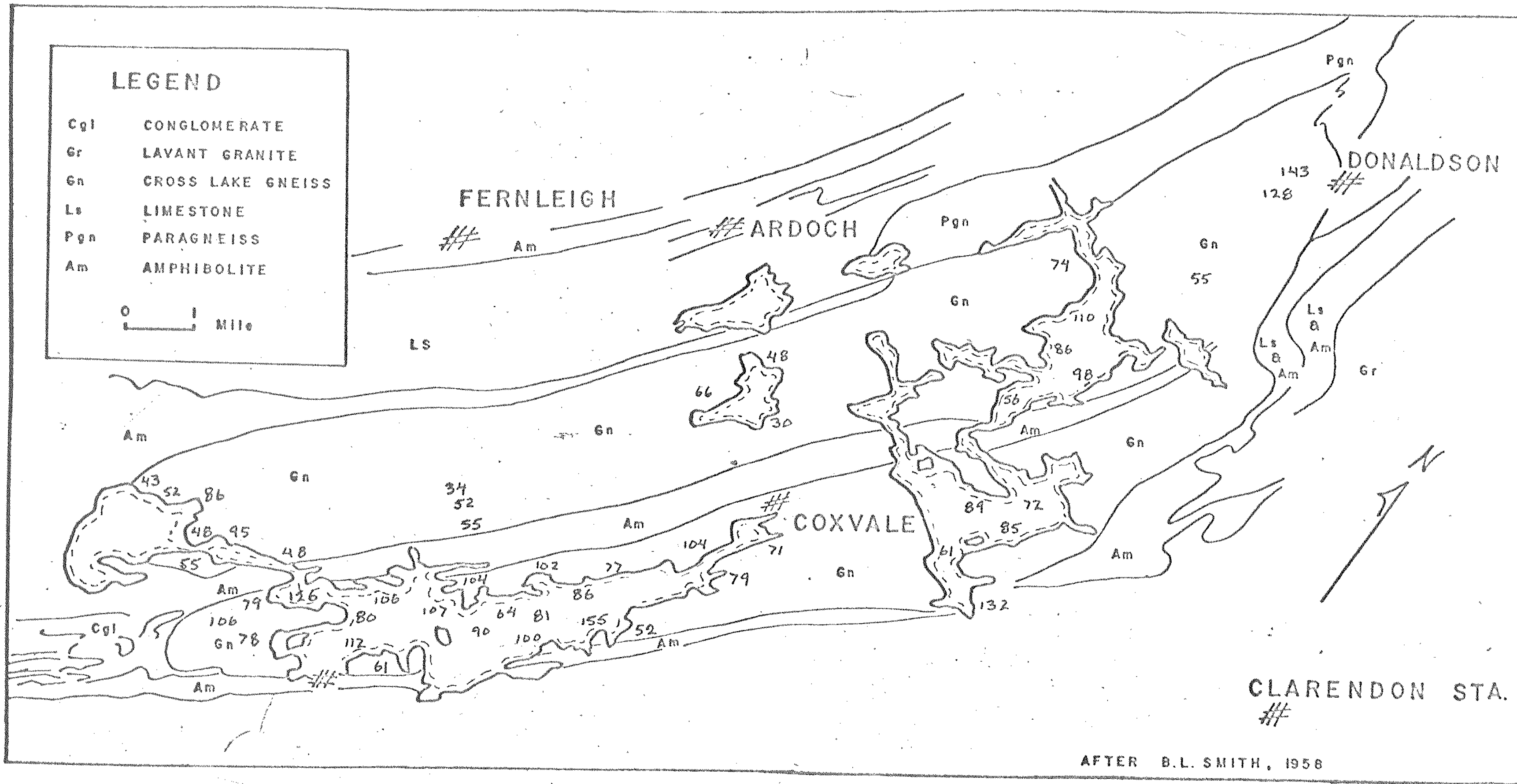


Figure 21. Distribution of Rb (ppm) in the Cross Lake Gneiss.

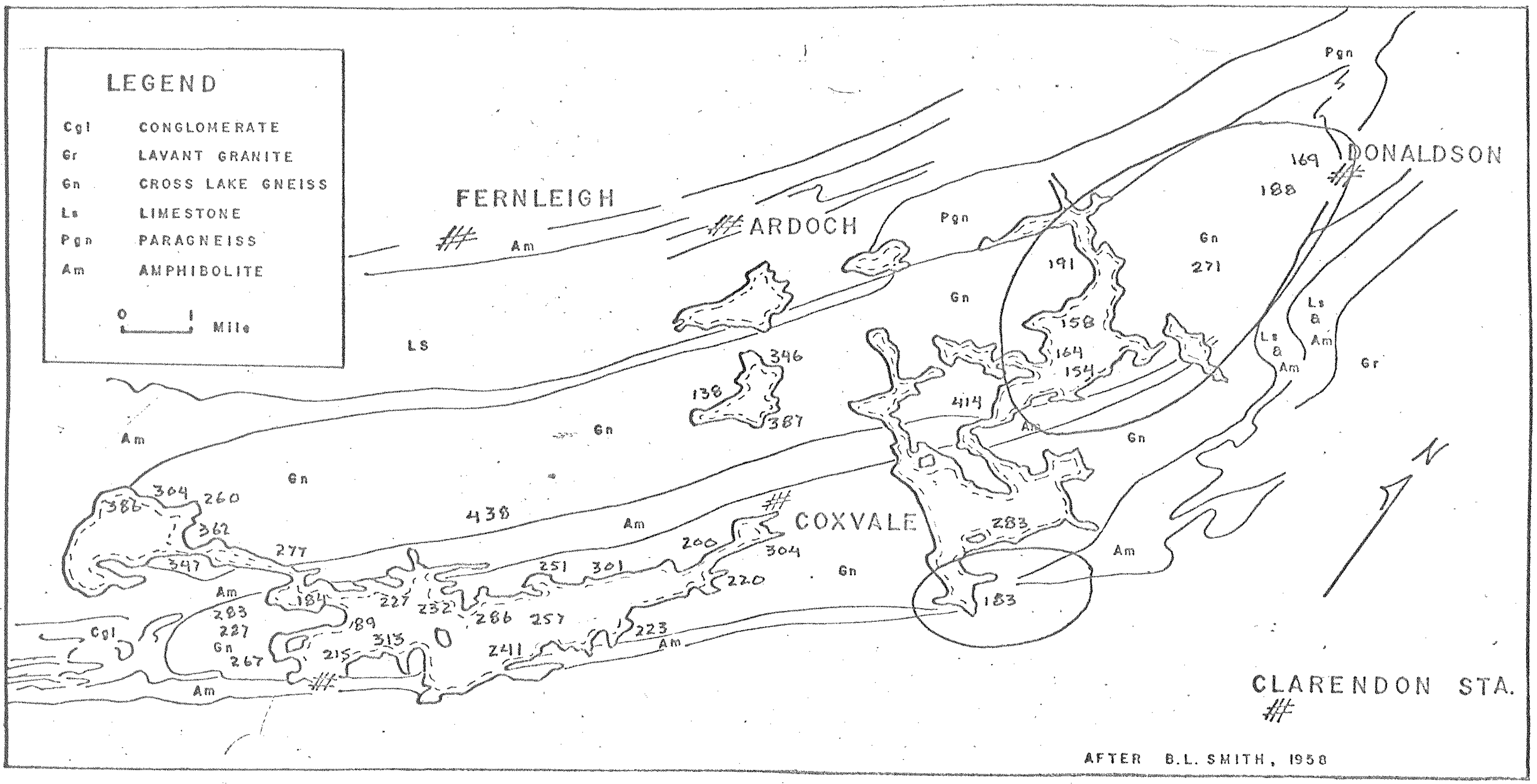


Figure 22. Distribution of K/Rb ratios. Areas of low ratio(high Rb) are circled.

rocks. There is no significant change in Ca/Sr ratio from west to east in either gneiss belt (see Figure 20); therefore, Sr does not increase with respect to Ca with increasing thermal gradient or disorder of the plagioclase.

Rb content of samples from the southern gneiss belt (average 91 ppm) is higher than in the northern belt (average 67 ppm). This coincides with higher K_2O content in the southern belt and is to be expected because of the coherence of Rb to K in the crystal lattice. High and low amounts of Rb coincide with high and low amounts of K_2O within each gneiss belt.

K/Rb ratios range from 138 to 387 and there is no significant difference between samples from the northern belt (average 283) and those of the southern belt (average 239). These values are well within the published range of values for other intermediate plutonic rocks. Although there are several pockets of high and low K/Rb in both gneiss belts, the pattern does not relate to late intrusives or to nearness to country rock. There are no patterns indicative of differentiation or assimilation. In addition, the ratio does not vary with amounts of K. In other words, higher K_2O content (e.g., near aplites) does not coincide with a lower ratio (higher Rb).

There is no significant west-to-east variation in Rb content with respect to K within the southern gneiss belt. Any pattern that may have existed has been destroyed by the intrusion of the aplites.

The most significant observation from the Rb analysis is that there is a distinct increase in Rb with respect to K from west to east within the northern gneiss belt (Figures 22 and 25). This coincides with other evidence that indicates a rise in metamorphic grade to the east.

Distribution of Sr and Rb with Respect to Metamorphic Gradient

Trace element distribution in metamorphic rocks has been used (a) to study the mechanics of chemical migration, (b) to identify the parent rock type (Taylor, 1965), and (c) to establish variations in individual coexisting minerals with increasing metamorphic grade (Heier, 1960; Griffen *et al*., 1967). The second use is of little help here as the Ca/Sr ratios (average 28) and K/Rb ratios (average 261) of the Cross Lake Gneiss are similar to those of other granodiotrites, andesites and many sediments.

Sr and Ba contents in feldspars are lower in amphibolite facies rocks than those of the granulite facies (Heier, 1960). In contrast, the concentrations of alkali metals (K, Rb, Cs) in rocks increases to a maximum in those submitted to amphibolite facies conditions, and further metamorphism causes loss in these elements (Ramberg, 1952a; Heier, 1960; Heier and Adams, 1963). The trend may be caused by the instability of the K-bearing minerals under high grade conditions, and by the tendency of the alkali minerals to be concentrated in early formed melts. This trend should be best illustrated by the K/Rb ratio; Rb has a smaller activation energy than K and will decrease faster (Figure 24).

The K/Rb data from the northern belt fall within the same range as those of Heier and Adams (Figure 25); however, in the northern belt, the pattern is reversed with Rb increasing faster than K with increasing metamorphism to the east. This can be explained if the K/Rb ratios from the west represent magmatic conditions whereas those to the east represent middle amphibolite grade.

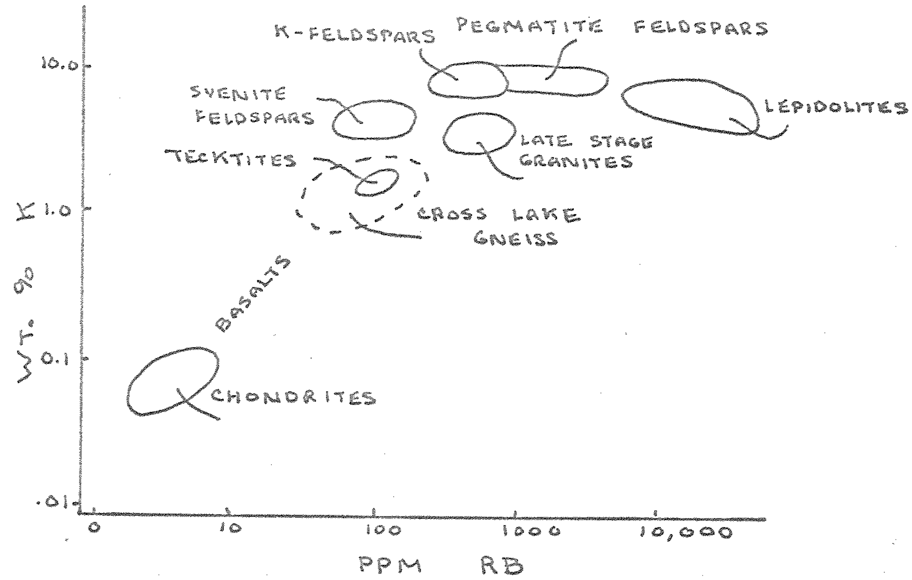


Figure 23. Relationship between K and Rb in common rocks and minerals (after Taylor, 1965).

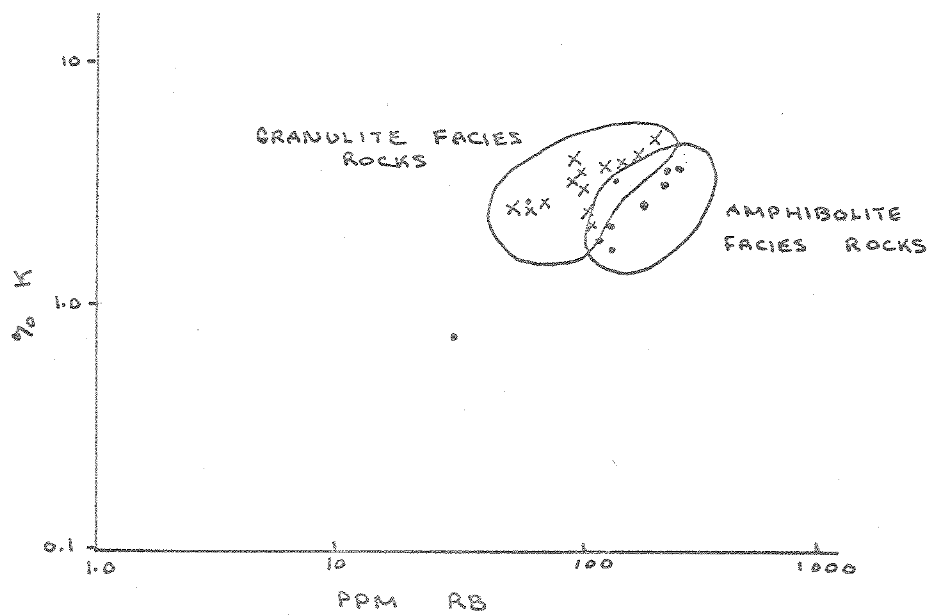


Figure 24. Relationship between K and Rb in metamorphic rocks (after Heier and Adams, 1963).

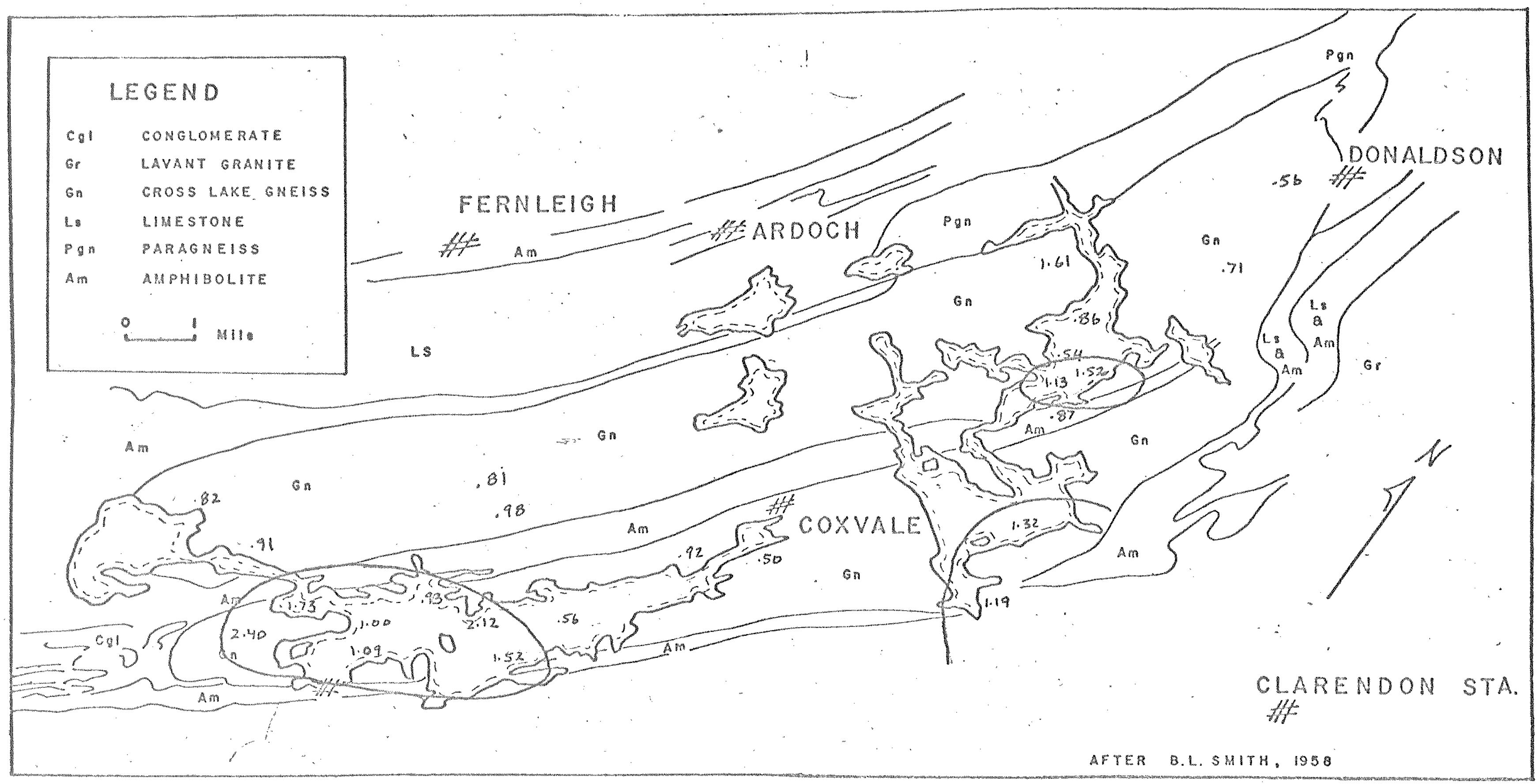


Figure 26. Distribution of mole percent Or in plagioclase. Areas of high Or content are circled and correlate, in part, with intrusive areas.

assumed that the system is saturated in K_2O. The average Or content of plagioclase from the Cross Lake Gneiss is 1.2 mole percent, and the range, 0.5 to 2.4%. This agrees with the values given by Sen for plagioclase from the amphibolite facies and is substantially lower than that for the granulite facies. It is also lower than the values given by Vogel _et al_. (1968) for granites and granite gneisses from the lower granulite facies of the New Jersey Highlands.

Within the gneiss belts themselves, however, there is no variation in Or content from west to east, and, therefore, no variation with plagioclase structural state or with increasing thermal conditions.

There is a correlation of high Or content with the three major areas of K-rich intrusives; thus variation appears to relate more closely to rock K_2O content than with west-to-east temperature gradient. This would suggest that the Or in the plagioclase of the Cross Lake Gneiss is controlled by K_2O availability, not temperature, and that the system was not saturated in K_2O. It is also possible that the intrusion of the aplite caused local thermal highs which increased the ability of these plagioclases to accept Or.

The major conclusion from these data is that the Or in the plagioclase does not vary with the thermal gradient in these isochemical (from west to east) rocks and therefore might not be as sensitive as Sen (1959) originally believed. Sen worked with rocks of diverse compositions and these data might be more significant than his.

Structural State of the Plagioclase

The distribution of Al and Si in the tetrahedral sites of feldspars is sensitive to the thermal history. A high energy environment causes random placement of the Al and Si and the structure is considered disordered. In the ordered form, all the Al is in special sites. Variation of structural states of feldspars from the Cross Lake Gneiss should reflect the thermal history of the rock.

The structural state of plagioclase may be determined by measuring the $2\theta_{cu}(1\bar{3}1)$ - $2\theta_{cu}(131)$ X-ray diffraction peak separation, if the composition of the plagioclase is known (Slemmons, 1962; Wright and Stewart, 1968, p. 62). The resulting 'intermediacy index' (I.I) may range from 100 (most ordered) to 0 (least ordered). Indices measured for specimens of similar histories are usually closely grouped (e.g., volcanic plagioclase: I.I. = 0-42%; plutonic, igneous and metamorphic plagioclase: I.I. + 39-100%).

The structural states of plagioclases from 50 samples of coarse gray gneiss are given in Figures 27 and 28. In Figure 27, the plagioclase composition range for the entire gneiss is indicated by the two vertical lines. Points are plotted according to peak separation (in degrees 2θ) and the mean An composition of the ten grains measured

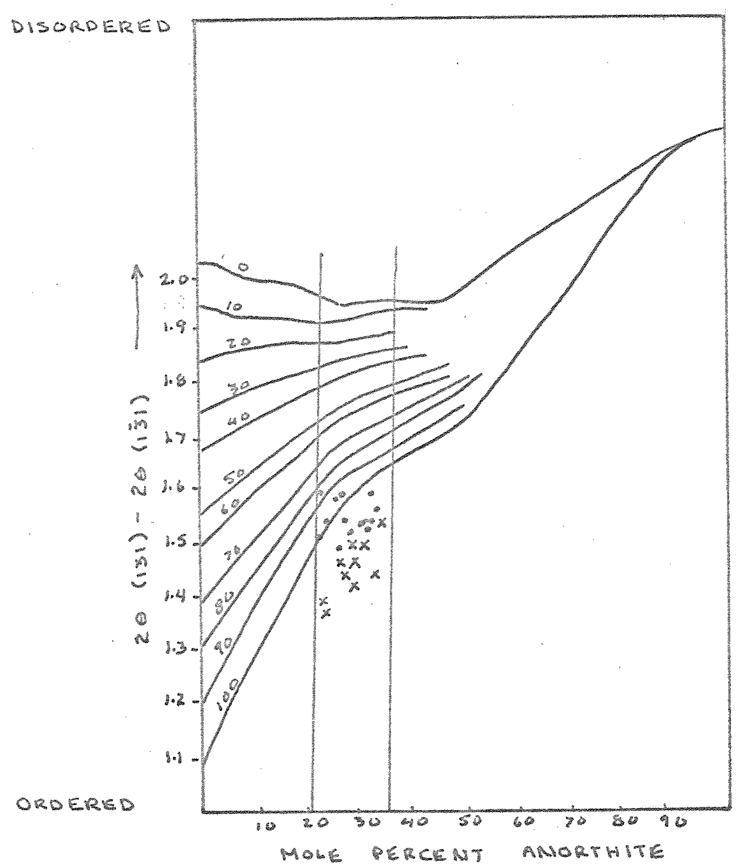


Figure 27. Intermediacy Indices for plagioclase from the west of Coxvale(X) and from the east of Coxvale (•). After Slemmons, 1962.

per sample. The variation within samples is less than the variation between samples from west to east. The distribution of structural states is plotted on Figure 28 in the form of peak separation in degrees 2θ because of the high degree of ordering of all samples.

Peak separation values to the east of Coxvale range from 1.50 to 1.60 degrees 2θ. Those to the west of the first K-rich intrusive (Figure 5) range from 1.40 to 1.50. Therefore plagioclase becomes slightly more disordered to the east. The change in structural state coincides with the appearance of hornblende and anhedral plagioclase; therefore, it is probably related to a change in thermal conditions from west to east.

Ab Content of the K-Feldspar

High temperature favors the solubility of Na in K-feldspar (see, for example, Heier, 1962, p. 420). The relative bonding energy for K is 90 and bond length is 2.77; its coupled RTBE is 470. The values for NaSi are 480 and 2.40, and for CaAl, 500 and 2.40. Na and Ca will be incorporated preferentially with respect to K if the environmental conditions are right (see Table 6). Therefore a favorable pattern of Ab distribution might give further evidence for a rise in metamorphic grade from west to east. However, change in K-feldspar Ab content might also be changed by (a) local changes in P H_2O, (b) change in bulk amount of Ab to be distributed between the plagioclase and the K-feldspar and (c) nearness to K- and Na-rich late intrusives. An attempt to separate these effects will be made in the following discussion.

Much work has been done recently on alkali metasomatism and alkali exchange (Orville, 1963, 1967). The best review of the petrographic significance of alkali exchange is given by Orville (1963). Values for mole percent Ab for 25 unheated and heated K-feldspar samples and their corresponding structural states are given on Figures 29 and 30. The difference between $2\theta_{Cu}(\bar{2}01)$ K-feldspar diffraction peak and the (101) peak of $KBrO_3$ has been plotted directly against mole percent Or (Orville, 1967). Both unheated and homogenized K-feldspars were analyzed to determine the amount of Ab in solution in the matrix before homogenation and the total amount in solution after homogenation.

Samples collected from the far west contain exceedingly high amounts of total Ab (up to 28%). Samples to the east contain between 6% and 17% total Ab with no variation from west to east or between belts (see Figure 29). There is no correlation of K-feldspar Ab content with nearness to late intrusives. All unheated K-feldspar samples contain from 0 to 7 mole percent Ab in the matrix unexsolved and there is no variation from west to east or between belts.

The amount of Ab in solution in the crystal structure after homogenation should represent the amount that

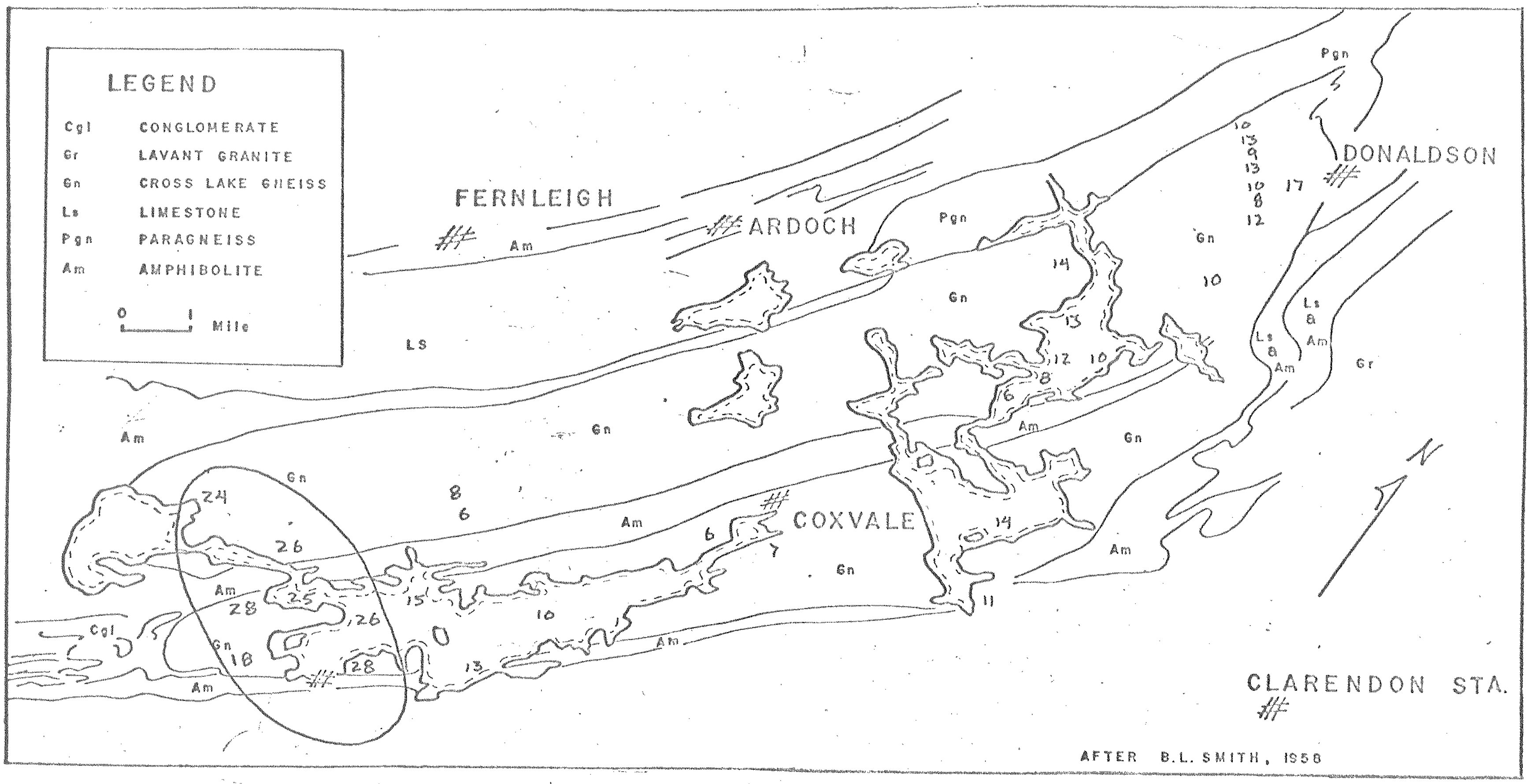


Figure 29. Distribution of total mole percent Ab in K-feldspar. The area with K-feldspar of high Ab content is circled.

the lattice could hold at the fixation temperature. The high amount of Ab in the K-feldspar to the west represents igneous conditions whereas the microclines to the east have recrystallized in response to the metamorphic conditions.

Structural State of the K-Feldspar

Structural states of the K-feldspars are controlled by the thermal history. K-feldspar triclinicity (Δ) may be used as a measure of the structural states and may be defined by the separation of the $1\bar{3}1$ and 131 X-ray diffraction peaks. These two peaks merge into one with monoclinic symmetry. Most physical parameters of K-feldspar are dependent on both structural state and composition. All methods to determine structural state or composition assume that the K-feldspar is a perfect crystal, which is commonly not the case; for example, alkali feldspar grains may be a mosaic of tiny domains, each having its own composition, degree and type of ordering and degree of twin development (McGraw, 1959; Christie, 1962; Laves and Viswanathan, 1967). Certain features such as sub-X-ray twinning could cause a triclinic lattice to appear monoclinic. A second method is based on measurement of 2θ for the three diffraction reflections (060), (204) and ($\bar{2}01$), representing the a, b and c unit cell parameters, respectively (Wright, 1968; Wright and Stewart, 1968). Plotting of these parameters may give structural state and/or establish at the same time whether the particular K-feldspar has an 'anomalous' separation varies with both structural state and Ab composition. The latter becomes important when Ab content is greater than 15% (Orville, 1967). The Ab content of these homogenized samples is greater than 24%.

Total Ab content appears to be related to structural state; most of the disordered microclines contain medium to high amounts of Ab (15 to 30%). This is especially true of the samples from the far west. The pattern is less clear to the east. Plots of the structural state vs. Ab mole percent are given in Figures 31, 32 and 33. The samples appear to fall into three groups:

Far western Clarendon Lake: high total Ab content, disordered

Mid-section, both gneiss belts: low to medium Ab content, ordered

East of Coxvale: low to medium Ab content, disordered to ordered.

There is no clear change in structural state from west to east; however, structural state patterns vary with rock composition and nearness to aplite areas. Rocks with high K_2O content tend to have ordered K-feldspars; those with low K_2O content contain disordered K-feldspars. Aplite intrusion could cause thermal highs and introduction of water, encouraging change of structural state. It may even be that the microcline of these samples is ordered material introduced directly from the aplite.

If the granodiorite is a pluton that intruded at

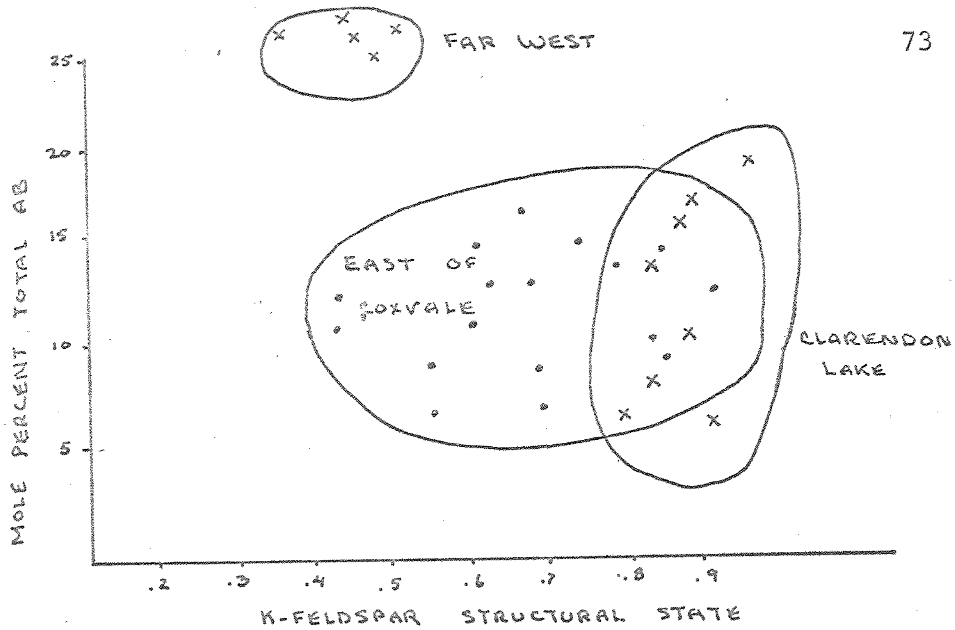


Figure 31. Mole percent Total Ab in K-feldspar vs. structural state.

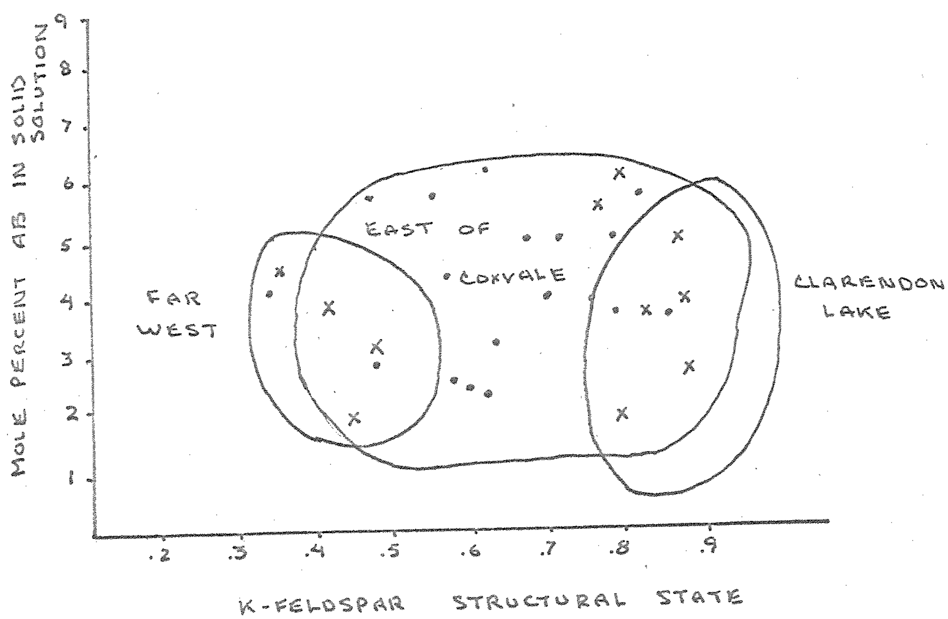


Figure 32. Mole percent Ab in solid solution vs. structural state.

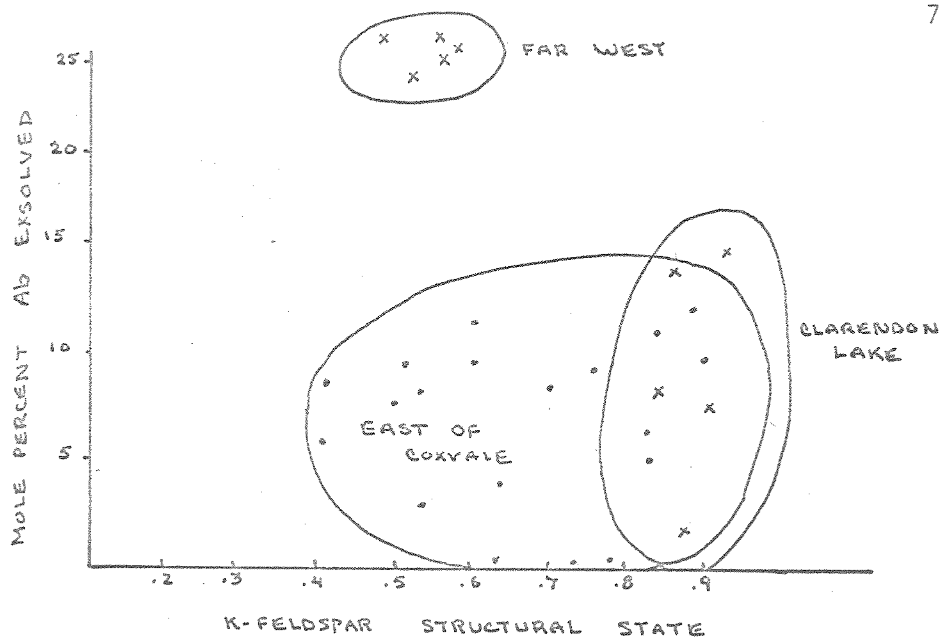


Figure 33. Mole percent Ab exsolved from K-feldspar vs. structural state.

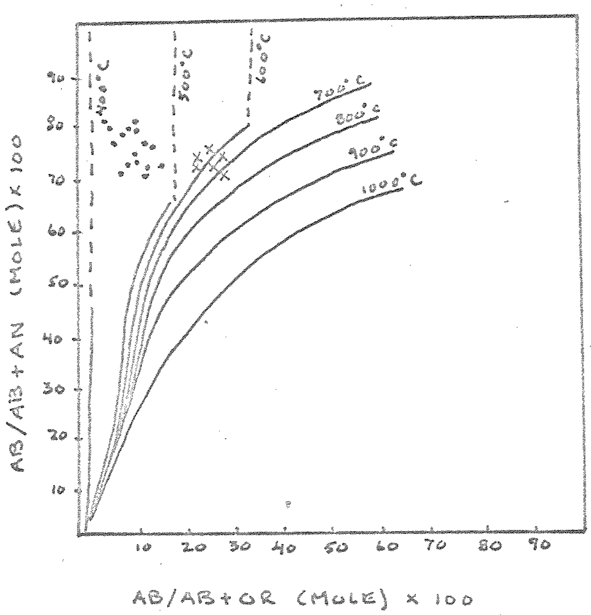


Figure 34. Geothermometer based on the distribution of Ab between K-feldspar and plagioclase(after Perchuk and Ryabchikov, 1968). Coarse gray gneiss feldspars from the west of aplite 1#(X) and from the east(•) are indicated.

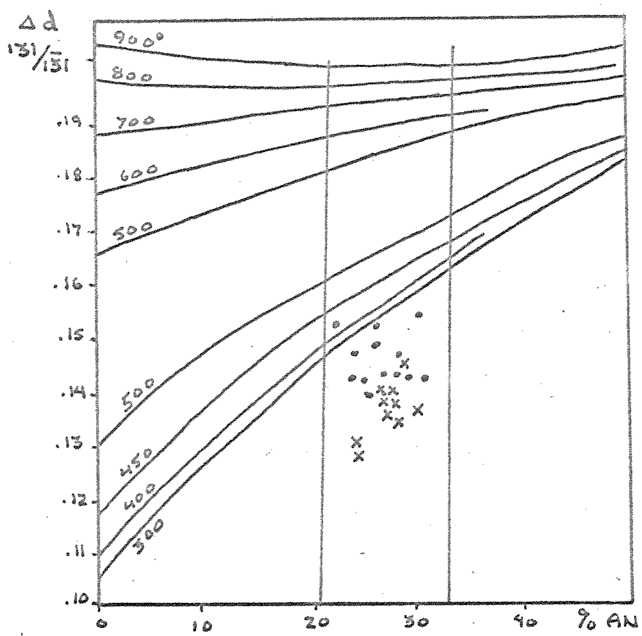


Figure 35. The plagioclase geothermometer(after Christie, 1962). Vertical lines show the maximum range of plagioclase compositions found. Feldspars collected west of Coxvale are indicated as (X), those collected east of Coxvale as (•).

STRUCTURE OF THE CROSS LAKE GNEISS

Introduction

The three granodiorite belts are a series of phacolith-like sheets which appear to have intruded into the preexisting metavolcanic and paragneiss sequence (Smith, 1958). The foliation and lineation of the granodiorite outline an elongated domal structure which is most deeply dissected in the vicinity of Coxvale. This is shown diagrammatically in the model in Figure 36. The dips of the foliation suggest that the southern belt is stratigraphically higher than the northern belt and that both belts were folded at the same time. The southern belt has been disturbed by three major pegmatitic and aplitic intrusive masses. The entire structure plunges to the east where it is cut by many pegmatites, and to the west where it is overlain by metaconglomerates and metasediments. Foliation, with a few exceptions, is generally concordant to contacts and to compositional layering, even at fold crests (Figure 37). There appears to be a relationship between the well-developed joint sets, the major structure and the orientation of the pegmatite and aplite dikes.

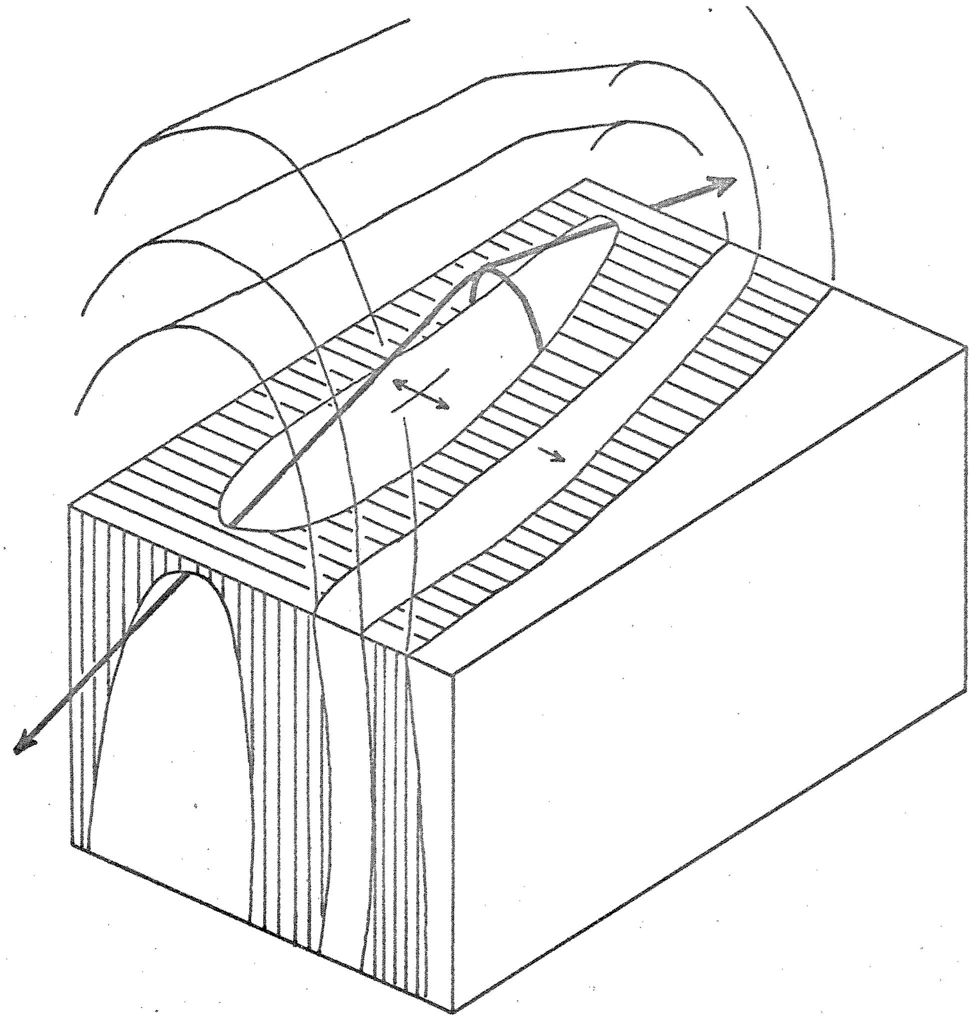


Figure 36 . Simplified model of the relationship of the granodiorite to country rock and folding.

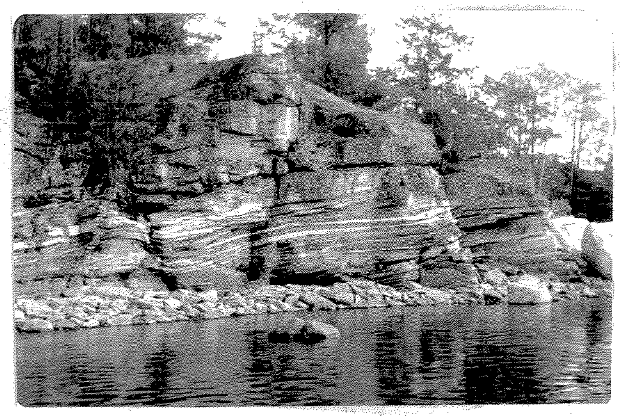


Figure 37. Nearly horizontal layering at the structural axis, northern gneiss belt. The foliation is parallel to the contacts.

Folding

The doubly plunging elongated fold is delineated by foliation, mineral lineation and compositional layering (including mafic bands and pods). Lineations to the east of Coxvale plunge 5° to 45° to the northeast; to the west of Coxvale, gently (0° to 5°) to the southwest. The steeper plunge of the fold axis to the northeast may explain the increase in continuous mafic bands and heterogenous outcrops, as amounts of poorly assimilated country rock should increase near the structural roof.

Foliation is parallel to compositional layering at the crest of the fold (northern gneiss belt, see Figure 37). Thus the foliation may have formed by recrystallization before folding and have been later folded with the compositional layering. This concordancy might also be explained by flow-folding (Wynne-Edwards, 1963); however, this mechanism requires upper amphibolite to granulite facies conditions and implies complete recrystallization of the material. As pointed out in an earlier section, there are many primary features which indicate that parts of the Cross Lake Gneiss have not been recrystallized. If these primary features can be retained throughout flow-folding, then perhaps the flat foliation at the structural axis can be explained this way also.

There remains the possibility that the Cross Lake Gneiss has not been mechanically folded at all. The foliation pattern may be a result of original flow and doming of the viscous magma. The formation of the minor fold (see discussion below) with its axis and plunge parallel to the major structure is unexplained by this mechanism. In addition, jointing would be solely controlled by doming, and sets would have formed coincident with cooling and very early in the sequence. The relationships of the joints to the dikes are then left unexplained.

Figures 38a and b show a small fold (4 feet in width) with well-developed subsidiary folds on either limb. This synclinal structure plunges 21^{o} to the northeast. Shearing faces and some (but not all) foliation cut through the structure (and thus the compositional layering) parallel to its fold axis. The gneiss appears to have been folded first, then later sheared with coincident reorientation of some biotite. This is one of the few instances in which the foliation and the shearing are normal to the compositional layering, and thus is one of the few examples in which the compositional layering is at a relatively high angle to the axis of the major northeast trending fold. This is probably a small synclinal fold (drag fold?) on the southern limb of what may be the stratigraphically higher granodiorite sheet (southern gneiss belt). If so, then major and minor folds were formed at the same time.

The folding of aplites and pegmatites is discussed on page 89.

Figure 38a. Small synclinal fold in the Cross Lake Gneiss. Structural axis strikes N 40° E, plunges 21° NE. Some foliation follows layering, some the shearing and axis.

Figure 38b. Detail of the fold shown above. Hammer is parallel to the foliation, shearing and major structural axis.

Foliation and Lineation

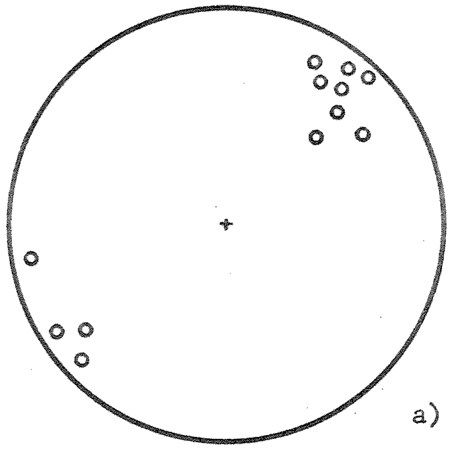
Lineation and foliation outline the major structure. Twenty-six lineation measurements, all determined on elongated minerals, are plotted on Figures 39a, b and c. The two gneiss belts are divided into four sections for the purpose of discussion (far west, Mid-Clarendon Lake, north and south of Coxvale and east of Coxvale: see Figure 40). No values were taken to the far west.

To the east, eight of fourteen values plunge relatively steeply to the northeast and three gently to the southwest. At Coxvale, two plunge to the northeast and two to the southwest. In the Mid-Clarendon Lake area all values plunge gently to the southwest.

If the plunge of the mineral lineation is parallel to the structural axis, then the axis of the major anticlinal fold plunges eastward to the east of Coxvale, becomes horizontal and then plunges gently to the southwest to the west of Coxvale. These data support the conclusions reached by Smith (1958).

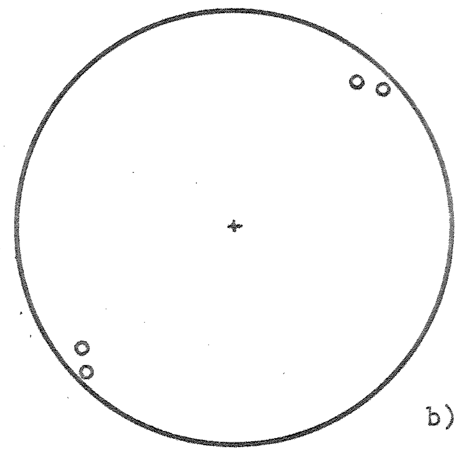
Over one hundred foliation attitudes were measured from all parts of the Cross Lake Gneiss. The strong foliation results from the parallel orientation of biotite (either in separate flakes or in knots) and of elongate leaf-shaped quartz grains.

There is a decided change in the nature of mineral alignment from the far west to the far east. To the west, biotite and quartz form knots or aggregates and the



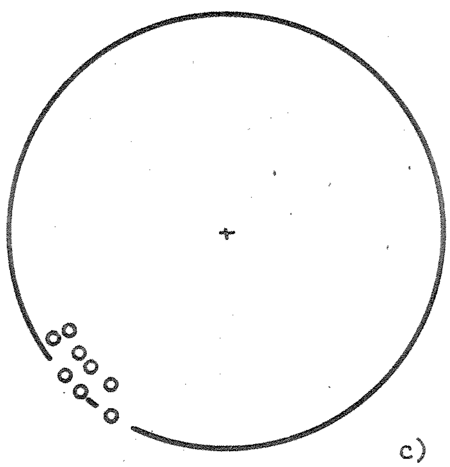
a)

East of Coxvale



b)

North and south of Coxvale



c)

Mid Clarendon Lake

Figure 39 . Lineation distribution within the Cross Lake Gneiss.

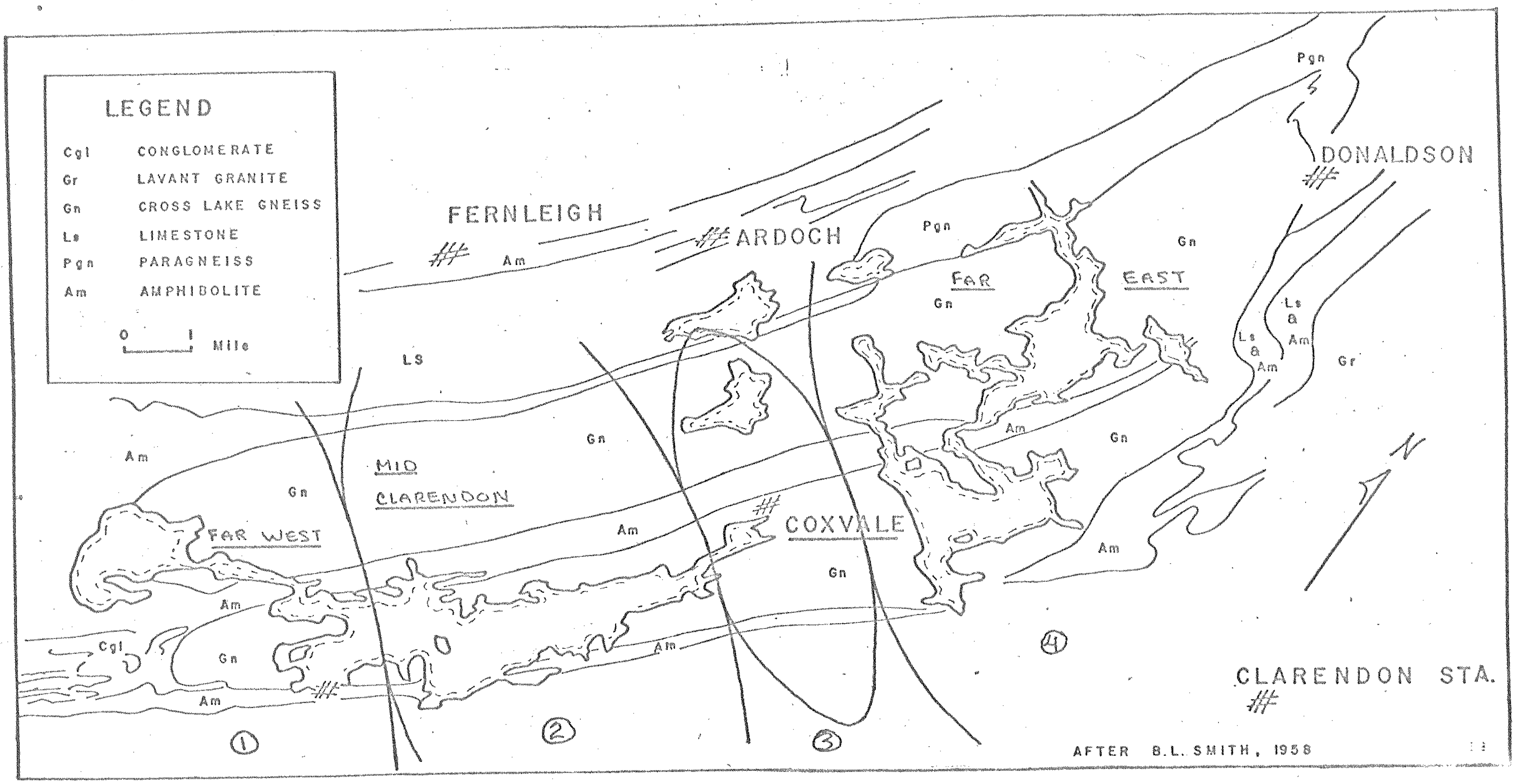


Figure 40. Location of the four sections referred to in the structure section.

foliation becomes almost a pencil lineation (Figures 9a, b). To the east, the biotite is disseminated throughout the quartz and feldspar and forms planar foliation. This change in texture may be related to the amount of shearing, local metamorphic temperature and pressure conditions, presence of water or a combination of these. One thing is certain: the segregation of biotite into knots and the textural variation from west to east are not magmatic phenomena.

Possible subhedral plagioclase suborientation and early northeasterly dike intrusion indicate the presence of at least remnant magmatic flow foliation.

A second weak foliation trend may exist in rocks to the west and in certain areas to the east that contain muscovite. Free muscovite flakes appear to be oriented at a high angle to the major biotite-quartz foliation. If this is so, textural thin-section evidence indicates that the orientation of these grains was later than that of the biotite. The only other linear trend at a high angle to the foliation is the northwesterly trending joint set formed at the time of folding. Thus a light northwesterly stress related to folding and jointing may have caused recrystallization of the muscovite.

Shearing

Shearing may be an important factor in the formation of some of the west-to-east trends. There is a strong

Figure 41a. Detail of figure 37. Possible pegmatite boudin in biotite-rich layers.

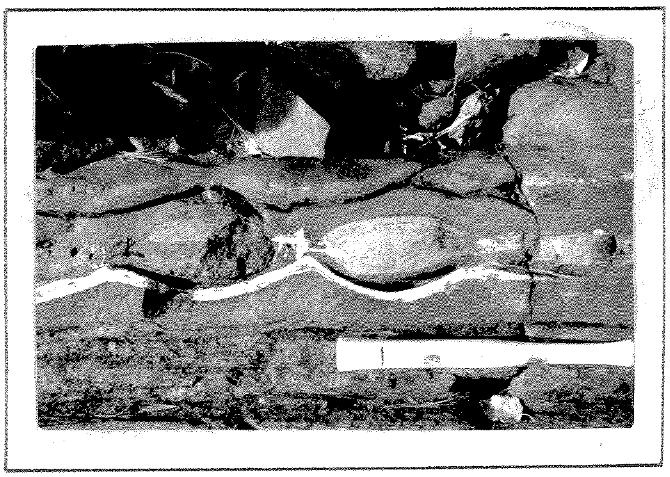


Figure 41b . Possible boudinage structures in amphibolite near contact of the southern gneiss belt with the southern-most mafic septum.

shear component parallel to the biotite foliation in most members of the Cross Lake Gneiss. Evidence of this transport is given by contorted aplites and pegmatites, and displacement of segments of pegmatite intruded at a high angle to the foliation (Figures 42a, b). The axes of these folds are always parallel to the foliation. The shear has transported material parallel to the foliation of the gneiss and can only be detected easily when a dike crosscuts it. All contorted dikes then are formed by shearing parallel to the regional foliation. In Figures 43a, b and c, a thin pegmatite vein cutting across the gneiss at a high angle is contorted by selective transport along shear faces parallel to the foliation. The top of the darker, more biotite-rich layer has moved further than the bottom. Transport is less in the coarse-grained, less mafic gneisses.

The shearing cuts and postdates the dikes. Textures in thin-sections show that the shears have been healed and that biotite has recrystallized parallel to the shear direction and perhaps in response to it. Thus the shearing predates at least some of the biotite and quartz foliation.

Many more dikes were found to be folded to the east than to the west, and it may be that translation was greater to the east.

Figure 42a. Aplite dike sheared into segments. Hammer is parallel to the foliation and the shear planes.

Figure 42b. Detail of the aplite shown above. Some biotite has recrystallized parallel to the shear planes that cut the dike.

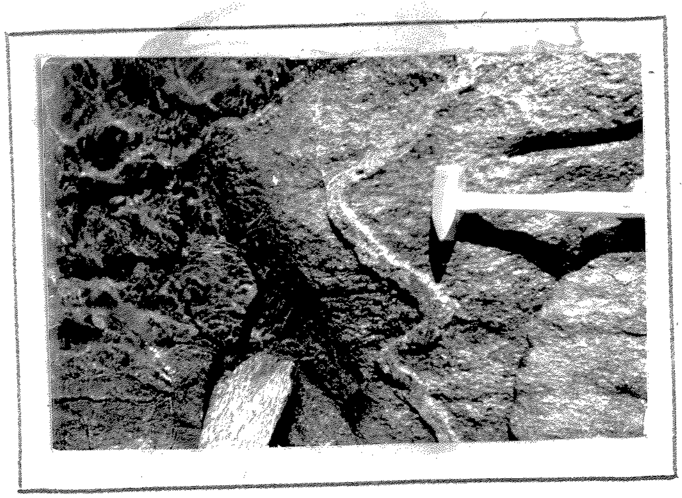


Figure 42 . Small aplite dike folded by shear. Shear planes and foliation of the coarse gray gneiss are parallel to the hammer.

Figure 43a. Outcrop containing coarse gray gneiss(a), aplite(b) and biotite-rich gneiss(c). Note thin contorted pegmatite vein cutting all layers.

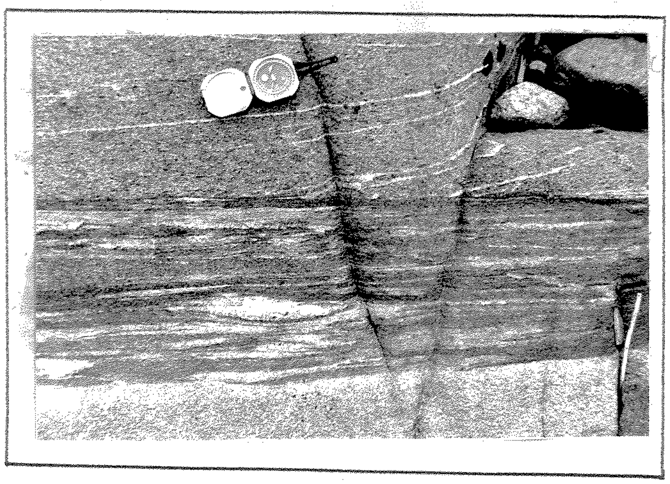


Figure 43b. Detail of figure 43a .

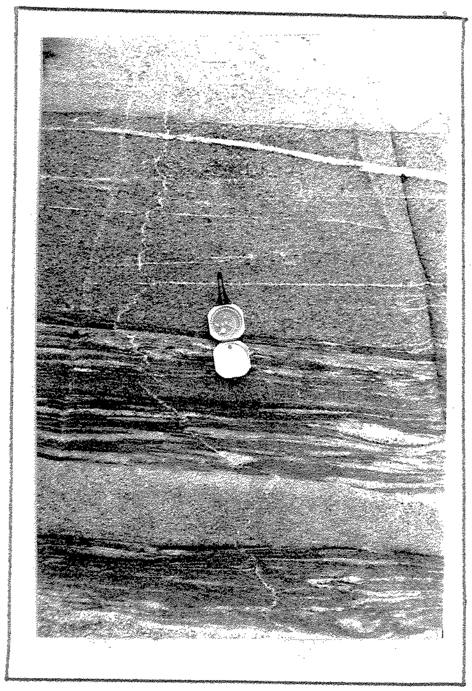


Figure 43c. Detail of figure 43a. Note different degree of transport by shear in the different layers.

Jointing and Intrusion of Dikes

The relationship of joints, dikes and foliation can be used to determine their relative order of formation. Approximately one hundred joint measurements from all parts of the Cross Lake Gneiss are plotted on four diagrams (Figures 44a, b, c, d) and again, the gneiss mass has been divided into four sections. Most joint sets dip between 70° and 90°, therefore only the strikes are plotted.

The prevailing pattern includes joints parallel and subnormal to the structural axis and there does not appear to be any well-developed conjugate shear set. In the three western sections, there is a strong N50°E joint set which follows the axis of the major fold. In the eastern section, this joint set has shifted to N30°E in accordance with a slight shift in the structural axis (and foliation). The joint dips are nearly vertical and independent of foliation dips. N40°W and N50°W sets, transverse to the fold axis, are well developed in all four sections. N70° to 80°W joint sets occur in the three eastern sections, but are missing to the far west. Pegmatites that follow joint sets are themselves cut by joints; therefore, there have been several periods of joint formation.

Pegmatite and aplite attitudes from all parts of the Cross Lake Gneiss are plotted in Figures 45a, b, c and d. Each line on the plot is identified as pegmatite (p), aplite (a) or quartz vein (q). The histogram in Figure 46 illustrates (a) the strong pattern of northeastern and

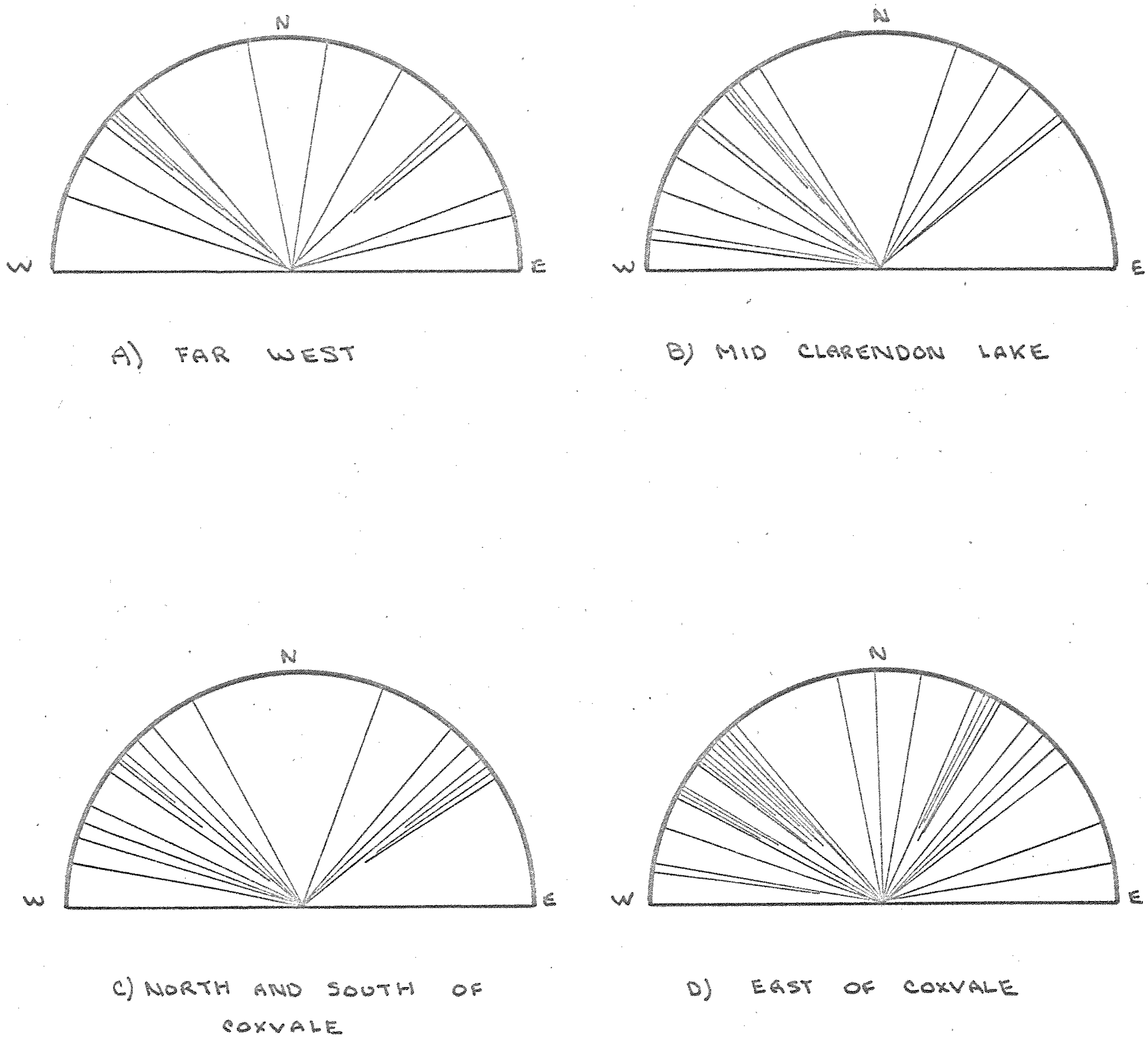


Figure 44. Distribution of joint orientations within the Cross Lake Gneiss.

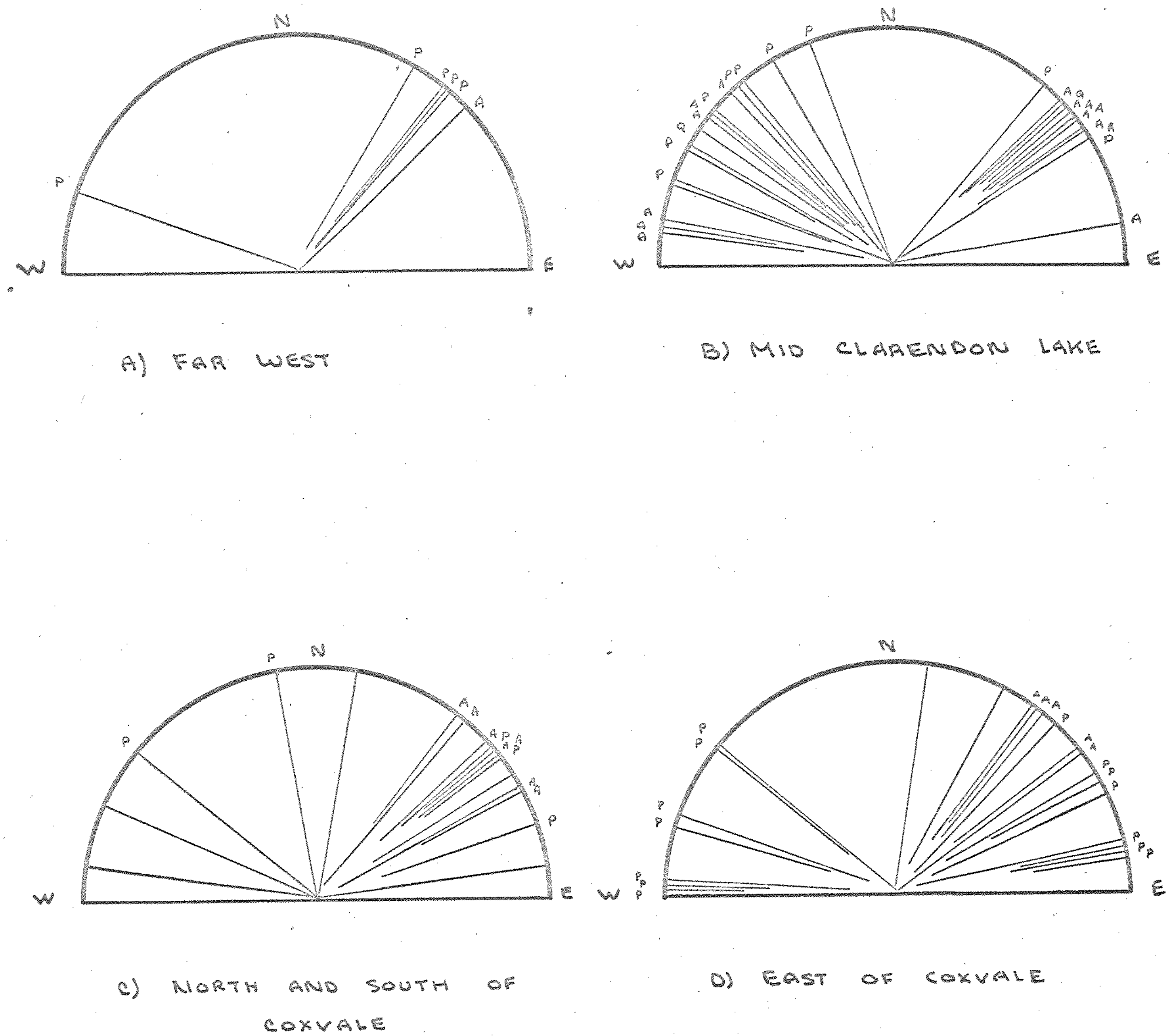


Figure 45. Distribution of dike orientations within the Cross Lake Gneiss. Each plot is identified as aplite(A), pegmatite(P) or quartz vein(Q).

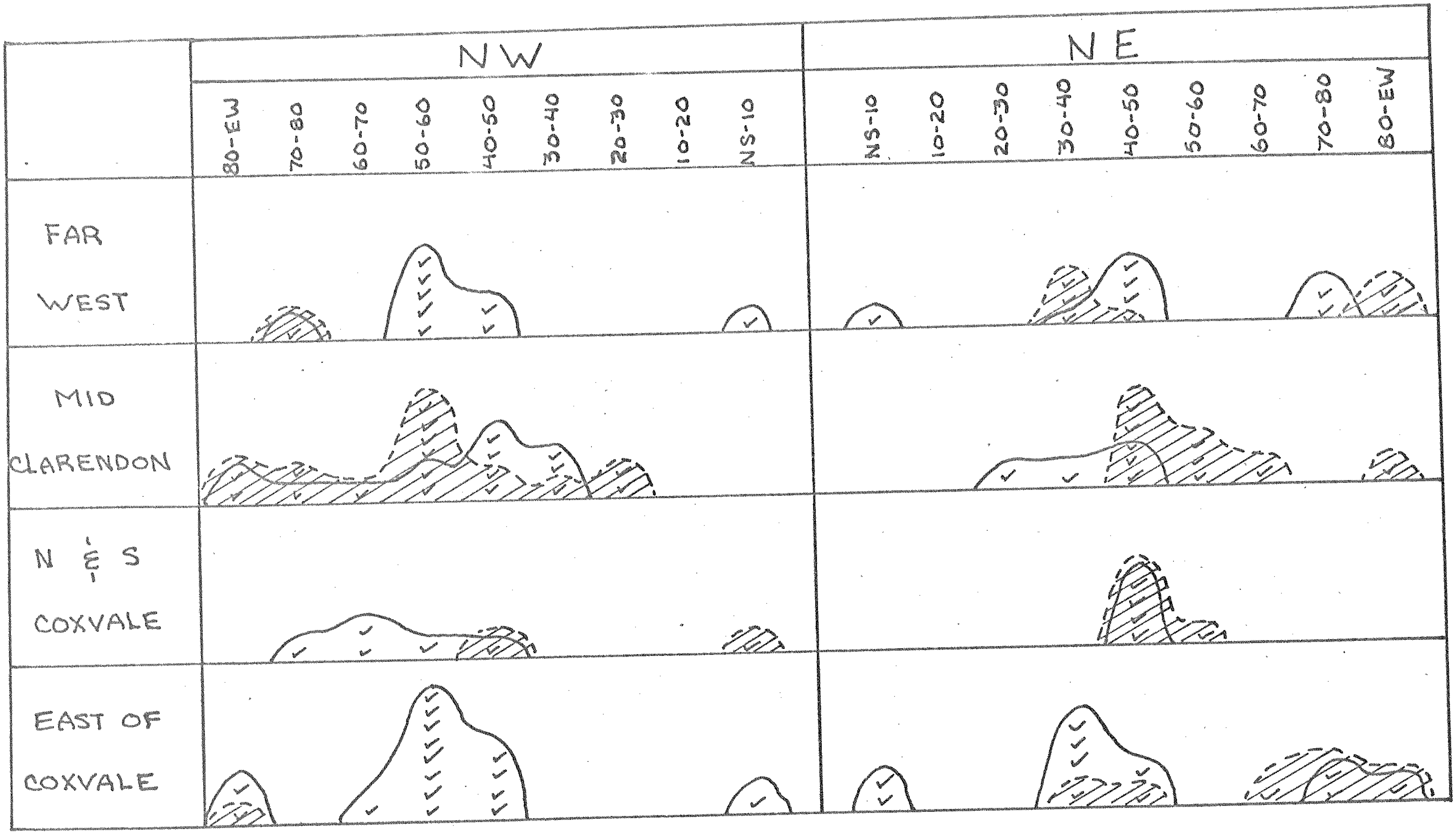


Figure 46. Histogram showing the relationship between joint (solid lines) and dike (dashed and lined) orientation.

northwestern trending joint sets, (b) the complete lack of northwest trending dikes in all but the Mid-Clarendon Lake section and (c) the coincidence of dikes with the N30^{o}-60^{o}E joint sets (and structural axis).

Most aplites trending approximately N50^{o}E tend to follow the dip of the foliation, at least in part (Figure 6). Aplite and pegmatites striking to the northwest, or other than N50^{o}E, dip at a steep angle and appear to be joint controlled.

The coincidence of many aplites with foliation suggest that they may have been intruded very early, before the folding of the major structure, and were controlled in part by the early foliation (or flow foliation). In all areas but the Mid-Clarendon Lake area, the northeast dikes are parallel to the foliation and not parallel to any joint set, and it is concluded from this that these dikes developed after the formation of foliation and before the formation of the joints. In the Clarendon Lake area, the dikes are parallel to the northwest and northeast joint sets and therefore must postdate them.

The joints are directly related to the fold axis with one set parallel and one perpendicular to the axis. If magmatic doming caused the structure, the formation of the joint sets would have been early. Since the joint sets formed after many of the dikes, this precludes the formation of the major structure by magmatic doming.

SUMMARY AND CONCLUSIONS

The heterogeneity of many outcrops of the Cross Lake Granodiorite Gneiss gives the mass a layered metasedimentary appearance; however, crystallization from a melt is indicated by the presence of aligned, subhedral plagioclase, Carlesbad twins, plagioclase zoning and possible chilled contacts. The melt intruded and cooled completely before it was subjected to metamorphic conditions as all parts of the mass have been affected in some way. Andesine, K-feldspar, quartz biotite and epidote are common to all parts of the gneiss and probably represent the original igneous assemblage. Chemical analyses show that all variations occur within a framework of constant CaO and K_2O, and it is assumed that P_{H_2O} was constant and fairly low throughout.

The granodiorite has been affected by a regional metamorphic gradient which increased from west to east. The rocks to the west retain much of their original character, whereas those to the east are nearly completely recrystallized, either by microscopic shearing, high temperature conditions or both. To the west, the assemblage consists of epidote, muscovite, traces of calcite and partly sericitized plagioclase with albitic rims (An < 12 and An 15-18) depleted in anorthite. This assemblage suggests that the western part of the Cross Lake Gneiss has been subjected to a fairly low grade of metamorphism and that equilibrium was not reached. The tendency for plagioclase to break down into albite and sodic oligoclase suggests upper greenschist to lower amphibolite facies conditions (Fyfe et al., 1958; Rutland, 1961, 1962; Brown, 1962, 1965; Noble, 1962; Winkler, 1965; Crawford, 1967).

Temperatures increased, perhaps to middle amphibolite grade, to the east and biotite and epidote reacted to form hornblende. Muscovite did not form. Plagioclase recrystallized and became slightly less ordered, but the composition remained essentially the same (An 25-35)--a stable range for this environment. K-feldspar also recrystallized, expelling most of the Ab held in solution since original crystallization, and still retained to the west. Total Rb in the gneiss increases to the east with respect to K indicating increased tolerance of the host minerals in this metamorphic environment over that of the melt.

The Cross Lake Gneiss consists of two northeasterly trending belts which are folded into an elongate domal structure. All parts of the gneiss are well foliated and the foliation is generally concordant with contacts and compositional layering, suggesting that foliation was formed before folding occurred. Biotite has a segregated, knotted texture to the west, but is evenly disseminated to the east. The change is probably related to increased metamorphism and/or later shearing to the east.

The following is a possible order of events: first, the granodiorite intruded into preexisting country rock and some foliation of biotite and plagioclase developed as a result of flow. After crystallization was complete, the region was metamorphosed. The new temperature and pressure conditions resulted in the formation of characteristic mineral assemblages and textures in the eastern part, but only partial recrystallization to the west. The strong biotite foliation was formed at this time. Finally, the foliated gneiss and interlayered country rocks were folded. Jointing formed parallel and perpendicular to the structural axis and several large, late K-rich intrusives invaded the southern gneiss belt.

The K-poor Cross Lake Gneiss and the Elsevir and Weslemkoon Plutons all appear to be older than the K-rich plutons of the Southeastern Ontario area. The Elzevir and Weslemkoon Plutons intruded, for the most part, after the culmination of regional metamorphism and superimposed contact metamorphic aureoles on the already metamorphosed country rock which they cross-cut (Lumbers, 1967). The Cross Lake Gneiss, however, intruded before metamorphism, and its concordancy is partly due to later recrystallization and folding with the country rock. Therefore, the Cross Lake Gneiss intruded before these other plutons, and before regional metamorphism and deformation.

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