

PETROLOGY OF THE GRANVILLE LAKE GABBRO

A Thesis

Presented to
the Department of Geology and Mineralogy
The University of Manitoba

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
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May 1964



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ABSTRACT

The Granville Lake Gabbro is a strongly differentiated tabular layered intrusion, approximately five miles long and one mile wide. The intrusion crystallized in a nearly horizontal position and has since been tilted on edge by folding of the enclosing sediments. It consists of a basal gabbro zone, a transition zone, and an upper granite zone. The specific gravity of rocks of the intrusion is closely related to their silica content, and provides an easily determined index of differentiation.

The differentiation trend of the parent magma closely followed the trend of the calc-alkaline series of igneous rocks, as illustrated by the standard $\text{FeO-MgO}-(\text{Na}_2\text{O} + \text{K}_2\text{O})$ triangular diagram. In this regard the Granville Lake intrusion is dissimilar to the Skaergaard and most other differentiated intrusions. The unusual differentiation trend of the Granville Lake Gabbro is attributed to the relatively high water content of the undifferentiated magma.

The Ballad of Cranstone's Mines Branch

(Ode to a Blowhard)

by G.D. Scott Brisbin

August 1961

Tune: "The Ballad of John Henry"

1. Well, the Mines Branch they tell a story,
Of a party long ago,
Who decided to do some blastin', boys,
But they blew a mighty hole in their canoe,
Lord God!
They blew a mighty hole in their canoe.
2. Well, Don Cranstone, he was the party chief,
And a damn fine one he'd been,
Until the day he spotted that gabbro plug,
And he figured that a blast would be real keen,
Lord God!
Yes he figured that a blast would be real keen.
3. Well, some dynamite and some blastin' caps,
In a prospector's shack he found,
So he pilfered them and the very next day,
He headed for that gabbro ground,
Lord God!
He headed for that gabbro ground.
4. Well, the senior, he went with him,
And so did the juniors three,
For the thought of seeing that Gabbro blow,
Was something that they all wanted to see,
Lord God!
It was something that they all wanted to see.
5. Well, the dynamite was in the stern of the boat,
And the caps were in the bow,
When the senior, he lit up an Export-A,
And then there was a hell of a KA-Pow,
Lord God!
And then there was a hell of a KA-Pow.
6. Well, they found the remains of the motor,
And a piece of the senior's jaw,
And the bodies of the party flew all over the place,
From Sasaginnigak right to The Pas,
Lord God!
From Sasaginnigak right to The Pas.

7. Well they took our senior to the graveyard,
But they wouldn't let him in,
Sayin ' "This here place is holy buryin' ground,
And that boy has led a life of sin,
Lord God!
That boy has led a life of sin".
8. Well, the juniors they went up to heaven,
Their job on earth done well,
But the senior and the party chief,
Will rot down in the depths of hell,
Lord God!
They will rot down in the depths of hell.
9. So if your boy's joining the Mines Branch,
You should sip on your beer and cry,
For the Mines Branch is just like the G.S.C.,
They give you 50-50 odds you're gonna die,
Lord God!
They give you 50-50 odds you're gonna die.

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INTRODUCTION

The Granville Lake Gabbro is a predominantly basic intrusion at Granville Lake in northern Manitoba, 30 miles southeast of the nickel mining town of Lynn Lake (figure 1). The intrusion, approximately six miles long and one mile wide, is located along the central narrows of the northwest arm of Granville Lake, about 1500 feet inland from the southwest shore.

The intrusion was mapped by the writer during the summer of 1961, while preparing the Watt Lake (east half) map sheet (longitude $100^{\circ}30'W$ to $100^{\circ}45'W$, latitude $56^{\circ}15'N$ to $56^{\circ}30'N$) for the Manitoba Department of Mines and Natural Resources.

Statement of problem

While traversing the Granville Lake Gabbro, it soon became evident that the intrusion is apparently a strongly differentiated tabular body, presumably the result of considerable fractionation during the period of cooling and crystallization which followed its intrusion. It strikes northwest, and the sequence observed in the field is a massive medium-dark grey gabbroic zone along the northeast side, grading through a massive pinkish grey dioritic transition zone, which changes comparatively sharply to a

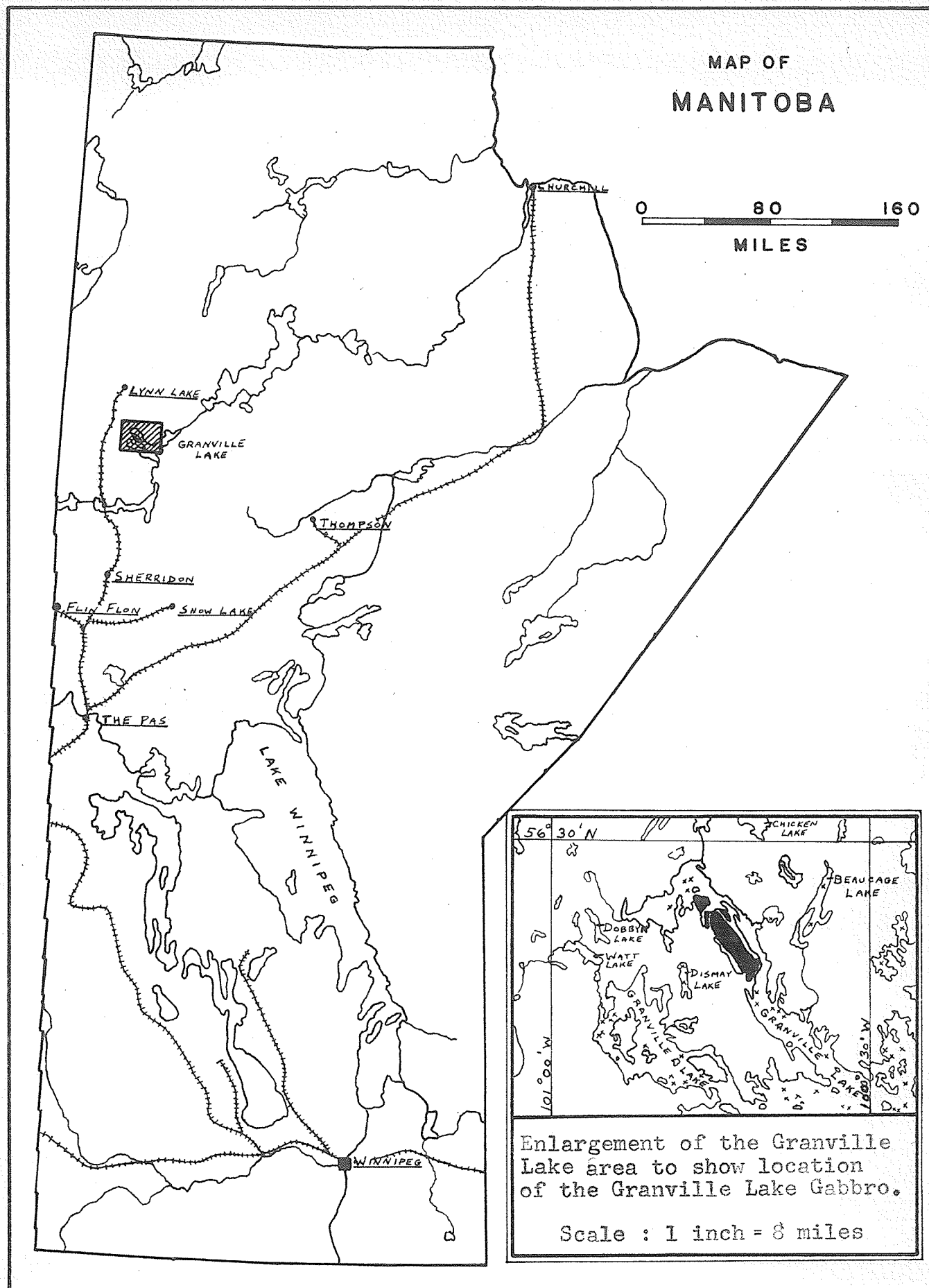


Figure 1. Map of Manitoba, showing location of the Granville Lake Gabbro.

massive pink granite zone along the southwest side of the intrusion.

Several possible origins can be postulated for such a sequence. The object of the present study is to provide a satisfactory interpretation of the geology, petrology, and petrogenesis of the Granville Lake Gabbro. Results are presented for petrographic studies, including modal analyses, plagioclase composition determinations with the universal stage, and also studies of chemical variation, rock specific gravity variation, and other topics.

It is concluded that the observed sequence of rocks represents a strongly differentiated layered intrusion, which crystallized in a nearly horizontal position, but with a tilt of several degrees, the present southeast end having been structurally higher than the northwest end at the time of crystallization. Later regional folding of the enclosing sediments tilted the intrusion so that it is now lying on edge. Erosion to the present topographic surface has resulted in exposure of a complete cross-section of the Granville Lake Gabbro.

The intrusion is compared to and contrasted with a number of other intrusions which are known to be differentiated, and an attempt is made to explain the similarities

and differences. A possible composition is proposed for the primary magma. Finally, an attempt is made to predict the possibility of occurrences of economic minerals in the intrusion.

Related studies of nearby mafic intrusions

A considerable number of small- to medium-sized gabbroic intrusions are found in the Lynn Lake district of northern Manitoba. The Lynn Lake Gabbro, at Lynn Lake, has been studied by Allan (1948), Hunter (1950), and Dornian (1950). Recently, both the Lynn Lake Gabbro and the nearby Fraser Lake Gabbro have been studied in detail by Emslie (1961), who concluded that both are strongly differentiated layered intrusions, which crystallized in a horizontal position. The Lynn Lake intrusion was subsequently tilted to a vertical position, and shows a sequence grading from ultramafic rocks near the base, through pyroxenites and norites, to normal gabbro in the upper part of the intrusion. The rocks are completely uralitized. Nickel-copper bearing sulphide minerals have accumulated by magmatic segregation, and form orebodies near the base of the Lynn Lake Gabbro. Milligan (1960) considers formation of the orebodies by magmatic segregation to be questionable.

Hunter (1954, 1958) studied the Tow Lake Gabbro, about 35 miles north-northeast of the Granville Lake Gabbro.

He found that the intrusion is zoned, with three mappable zones, the "A", "B", and "C" zones, respectively. The "A" and "C" zones are similar, and the "B" zone differs only in having 5-10% apatite and a more sodic plagioclase, presumably a result of the calcium of the magma having been taken up by apatite. All rocks have been subsequently metamorphosed, with alteration of pyroxene to deuteritic blue-green amphibole. The intrusion crystallized horizontally, and has since been tilted on edge. Hunter concludes that on the basis of his postulated petrogenesis for the intrusion, no concentrations of nickel-bearing sulphides will be found.

Previous work

Little geological work has been conducted in the immediate area of the Granville Lake Gabbro. Norman (1933), and Downie (1935) mapped the Granville Lake Area on a scale of four miles to one inch. Norman gives a brief description of the Granville Lake Gabbro, but makes no mention of the granitic and transitional portions of the intrusion, nor does he offer any suggestion that it could be differentiated.

A large amount of geological mapping has been conducted a few miles to the north of the Granville Lake Gabbro, by geologists of the Manitoba Department of Mines and

Natural Resources. The latest and most comprehensive study is that of Milligan (1960).

Present work

The Granville Lake Gabbro was mapped by the writer during the month of August, 1961. Most of the intrusion was covered first by traverses spaced at intervals of approximately 1500 feet. When it became evident that a study of the petrology of the intrusion would provide a suitable thesis problem, it was traversed again at intervals of one quarter mile; this interval was increased to 1500 feet at the northwest end, because of a shortage of time. This second set of traverses was run chiefly for the purposes of locating contacts accurately, and collecting a large suite of accurately located specimens.

Traverses were run by pace and compass methods, with the use of vertical air photographs on a scale of one half mile to the inch. It was found possible to pick out accurate reference points on these photographs along the traverse lines. These reference points were generally at intervals of 1000 feet or less, and seldom at intervals of greater than 2000 feet. With such points, it was possible to locate all specimens accurately.

A base map on a scale of one half mile to the inch was prepared by the Provincial Air Photo Library, from the air photographs, with a sketchmaster and a slotted template photograph laydown. The writer made a tracing of the original map, which was photographically enlarged to a scale of one quarter mile to the inch. Traverses and specimen locations were carefully plotted on this map.

Specimens were collected at 200-foot intervals along all traverses. This interval was frequently decreased to 50 or 100 feet in the vicinity of contacts of the various zones within the intrusion. The exposure of the intrusion is excellent, and it was rare that specimens could not be obtained at the desired 200-foot intervals. Approximately 450 specimens of the rocks of the intrusion were collected in a period of ten working days. In the opinion of the writer, nearly all these specimens have been plotted on the base map (1 inch = 1/4 mile) within 50 to 100 feet of their true ground location.

Petrographic and other studies on the intrusion were carried out at the Department of Geology and Mineralogy of The University of Manitoba during the 1961-62 term, under the guidance of Dr. H.D.B. Wilson.

Acknowledgments

The writer conducted his field study of the Granville Lake Gabbro while mapping the Watt Lake area (east half), for the Manitoba Department of Mines and Natural Resources, Mines Branch, Geological Division. The Department also provided approximately ninety thin sections and eight rock analyses.

The writer is indebted to Dr. J.F. Davies, Chief Geologist of the Mines Branch, and to Dr. H.D.B. Wilson of the University of Manitoba. Dr. Davies made the original suggestion of the thesis problem and provided the opportunity to map the intrusion. Dr. Wilson acted as advisor during the study. Both contributed many valuable discussions and helpful suggestions.

Fellow graduate students at The University of Manitoba contributed several suggestions which were greatly appreciated.

Messrs. Scott Brisbin, Kenneth Day, and Walter Gibbins, field assistants, helped the writer at various times during mapping, and in collecting and carrying the many rock specimens.

Mr. Wilfred ("Bob") Lambo, senior assistant, carried on with the mapping of the area while the writer was

engaged in mapping the intrusion. His work was much appreciated.

My wife Patricia, a graduate geologist, provided much useful argument, advice, and constructive criticism, which were particularly helpful.

The writer also wishes to express his appreciation to Miss Gwenyth Springham, who spent many hours typing the thesis for presentation.

Financial assistance was provided during the 1961-62 term by a fellowship from The University of Manitoba.

GEOLOGY OF THE GRANVILLE LAKE AREA

General geology of the area

The rocks of the Watt Lake area (east half) are of Precambrian age. Norman (1933) and Downie (1935) mapped and named the Sickie series, an extensive series of greywackes or arkoses, which lies unconformably above an older pre-Sickie series of volcanic and sedimentary rocks. The term Wasekwan series was proposed by Bateman (1945) for pre-Sickie volcanic and sedimentary rocks in the McVeigh Lake area. The Wasekwan has since been extended by various geologists, mapping for the Manitoba Department of Mines and Natural Resources, to include similar rocks mapped by Norman and Downie throughout the Lynn Lake area, including the Watt Lake map area (east half).

Figure 2 is a generalized geological map of the Watt Lake area (east half). Rocks of Wasekwan age closest to the Granville Lake Gabbro are located about five miles to the northeast of the intrusion, covering an area of a few square miles immediately east of Beaucage Lake. There the Wasekwan rocks are a series of sediments (greywacke, arkosic greywacke, quartzite, conglomerate, iron-formation) and intermediate to basic amphibolitic volcanic rocks; this series is complexly interbedded, folded, and faulted.

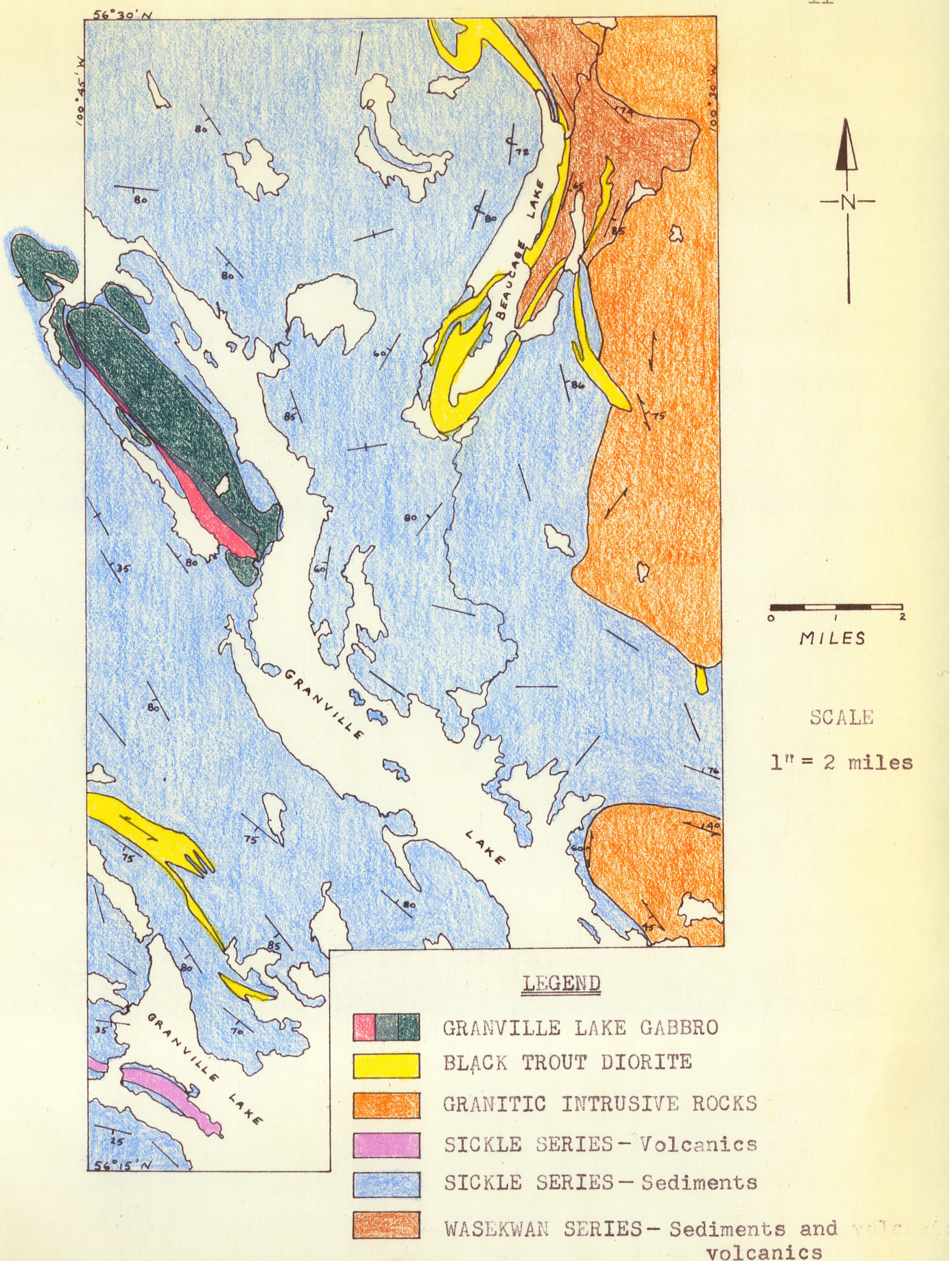


Figure 2 . Generalized geological map of the Watt Lake area (east half)

The Sickie series is a remarkably uniform series, consisting predominantly of well-bedded grey, to pinkish or brownish grey, fine-grained greywackes, and their slightly recrystallized equivalents. The latter consist mainly of plagioclase, quartz, and biotite, and in many specimens microcline, muscovite, and magnetite. They are granular and coarser grained than the original non-recrystallized greywacke, but are still fine grained and well bedded.

The unconformable contact between Sickie and Wasekwan rocks is marked by the Sickie basal conglomerate, which has a thickness ranging from a few tens of feet to a maximum of about 1000 feet. The unconformity is also marked by a notable increase in folding, faulting, and metamorphic grade, as well as a pronounced change in lithology, when passing from the younger Sickie to the older Wasekwan.

For ten to fifteen miles south and west of Beaucage Lake, the rocks consist almost exclusively of typical Sickie greywacke. On the southwest side of the northwest arm of Granville Lake, Sickie greywacke has been intruded by the Granville Lake Gabbro.

Wasekwan and Sickie rocks have both been invaded by many types of igneous intrusive rocks. These are chiefly granitic to granodioritic intrusions, which are found to

the east and southeast of Beaucage Lake, as well as the Black Trout Diorite, and the Granville Lake Gabbro.

Summary of the geological history of the area

The oldest exposed rocks in the vicinity of Granville Lake are sedimentary and volcanic rocks of the Wasekwan series, of possible Archaean age. Deposition of this series was followed by folding, faulting, and regional metamorphism.

After a period of uplift and erosion, the rocks of the Sickie series were laid down. The order of deposition within this series, from oldest to youngest, is: basal conglomerate; an extensive and thick sequence of well bedded greywacke; arkose; basic volcanic rocks; greywacke; intraformational conglomerate; greywacke.

Wasekwan and Sickie rocks were then folded, faulted, regionally metamorphosed, and intruded by the Granville Lake Gabbro, Black Trout Diorite, and some of the granitic intrusions. Ages of the other granitic intrusions relative to the Sickie and Wasekwan series is uncertain. The ages of the Granville Lake Gabbro, Black Trout Diorite, and the granitic intrusions relative to each other are not known. The internal structure of the Granville Lake Gabbro

indicates that it was intruded in a near horizontal position, and tilted into an almost vertical position by folding. Uplift, erosion, and Pleistocene glaciation have combined to form the present topographic surface.

GEOLOGY OF THE GRANVILLE LAKE GABBRO

Field observations

The Granville Lake Gabbro is six miles long and one mile wide. It is intruded concordantly along the core of what appears to be an overturned isoclinal anticline in well-bedded greywacke of the Sickie series, and consists of six or more contemporaneous intrusive masses. The main body is almost five miles in length, and 4000 to 5000 feet in width. Five, or possibly more, satellite intrusions surround the main one; these range in size approximately from 5000 feet by 4000 feet to 4000 feet by 500 feet. It is possible that both the largest and the smallest satellite intrusions may actually consist of two or more smaller bodies, but this could not be established due to poor exposure. Map 1_A is a geological map of the Granville Lake Gabbro and the enclosing rocks.

The rocks of the intrusion are more resistant to erosion than the sedimentary rocks. As a result, gabbro-sediment contacts are generally marked by steep scarps, the rocks of the intrusion standing as high as 250 feet above the surrounding sedimentary rocks. The contacts could therefore be located accurately by stereoscopic examination of air photos wherever it was not possible to do so by examination of outcrops.

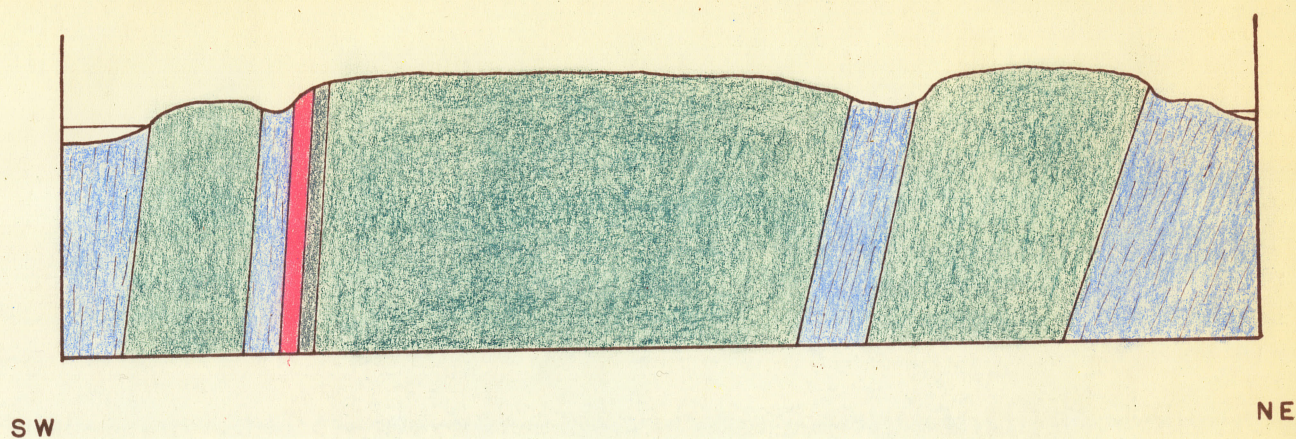
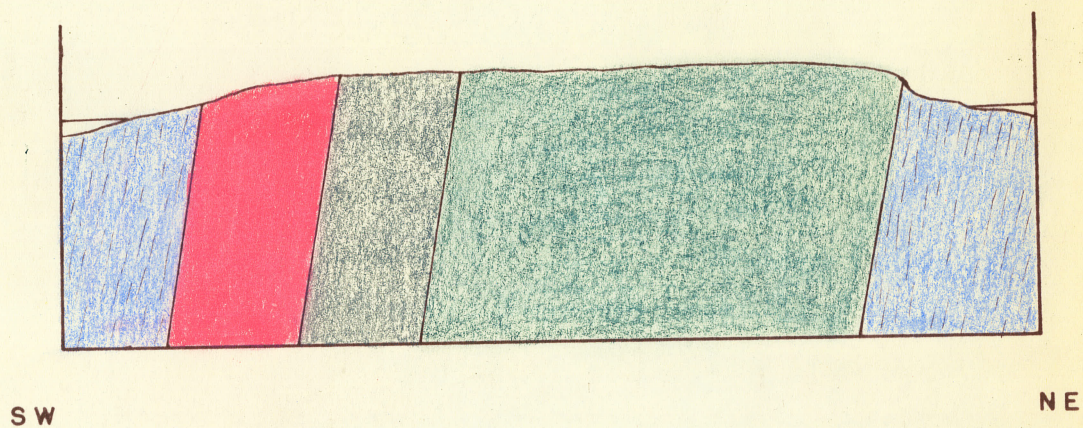
The main intrusion is a tabular body, striking north 40 degrees west and dipping 70 degrees to 85 degrees to the southwest. The rocks of the Granville Lake Gabbro were divided into three units during the field study and from later examination of specimens collected in the field, as follows:

- A. Gabbro zone
- B. Transition zone
- C. Granite zone

Vertical geological sections across the intrusion are shown in figure 3. Figure 4 is an index map of the intrusion showing the location of traverses.

Rocks of the gabbro zone are, in general, medium to dark grey massive gabbro, composed of approximately 65 per cent grey plagioclase, and 35 per cent black hornblende. Slight variations in colour and composition are common. The gabbro zone comprises about 75 per cent of the main intrusion, grading into the transition zone to the southwest. The contact between these two zones is completely gradational, across a distance of 200 to 500 feet.

Transition rocks are medium grained and pinkish grey in colour. They contain more feldspar and quartz, have a lower mafic content than those of the gabbro zone, and are

TRAVERSE CG 16TRAVERSE CG 7LEGEND

- Sediment
 - Gabbro
 - Transition
 - Granite

Horizontal and vertical scale : 1 inch = $\frac{1}{4}$ mile

MILES
 0 ————— 1/4

Figure 3 . Vertical geological sections of the Granville Lake Gabbro along traverses CG 16 and CG 7 , looking northwest.

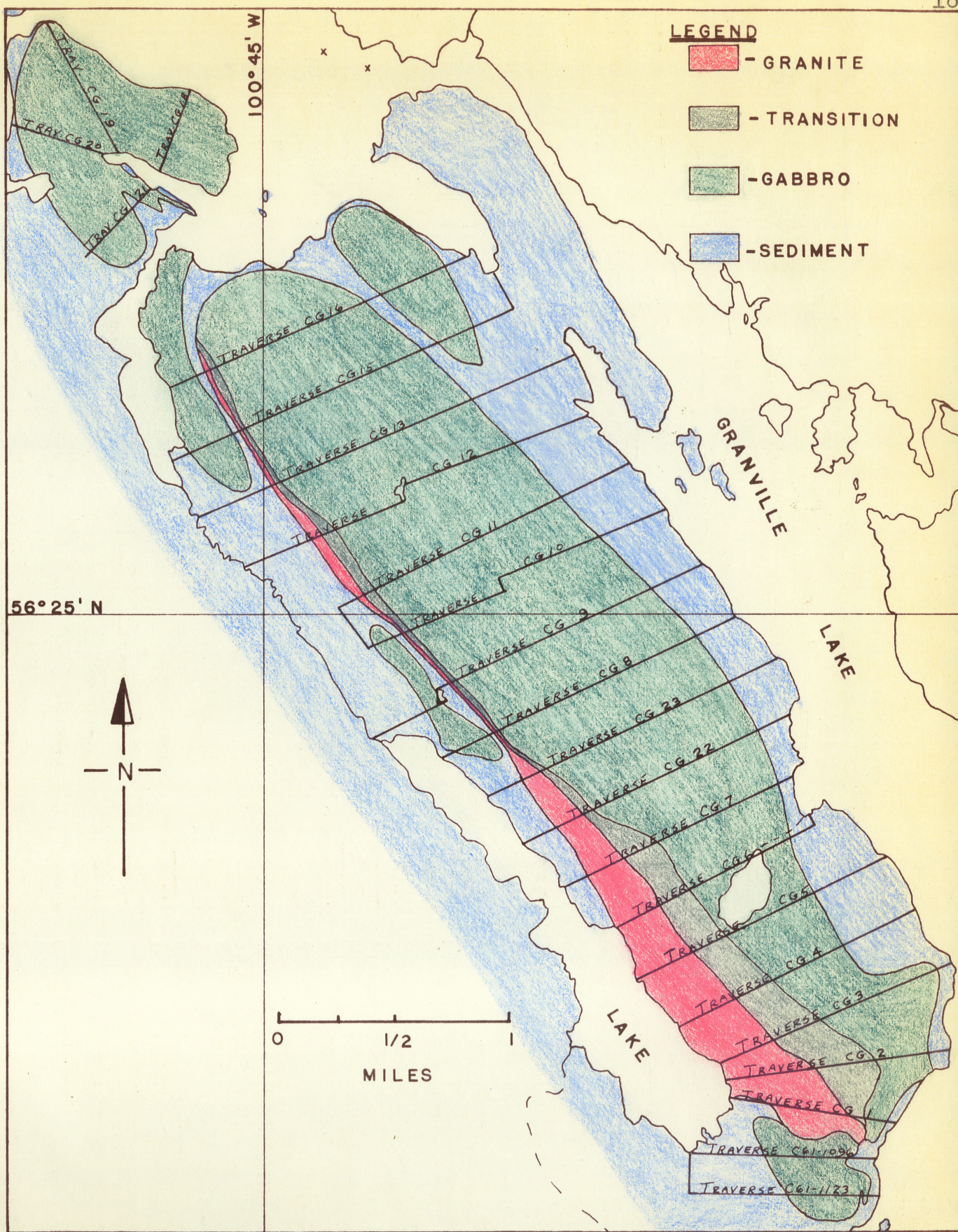


Figure 4. Index map showing locations of traverses.

highly variable in texture and composition. The transition zone comprises about ten per cent of the main intrusion.

The granite zone consists of medium-grained, pale to medium orange-pink granite composed of pinkish feldspar, quartz, and a small percentage of mafic minerals. The contact between the granite zone and the adjacent transition zone is relatively sharp, but the degree of sharpness is variable. In general, this contact is gradational over a distance of five to fifty feet. In one place the contact is almost knife-sharp, and dips steeply to the southwest, parallel to the plane of the intrusion. Transition rocks immediately adjacent to the granite zone are cut by a few small dykes of granitic material, which have very poorly defined gradational contacts with the enclosing transition rocks.

In general, the width of the granite zone is slightly greater than that of the transition zone. Both zones are widest at the southeast end of the main intrusion, where the granite has a maximum width of approximately 1500 feet, and the transition zone a maximum width of 1200 feet. Both zones taper irregularly to the northwest, where they are each approximately 100 feet wide.

In the gabbro zone, gabbro immediately adjacent to and within as much as 200 feet or more of the northeast

gabbro-sediment contact has a lighter grey colour than typical medium-grey gabbro. This is due to the lower hornblende and higher plagioclase content of this rock. Little or no evidence of chilled contacts was observed along the edge of the main intrusion. However, the precise contact is nearly always covered by a few feet of overburden. Minor assimilation of greywacke by the hot gabbro magma apparently took place along the contact.

The granite-sediment contact along the southwest edge of the intrusion is not exposed. On traverse CG 1, an outcrop of greywacke is exposed less than 100 feet from the last outcrop of granite. This fine-grained greywacke contains phenocrysts of dirty orange albite, up to about one eighth inch across, which comprise about ten per cent of the rock. The phenocryst content of the greywacke progressively decreases to zero within another hundred feet.

Small outcrops of what appears to be a shatter breccia were observed at six separate locations along the gabbro-sediment contacts of the various intrusions. This breccia consists of angular greywacke fragments as much as two inches across, cemented in one place by a highly biotitic matrix, in others by pulverized rock flour, and in at least one outcrop by probable chilled magma.

Unlike the main intrusion, the satellite intrusions of the Granville Lake Gabbro have knife-sharp chilled contacts with the enclosing sediments, with grain size increasing towards the centre of each intrusion.

Rocks of the gabbro, transition, and granite zones, as well as enclosing sediments are all cut by dykes, sills, lenses, and irregular bodies of a variety of pegmatites. In the main intrusion, a few short dykes of a fine-grained white to pinkish aplite occur in the gabbro, within 100 or 200 feet of the northeast gabbro-sediment contact.

Rhythmic layering and igneous lamination were not observed in the intrusion.

Petrology

A. Gabbro zone

Gabbro is typically massive, uniform in composition and texture, medium-to coarse-grained, and medium grey to dark grey in colour. It appears in hand specimen to consist of 60 to 65 per cent medium-grey plagioclase, and 35 to 40 per cent black amphibole. Plagioclase commonly shows lath-shaped cleavage faces, but laths are not well developed and have no preferred orientation. Amphibole grains are irregular in shape and equidimensional. Examination of

specimens with a hand lens reveals small quantities of dark brownish black biotite associated with amphibole. Small grains of magnetite or ilmenite are common in some specimens. Tiny specks of pyrite are rarely present.

Grain size of gabbro zone rocks is generally three to five millimetres, with many plagioclase laths as long as eight to ten millimetres. Colour of the weathered surface is grey to buff.

In the gabbro zone, variations in composition, colour, and texture from the typical gabbro are not common, and usually consist of small variations in proportions of plagioclase and amphibole. In the extreme cases the mafic content of the rock is approximately 20 and 55 per cent, the remainder of the rock being primarily plagioclase.

A slightly pink variety is found in small local areas of the gabbro zone. The pink colour is caused by pinkish grey plagioclase. Thin section examination indicates that the pink coloration accompanies strong saussurization of plagioclase in these rocks, with no apparent change in chemical composition.

Rocks of the gabbro zone are a hypidiomorphic granular intergrowth of moderately well developed plagioclase

laths and a variety of coarse to fine granular, and less commonly fibrous, amphiboles of the hornblende group. Biotite laths and grains are common in most sections. Small quantities of quartz and opaque oxides in the form of irregular grains are almost ubiquitous. Remnants of clinopyroxene partially altered to granular and uraltitic hornblende were observed in a few sections. Apatite and sphene are common accessories, with scattered pyrite grains, rare zircon, and rare primary clinozoisite. Saussuritic alteration of plagioclase is well developed in some sections, but absent in most. In other sections, patch and vein scapolite has formed as an alteration of plagioclase. Chlorite and leucoxene are rare alteration products.

Major mafic constituents of the gabbroic rocks tend to occur as irregular clusters or clumps, surrounded by an intergrowth of plagioclase and the same mafic minerals. Such clusters are not well developed.

Figure 5 is a photomicrograph of typical gabbro.

An ophitic texture is commonly displayed in rocks from the central portion of the gabbro zone, in the northwest half of the main intrusion. Many thin sections from this area have irregular plagioclase laths enclosed within large grains of hornblende.

Thin sections of chilled gabbro from the edges of satellite intrusions show a ragged intergrowth of tiny irregular plagioclase and hornblende grains (figure 6).

On the basis of the Grout classification, rocks of the gabbro zone are gradational from gabbro to diorite, with relatively minor quartz gabbro and quartz diorite. Precise distinction between gabbro and diorite is impossible because of strong zoning in the plagioclase. A gabbro which is close to diorite in composition probably predominates.

Mineralogy of the gabbro zone

Mineralogy of the rocks of the intrusion was studied with the petrographic microscope. Mineral percentages were determined by means of a modal analysis of one standard-sized thin section of each specimen. Comparison of modal analyses with corresponding hand specimens indicates that the modal analyses are representative of the actual compositions of the rocks. Outcrop areas of the intrusion are uniform in texture and composition; changes within a zone are generally gradational across a distance of at least one hundred feet. Therefore rock compositions obtained by modal analysis are probably representative of local outcrop areas.



Figure 5. Photomicrograph of typical gabbro, specimen CG 9-21 (crossed nicols). Diameter of field of view is 7 millimetres.

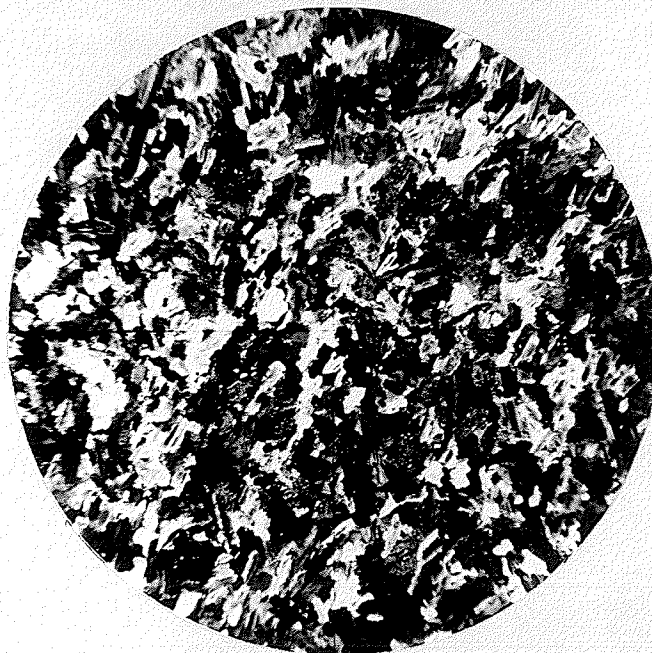


Figure 6. Photomicrograph of typical chilled gabbro, specimen CG 15-1 (crossed nicols). Diameter of field of view is 7 millimetres.

a) Primary minerals

Plagioclase

Plagioclase is the most abundant mineral in the gabbro zone, and occurs both as large anhedral but definitely lath-shaped grains, and as smaller equidimensional anhedral. It is generally well twinned, clear and unaltered in thin section. In a few sections, plagioclase is moderately to strongly saussuritized. This saussuritization is best developed in the core zones of plagioclase laths.

Moderate normal zoning is invariably present.

Plagioclase composition determinations were made by measurement, on a universal stage, of maximum extinction angle in the zone perpendicular to (010). Composition diagrams from Winchell (1951) were used. Composition was determined for the centres and edges of six or more grains in each thin section. Plagioclase determinations are listed in table 1. The most calcic plagioclase noted in the gabbro zone ranged from An_{71} at the core to An_{54} at the outer edge of the grain. The most sodic plagioclase noted ranged from An_{53} to An_{28} . It is possible that more calcic plagioclase may be present in any section, but not noted because the plane of section did not transect a true grain core.

TABLE 1

Plagioclase composition determinations for the Granville Lake Gabbro

Specimen	Specific gravity of rock	Maximum extinction angle on (010)		Plagioclase composition range	Zone
		Grain core	Grain edge		
CG 2- 2	2.60	15	15	An ₇	Granite zone
CG 2-10	2.65	9.5	9.5	An ₁₃	Granite zone
CG 6-22	2.67	12	12	An ₁₀	Granite zone
CG 6-25	2.64	9	12.5	An ₁₀ -An ₁₃	Granite zone
CG 6-26	2.62	12.5	12.5	An ₁₀	Granite zone
CG 11- 2	2.65	13	13	An ₉	Granite zone
CG 23- 1	2.65	13.5	13.5	An ₈	Granite zone
CG 2-12	2.71	11	9	An ₂₇ -An ₂₉	Transition zone
CG 2-14	2.82	14	8	An ₂₆ -An ₃₁	Transition zone
CG 6-14	2.86	22	12.5	An ₃₀ -An ₄₁	Transition zone
CG 6-21	2.77	4	4	An ₂₃	Transition zone
CG 10-23	2.78	31	5	An ₂₄ -An ₅₆	Transition zone
CG 11- 3	2.72	16.5	11.5	An ₂₉ -An ₃₅	Transition zone
CG 12-21	2.71	15	8	An ₂₆ -An ₃₃	Transition zone
CG 23- 3	2.76	8	5	An ₂₄ -An ₂₆	Transition zone
CG 6- 1	2.86	32	15.5	An ₃₃ -An ₅₇	Gabbro zone
CG 6- 4	2.88	32	19	An ₃₈ -An ₅₈	Gabbro zone
CG 6- 6	2.91	32	9.5	An ₂₈ -An ₅₈	Gabbro zone
CG 10- 5	2.92	34.5	20.5	An ₃₉ -An ₆₃	Gabbro zone
CG 11- 5	2.86	28	8	An ₂₆ -An ₅₀	Gabbro zone
CG 11- 9	2.92	33	19.5	An ₃₈ -An ₅₉	Gabbro zone
CG 11-11	2.94	39.5	30	An ₅₄ -An ₇₁	Gabbro zone
CG 11-21	2.91	40	25.5	An ₄₇ -An ₇₀	Gabbro zone
CG 15-17	2.91	36+	18	An ₃₆ -An ₆₄₊	Gabbro zone
CG 23- 9	2.95	29	10	An ₂₈ -An ₅₃	Gabbro zone
CG 23-16	2.92	35	20	An ₃₉ -An ₆₃	Gabbro zone

Plagioclase content of gabbro zone rocks ranges from 43 to 78 per cent. The average of twenty modes is 58 per cent.

Amphiboles

Amphibole mineralogy in the gabbro zone is relatively complex. All the amphiboles are varieties of hornblende, generally finely granular and intimately intermixed. This complexity discouraged a program of mineral separation and optical study of the amphiboles.

Most if not all amphibole appears to have formed by deuteric alteration of primary pyroxenes, and a number of thin sections, primarily from the northwest half of the main intrusion, contain small remnants of partially altered clinopyroxene.

The predominant variety of amphibole is a relatively coarse equigranular hornblende, pleochroic from light brown to green to blue-green, and less commonly olive shades of these colours. The blue-green colour of this hornblende suggests that it is a sodic variety. Birefringence is moderate, and largely masked by the colour of the mineral. This variety commonly contains a parallel network of magnetite lamellae resembling schiller structure. Although these lamellae are commonly present in many or all grains

to a greater or lesser extent, they may be completely absent, or present in only a few grains in any one thin section. The quantity of the lamellae in any one grain ranges from a trace, to the extreme case seen in a few thin sections, where many grains appear almost black due to an abundance of magnetite lamellae. It is probable that the lamellae are a schiller-like exsolution feature formed during alteration of a relatively iron-rich pyroxene to a relatively iron-poor hornblende. If so, the lamellae may be ghost-like remnants of the original pyroxene cleavage or parting. However, in the one case where remnant clinopyroxene was present in "schiller" hornblende, there was no obvious relationship between the orientation of "schiller" inclusions in hornblende and cleavages or parting of the clinopyroxene.

A few non-parallel lamellae appear to have formed along cracks or fractures during alteration of pyroxene. Figure 7 is a photomicrograph of a grain of hornblende, pleochroic from light brown to green to blue-green, and showing particularly well developed magnetite lamellae. The well-developed prismatic cleavage of the hornblende is visible. Some lamellae appear to have formed in cracks or fractures which transect the plane of "schiller" lamellae. These appear to have formed in preference to "schiller"

lamellae, the latter being less evident in the immediate vicinity of the fractures.

Figure 8 is a photomicrograph of diopside partially altered to hornblende which is pleochroic from brown to green to blue-green. The diopside (the light mineral under the crosshairs) is surrounded by an alteration rim of, and altered along fractures to, hornblende (dark mineral).

A possible second variety of amphibole, almost as common as the first, is a pleochroic green to blue-green hornblende in a fine irregular granular intergrowth. This variety is lighter in colour, much finer grained, and does not show as pronounced a brownish and/or olive pleochroism. Magnetite inclusions, "schiller" or otherwise, are not present. Birefringence is relatively low and is masked by the colour of the hornblende. This fine granular hornblende grades to the uralitic variety described below, and is apparently similar to the coarser grained hornblende.

Uralitic amphibole is common in some sections. It varies from fine fibrous uralite to bladed uralite masses, and is gradational to the fine granular hornblende. Uralitic amphibole is generally colourless to pale green and blue-green. It is most commonly in the form of bladed



Figure 7. Photomicrograph of magnetite lamellae in hornblende, specimen CG 6-6 (plane polarized light). Diameter of field view is 2.8 millimetres.

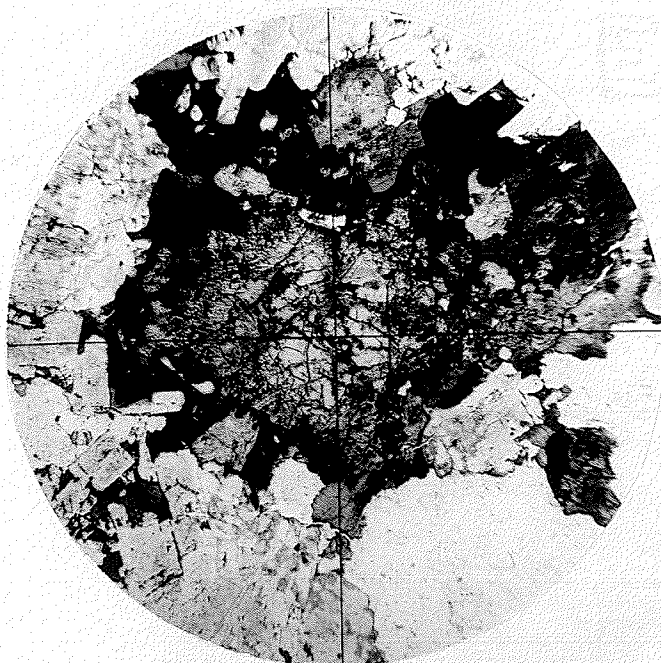


Figure 8. Photomicrograph of gabbro showing diopside (light grey mineral under crosshairs) partially altered to hornblende (dark grey to black), specimen CG 11-11 (plane polarized light). Diameter of field of view is 2.8 millimetres.

rather than fine well-developed fibres, and is apparently a sodic variety. Plagioclase grains are slightly corroded or invaded by the more fibrous uralite in some thin sections.

In some thin sections which contain grains of pyroxene, alteration of clinopyroxene to the fine fibrous and colourless to greenish uralite is evident. In one section the writer noted remnants of clinopyroxene surrounded by successive kelyphitic rims of mixed green amphibole and brown biotite, granular pleochroic blue-green amphibole, and colourless fibrous uralite. However, the texture of this specimen is atypical of normal gabbro zone rocks.

The content of individual varieties of amphibole has not been recorded in modal analyses. The range in amphibole content of gabbro zone rocks is 12 per cent to 51 per cent. The average of twenty modal analyses is 31 per cent. In general, those rocks unusually low in amphibole contain considerable quantities of biotite and/or pyroxene.

The three varieties of amphibole (coarse pleochroic hornblende commonly with schiller-like magnetite inclusions, fine granular pleochroic hornblende with no magnetite inclusions, and uralitic hornblende) are generally similar in appearance and colour. It is probable that they

are all of related origin and similar chemical composition. They all appear to be the result of deuteric alteration of original primary pyroxene.

Biotite

Biotite is invariably present in specimens from the gabbro zone. It is pleochroic from light brown to dark brown, and grain size ranges from coarse to very fine. Anhedral grains and granular intergrowths are almost as common as subhedral laths. Some sections contain only laths, others only anhedral grains, but usually both occur together. Pleochroic olive-brown and olive-green biotites are not uncommon, but are principally confined to rocks near the transition zone. Olive biotite almost invariably occurs as irregular grains. Although most biotite is intergrown with amphibole in clusters, there is no reason to believe that it has formed by alteration of amphibole.

Biotite content of gabbro zone rocks ranges from a trace to sixteen per cent. The average of twenty modes is 4.7 per cent.

Quartz

Quartz content of the rocks of the gabbro zone ranges between zero and twelve per cent, and is generally less than

five per cent. The average of twenty modal analyses is 3.1 per cent.

Two associations of quartz are present. The chief one is of irregular interstitial quartz grains. The other association is tiny irregular rounded grains of quartz contained in coarse granular hornblende. An average of perhaps one third of the quartz in the gabbro zone is of the second type.

Pyroxenes

Pyroxene is present in seven of the fifty thin sections of gabbro zone rocks; all seven sections are from the northwest half of the main intrusion. The pyroxene content of these seven thin sections ranges between a trace and six per cent, and averages three per cent. Pyroxene was positively identified in one section as the clinopyroxene diopside. In some thin sections it shows a well-developed diallage or malacolite parting, apparently parallel to (001). In other sections this is not evident, either because the section is parallel to (001), or else because the parting is not present. Well-developed twinning along (100) is evident in several thin sections.

One thin section contains a small amount of hypersthene, along with a larger quantity of diopside.

All grains of pyroxene are in various stages of alteration to granular and, less commonly, uraltic hornblende.

Opaque oxides

The opaque oxides magnetite, titaniferous magnetite and/or ilmenite are ubiquitous in gabbro zone rocks. Magnetite occurs as schiller-like lamellar inclusions in hornblende. Titaniferous magnetite and/or ilmenite is invariably present as small irregular grains, apparently unrelated to the lamellar inclusions in hornblende. The titaniferous nature of these grains is inferred from their typical association with granular sphene, generally clustered about the opaque oxide grains, and from alteration of some opaque oxide grains to leucoxene.

The content of opaque oxide grains in gabbro zone rocks, exclusive of the lamellar inclusions in hornblende, varies from a trace to four per cent. It was not feasible to determine the quantity of opaque oxides present as lamellar inclusions.

Apatite

Most sections contain from zero to two per cent apatite, in the form of well developed hexagonal rods and

rounded grains. The average apatite content from twenty modal analyses is 0.3 per cent.

Sphene

Sphene is the only other common accessory. Sphene content of the gabbro zone varies between zero and two per cent. The average is 0.4 per cent.

Pyrite, zircon, and clinozoisite

Pyrite, zircon, and clinozoisite are minor primary accessories. Pyrite and clinozoisite occur as tiny grains, and zircon as extremely tiny inclusions in brown biotite. Zircon grains can be identified only by the pleochroic halo zones which surround them.

b) Secondary minerals

The secondary alteration minerals are saussurite, scapolite, chlorite, penninite, and leucoxene.

Slight saussuritization of plagioclase is evident in a number of thin sections. In a few sections, plagioclase has been almost completely saussuritized, the plagioclase grains consisting almost entirely of a fine-grained granular intergrowth of albite, clinozoisite, epidote, sericite, and carbonate. Saussuritization is most intense in the

more calcic cores of zoned plagioclase grains. In hand specimen, such rocks have a pink cast, due to the pink colour of the strongly saussuritized plagioclase.

Scapolite is a common secondary alteration product of plagioclase, and occurs in the form of patches in plagioclase, and ^{as} veinlets along fractures in the rock. Scapolite is present in about one-quarter of the thin sections from the gabbro zone, in amounts ranging from a trace to two per cent. It is relatively uniform in composition, has a maximum birefringence of 0.016, and is Dipyre, $\text{Me}_{37}\text{Ma}_{63}$ (Winchell and Winchell, 1951, page 353).

Leucoxene is not common, and occurs as poorly developed whitish to rusty-white alteration rims around opaque oxides.

Chlorite occurs as a rare alteration of biotite along (001) cleavage planes. Penninite is an extremely rare alteration product of hornblende.

B. Transition zone

The transition zone incorporates all rocks gradational between the gabbro zone and the granite zone. Gabbro and granite zone rocks are different in colour, composition, and to some extent in texture. Each zone is

remarkably uniform in texture and composition. As might be expected, rocks of the transition zone vary widely in composition, colour and texture. On this basis the transition zone has been mapped in the field and its boundaries plotted on the map. Rocks which do not resemble typical gabbro, or typical granite, have been classed as transition rocks.

Transition rocks can be roughly classified into two main types, gradational into one another. The most common type is a massive fine- to medium-grained uneven-textured porphyritic variety, grey to medium pinkish grey in colour. It contains 15 to 20 per cent poorly formed pinkish orange feldspar phenocrysts up to four millimetres in length. The groundmass is a fine-grained intergrowth of the same feldspar with lesser hornblende and biotite; grain size varies from one to two millimetres.

The other variety is a massive medium-grained intergrowth of pinkish plagioclase and black hornblende. The texture and appearance of this type, with the exception of the pink plagioclase, is identical to that of typical gabbro zone rocks.

Small quantities of quartz can usually be discerned with a hand lens, particularly in the porphyritic variety.

All variations between the two main (transition) types are common. The porphyritic variety is greatly predominant, particularly in the southeast half of the main intrusion. The pinkish gabbroic variety is predominant in the northwest half of the main intrusion, where the transition and granite zones are thin. It is chemically intermediate between the porphyritic transition rocks and rocks of the gabbro zone.

In hand specimen, transition rocks are generally distinctive. They are almost invariably lighter in colour than gabbro, and considerably darker than granite, due to their intermediate content of mafic minerals. They are distinguished from gabbro by their pinker colour and normally different texture; from granite by their higher mafic mineral content. In general, little difficulty was experienced in classifying any particular specimen. However, because of the gradational and somewhat arbitrary nature of contacts between these zones, slight errors in the placement of boundaries have undoubtedly occurred.

Rocks of the transition zone are a hypidiomorphic to allotriomorphic granular intergrowth of plagioclase with anhedral pleochroic green amphibole, varying from a compact and granular texture to a highly irregular serate intergrowth. Subhedral to anhedral grains of biotite are

invariably present. Quartz ranges from one to ten per cent; it occurs commonly as highly irregular grains intergrown with feldspar. The intergrowth might be described as granophyric. Microcline is present in some sections, and may constitute as much as eleven per cent of the rock. Sphene, opaque oxides, and apatite are common accessories. Minor saussuritic alteration of plagioclase was observed in some sections. Alteration of plagioclase to scapolite is well developed in one thin section, but absent in all others. Traces of chlorite, carbonates, leucoxene, hematite, and muscovite occur rarely.

Figure 9 is a photomicrograph of a specimen from the base of the transition zone. It contains 1.1 per cent quartz but the field of view of the photomicrograph shows considerably more quartz (clear white) than this. It was chosen to show the peculiar highly irregular or granophyric (?) quartz-feldspar intergrowth which is common in the transition zone.

On the basis of the Grout classification, rocks of the transition zone range from diorite to quartz diorite, with minor granodiorite. Diorite predominates.

Mineralogy of the transition zone

Transition zone mineralogy is similar to that of the gabbro zone.

a) Primary minerals

Plagioclase

Plagioclase is the major constituent. Normal zoning is invariably present, but is not as strong as in the gabbro zone. Some grains are lath shaped, but these are not as numerous or as well developed as in the gabbro zone, and invariably have serrate edges. Plagioclase composition in the transition zone ranges from An_{23} to An_{35} . Transition zone plagioclase is considerably more sodic than that of the gabbro zone, and compositional variation is less pronounced. Albite twinning is not as well developed, and twins tend to be somewhat irregular and discontinuous. Plagioclase content of transition zone rocks ranges from 45 to 89 per cent. The average of twelve modal analyses is 66 per cent.

Amphibole

One or possibly two varieties of amphibole, both varieties of hornblende, are present in the transition zone. Most hornblende is pleochroic from light brown to intense shades of green and blue-green. It is commonly in the form of equidimensional grains. In some specimens hornblende grains are jagged, highly irregular in shape, and lighter



coloured than the normal variety. These probably represent a hornblende of slightly different composition.

Hornblende cleavage is well developed. No lamellar magnetite inclusions are present, and pyroxene was not observed. However, if the intrusion is differentiated, hornblende should have crystallized directly from the magma at this stage, rather than formed by deuteric alteration of primary pyroxene.

Hornblende content of transition zone rocks ranges from 12 to 38 per cent, and averages 21 per cent.

Biotite

Biotite content ranges from one to fifteen per cent; the average of twelve modes is five per cent. Most of the biotite is pleochroic in shades of olive-brown, olive-green, and olive; in some specimens the biotite is the pleochroic brown variety typical of the gabbro zone. Both varieties may be present in one specimen, but in these specimens, the brown biotite has a slightly olive cast. Brown biotite is commonly in the form of subhedral laths, but the olive shaded varieties are invariably in the form of highly irregular grains. Similar olive shaded biotites occur near the top of the gabbro zone. Olive biotite is peculiar to the vicinity of the transition zone. It probably represents a

compositional variation, related to residual magma composition at the time of crystallization.

Quartz

Quartz content of the transition zone ranges from one to nine per cent, and averages 3.4 per cent. This average is only slightly greater than that of the gabbro zone. Quartz grains are highly irregular, and in a few sections the intergrowth of quartz and feldspar could perhaps be described as somewhat granophyric (figure 9).

Microcline

As much as eleven per cent microcline is present in the rocks of the transition zone, but many specimens contain little or none of this mineral. It occurs in the form of tiny to moderately large interstitial grains, and also intergrown with plagioclase to form a patch perthite. Some grains exhibit typical gridiron twinning, but most are only poorly or apparently not at all twinned. The average microcline content of the zone is 2.8 per cent.

Sphene, opaque oxides, apatite, and pyrite

Sphene content of transition rocks ranges between 0.1 and three per cent. The average content is 1.5 per cent as opposed to 0.4 per cent for the gabbro zone. In the

transition zone, sphene is almost invariably in the form of anhedral rounded grains and granular masses, while in the gabbro zone it is often subhedral to euhedral. Subhedral sphene is rare, and euhedral grains are absent in the transition zone.

Opaque oxides, either titaniferous magnetite or ilmenite occur in the form of disseminated irregularly rounded grains. They typically constitute approximately 0.8 per cent of transition rocks.

Apatite occurs as rounded to hexagonal rods and grains identical to those in the gabbro zone, and constitutes 0.3 per cent of the average transition rock.

Traces of pyrite were noted in some specimens.

b) Secondary minerals

Saussurite, scapolite, epidote, leucoxene, chlorite, and hematite were observed as minor secondary alteration products in some specimens, as described for the gabbro zone.

C. Granite zone

Granite zone rocks are invariably massive and generally uniform in composition and texture. They are fine-to

medium-grained and dull orange-pink in colour, with scattered black specks or grains of the mafic constituents. In hand specimen they consist of 70 to 75 per cent orange-pink to dirty orange-pink feldspar and 25 to 30 per cent glassy grey quartz, with zero to five per cent black hornblende or biotite as disseminated small grains. A few specimens contain little or no quartz, and consist almost entirely of feldspar. Tiny specks of pyrite are rare.

Grain size of the granite is generally one to three millimetres. Colour of the weathered surface is rusty brown to orange. Variations in composition, colour, and texture are not common. Colour may vary from orange and orange-pink to almost pink; orange-pink predominates. The relatively minor variations in texture that do occur are largely due to variation in distribution and grain size of the mafic minerals, which occur as three or four millimetre clots or clusters, or as one millimetre grains evenly disseminated throughout the rock.

Rocks of the granite zone are a highly irregular allotriomorphic granular intergrowth of plagioclase, quartz, and microcline, with lesser hornblende and/or biotite. A patch perthite consisting of a highly irregular intergrowth of plagioclase and microcline is common in some thin sections. Sphene, opaque oxides, and apatite are minor

accessories. Traces of chlorite and leucoxene are present in some thin sections as alteration products of biotite and sphene, respectively. Microcline content of granite is highly variable, ranging from a trace to almost thirty per cent.

Figure 10 is a photomicrograph of typical granite. This specimen consists of an intergrowth of plagioclase and quartz, with accessory microcline, hornblende, opaque oxides, and sphene.

Mineralogy of the granite zone

a) Primary minerals

Plagioclase

Plagioclase content of granite zone rocks ranges from 47 to 91 per cent; the average of twelve modal analyses is 70 per cent. Albite twinning is well-developed. The twins are fine, irregular, and discontinuous, rather than broad, straight, and sharp as in the gabbro zone. Grain boundaries are highly irregular, due to the jagged intergrowth of adjacent grains.

Zoning is rare and very weak. The maximum composition variation observed in a single grain is An_{10} to An_{13} .



Figure 9. Photomicrograph of a basal transition rock showing granophyric (?) quartz-feldspar intergrowth. Quartz appears white. Specimen CG 6-14 (crossed nicols). Diameter of field view is 7 millimetres.

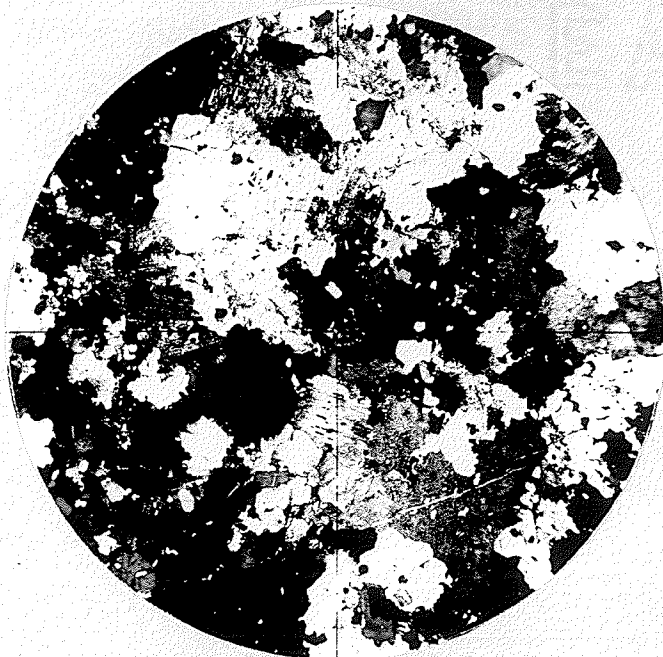


Figure 10. Photomicrograph of typical granite, specimen CG 6-22 (crossed nicols). Diameter of field of view is 7 millimetres.

Plagioclase is typically a calcic albite. The most sodic plagioclase is An_7 , the most calcic An_{13} .

Quartz

Quartz is clear and free from inclusions. It normally exhibits undulating extinction or strain shadows under crossed nicols. Quartz content is variable from zero to 31 per cent, and averages 17 per cent. Quartz does not occur in specimens CG 11-1 and CG 11-2, from the northwest half of the intrusion, where the granite zone is very narrow. Both specimens came from within 50 to 100 feet of the granite-sediment contact, and consist of an intergrowth of albite (90 per cent) and hornblende (10 per cent). The significance of this lack of quartz is uncertain. Specimens containing normal amounts of quartz were collected both to the northwest and southeast.

Quartz in the granite zone is commonly elaborately intergrown with plagioclase and, to a lesser extent, microcline. This texture might be described as granophyric in some cases, but is not well-developed in all specimens. Its development in any particular thin section is variable from place to place. A similar but less well-developed texture is present in the transition zone, and is very poorly developed in the gabbro zone. This intergrowth is not the

normal graphic or patchy graphic intergrowth which is prevalent in the late granitic portions of many differentiated intrusions, and it is questionable whether it should be described as granophyric. Figures 11 and 12 are photomicrographs selected to show the most extreme development of granophyric (?) quartz.

Microcline

Granite zone rocks have an average microcline content of ten per cent, but wide variations are normal. The minimum and maximum microcline content noted are zero and 27 per cent.

Gridiron twinning is generally poorly developed, and virtually nonexistent in many grains, so that sodium cobaltinitrite staining was necessary to permit the determination of mineral relationships and modal analyses.

Most microcline occurs in the form of irregular grains intergrown with other minerals. A patch perthite, consisting of albite with ragged irregular patches of microcline, is common in some specimens.

Amphibole

The amphibole is hornblende, almost invariably an intensely coloured pleochroic green to blue-green and less



Figure 11. Pronounced development of granophyric (?) quartz in granite. Quartz appears white. Specimen CG 2-2 (crossed nicols). Diameter of field of view is 7 millimetres.



Figure 12. Extreme development of granophyric (?) quartz in granite. Quartz appears white. Specimen CG 6-22 (crossed nicols). This is the same specimen as figure 10. Diameter of field of view is 7 millimetres.

commonly brownish green variety. It occurs normally as jagged irregular grains intergrown with the other constituents, but in some thin sections occurs as small rounded grains. A paler pleochroic green hornblende is present in a few specimens. Amphibole content of granite zone rocks ranges from zero to nine per cent, and averages 4.2 per cent.

Biotite

Biotite is invariably a brown pleochroic variety. Slight alteration to chlorite is common. Biotite content of specimens from the granite zone ranges from zero to four per cent, and averages 1.2 per cent.

Sphene

Sphene almost invariably occurs as rounded granules or fine granular aggregates. Rare euhedral and anhedral grains were noted. Sphene is commonly associated with the opaque oxides, and constitutes from a trace to 1.8 per cent of the rock, the average being 0.7 per cent.

Opaque oxides

Tiny irregular and rounded grains of titaniferous magnetite and/or ilmenite constitute from a trace to 1.7 per cent of the granite, with an average of 0.7 per cent.

Apatite

Minute quantities of apatite occur as rounded grains and less common hexagonal rods.

b) Secondary minerals

Secondary leucoxene, chlorite, saussurite, sericite, epidote, carbonates, and dusty hematite are present in trace quantities in some thin sections.

Metamorphism

Late deuteric alteration was an important factor in the crystallization of the Granville Lake intrusion. This is particularly evident in the gabbro zone. The significant result is the almost complete alteration of primary pyroxenes to hornblende and minor uralite by late magmatic solutions. The blue-green colour of the hornblendes indicates that they are sodic varieties. This is consistent with the alteration of pyroxenes by late sodic fluids from differentiation. The intrusion shows no evidence of significant regional metamorphism. Most of the calcic plagioclase shows little evidence of any metamorphic effects, except for a few places where relatively minor saussuritization and scapolitic alteration has occurred. These can be attributed to late deuteric reactions. The uralite was

most probably formed during crystallization of the magma, and is not due to regional metamorphism, because it is co-existing with and has not invaded the calcic plagioclase.

Sickle rocks of the Watt Lake area (east half) are of upper greenschist or lower almandine amphibolite facies. Sickle greywacke has an unusually well developed alignment of fine biotite flakes. It is finely schistose in some places in the immediate vicinity of and in a zone perhaps 1/4 mile wide surrounding the intrusion. Slight assimilation and possibly fusion of these sediments has occurred along the northeast side of the main intrusion, but is confined to a zone three or four feet wide. Contact metamorphic effects have been confined to within a few feet of the various intrusions. Where contacts of satellite intrusions with sediments are exposed, gabbro is seen to be chilled against baked fine-grained greywacke. The 1/4-mile foliated zone which surrounds the intrusion was formed by stresses induced in the sediments by later folding. At this time, the solid and unyielding intrusion was tilted from its original horizontal to its present nearly vertical attitude.

The few small areas of brecciated Sickle greywacke along gabbro-sediment contacts may represent remnants of a cataclastic breccia zone, which acted as a zone of weakness

along which the magma was intruded. It is more likely that the breccia was formed by limited shattering of enclosing sedimentary rocks by forcible injection of magma.

Mineralogical variation across the intrusion

Modal analyses of single standard-sized thin sections of Granville Lake Gabbro specimens are listed in table 2. Modal analyses and specific gravities of specimens collected on traverses CG 2, CG 6, CG 11 are plotted in figures 13, 14, and 15. Vertical lines indicate the relative position of each specimen along the traverse, and variation in rock type is indicated at the top of each diagram. Specific gravity is plotted in these figures only to facilitate comparison with modal analyses, and is discussed separately in a later section. Specific gravities of the specimens of which modal analyses were made are plotted as circles, and joined by a light dotted line. Figure 4 indicates the location of each traverse.

Plagioclase and Amphibole

Plagioclase and amphibole constitute the major part of most rocks of the intrusion. It follows that in general, increase in amphibole content is accompanied by a decrease in plagioclase. A general correspondence between specific gravity and amphibole content of each specimen is obvious

Specimen	Colour Index	Specific Gravity of Rock	Plagioclase	Amphibole	Quartz	Microcline	Biotite	Sphene	Opaque Oxides	Apatite	Pyroxene
CG 2- 2	1.4	2.60	76.7	1.1	22.0	tr	-	0.2	0.1	-	-
CG 2- 4	5.6	2.62	56.5	3.9	16.4	21.5	0.5	0.2	0.9	0.1	-
CG 2- 7	5.6	2.64	47.1	4.0	20.0	27.2	0.8	0.3	0.4	0.1	-
CG 2- 8	9.9	2.66	62.2	5.7	15.7	12.3	3.3	0.6	0.3	tr	-
CG 2-10	6.4	2.65	61.1	4.8	11.9	19.6	0.1	1.3	1.1	0.1	-
CG 2-11	12.3	2.70	74.0	8.9	2.6	11.1	-	1.8	1.4	0.2	-
CG 2-12	20.6	2.71	70.9	18.2	0.6	7.6	0.1	1.1	1.0	0.2	-
CG 2-14	33.1	2.82	61.6	16.9	3.6	1.5	15.0	0.6	0.3	0.3	-
CG 2-15	34.8	2.87	58.4	18.7	6.8	tr	15.4	0.1	0.2	0.4	-
CG 2-17	7.7	2.77	88.7	1.8	0.7	1.6	2.2	2.2	2.5	0.2	-
CG 2-19	48.4	2.92	44.9	38.4	5.3	1.1	6.3	2.8	-	0.9	-
CG 2-21	34.8	2.86	53.5	13.6	11.6	-	16.0	0.3	3.7	1.2	-
CG 2-23	30.9	2.87	62.6	19.9	6.3	-	9.1	-	0.8	1.1	-
CG 2-25	28.3	2.81	70.9	19.9	0.8	0.1	4.6	1.7	1.4	0.7	-
CG 6- 1	22.1	2.86	77.8	11.5	0.3	-	6.6	2.0	1.8	0.2	-
CG 6- 4	29.7	2.88	64.5	22.9	4.7	-	7.5	-	0.2	0.1	-
CG 6- 6	38.4	2.91	59.0	29.0	2.6	-	7.8	-	1.1	0.5	-
CG 6- 8	28.2	2.82	65.0	18.3	6.5	-	8.4	tr	0.7	0.8	-
CG 6-11	36.9	2.90	57.6	32.2	5.5	0.1	4.2	0.4	-	0.1	-
CG 6-14	37.9	2.86	61.8	32.6	1.1	0.3	3.9	1.0	-	0.4	-
CG 6-19	33.1	2.78	50.0	26.1	8.2	8.7	5.5	1.4	-	0.1	-
CG 6-21	25.3	2.77	54.6	21.4	8.7	11.3	2.6	1.1	0.2	tr	-

TABLE 2

Modal analyses, specific gravities, and colour indices,
Grenville Lake Gabbro

Specimen	Colour Index	Specific Gravity of Rock	Plagioclase	Amphibole	Quartz	Microcline	Biotite	Sphene	Opaque Oxides	Apatite	Pyroxene
CG 6-22	5.8	2.67	73.5	2.9	16.5	3.9	-	1.2	1.7	tr	-
CG 6-24	4.7	2.65	70.7	-	22.1	2.2	3.3	tr	1.4	tr	-
CG 6-25	3.5	2.64	53.4	0.3	23.4	19.6	1.5	0.6	1.1	tr	-
CG 6-26	4.7	2.62	61.5	-	30.9	2.7	4.3	0.1	0.2	0.1	-
CG 9-25	31.4	2.86	67.9	27.3	0.8	-	0.8	1.6	0.4	0.4	-
CG 10- 5	42.6	2.92	51.7	38.0	0.3	-	4.3	tr	0.3	-	-
CG 10-23	35.5	2.78	64.0	24.4	0.5	-	7.9	1.7	1.1	0.4	-
CG 11- 1	9.3	2.65	90.6	8.8	-	-	-	0.5	tr	-	-
CG 11- 2	12.1	2.65	87.9	10.3	0.1	-	-	1.1	0.1	0.6	-
CG 11- 3	18.1	2.72	79.7	13.3	1.7	0.1	1.1	1.8	2.3	0.1	-
CG 11- 4	24.7	2.74	72.8	17.8	1.7	0.9	1.8	2.9	1.8	0.4	-
CG 11- 5	38.5	2.86	56.3	30.3	5.1	tr	7.0	-	0.5	0.7	-
CG 11- 7	47.8	2.94	48.5	45.3	3.3	0.1	1.3	0.9	0.1	0.2	-
CG 11- 9	43.0	2.92	54.0	38.4	2.6	0.1	3.8	-	0.3	0.5	-
CG 11-11	39.9	2.94	59.6	37.0	0.5	-	0.4	-	0.5	0.1	1.9
CG 11-14	57.3	2.89	42.7	51.0	-	-	5.4	0.1	0.5	0.1	-
CG 11-16	34.9	2.90	65.0	32.6	0.1	-	0.7	-	1.4	-	-
CG 11-18	42.3	2.95	57.5	33.4	0.2	-	1.1	-	2.2	-	5.6
CG 11-21	40.0	2.91	59.1	38.4	0.8	-	1.4	-	0.1	0.1	-
CG 11-23	49.0	2.89	48.8	44.8	2.0	-	3.3	-	0.9	tr	-
CG 12-21	15.9	2.71	82.3	11.6	1.9	-	1.5	1.2	1.3	0.3	-
CG 15-17	45.3	2.91	54.5	43.8	0.2	-	0.1	0.2	1.1	0.1	-

TABLE 2 (concluded)

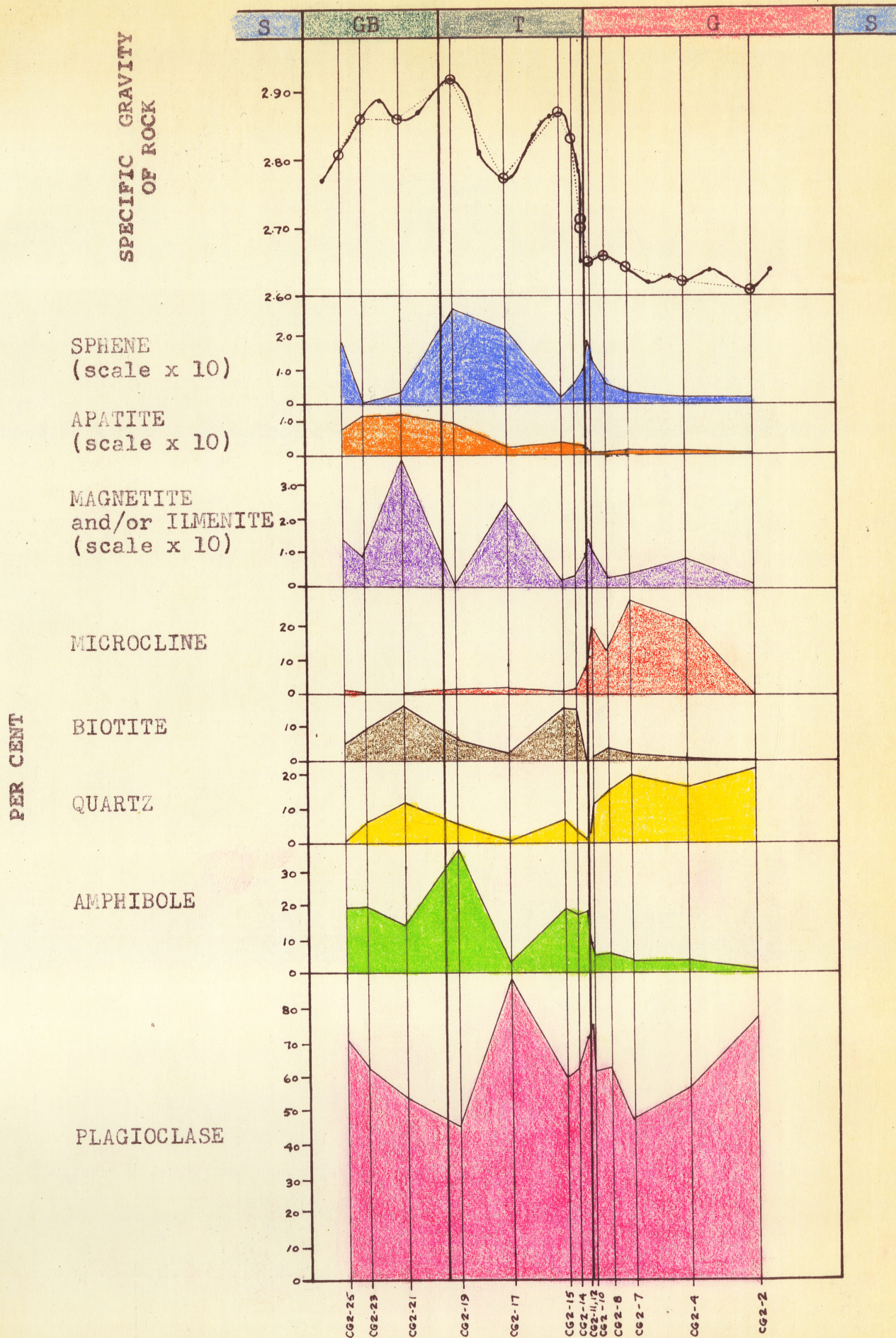


Figure 13. Plot of modal analyses, traverse CG 2.

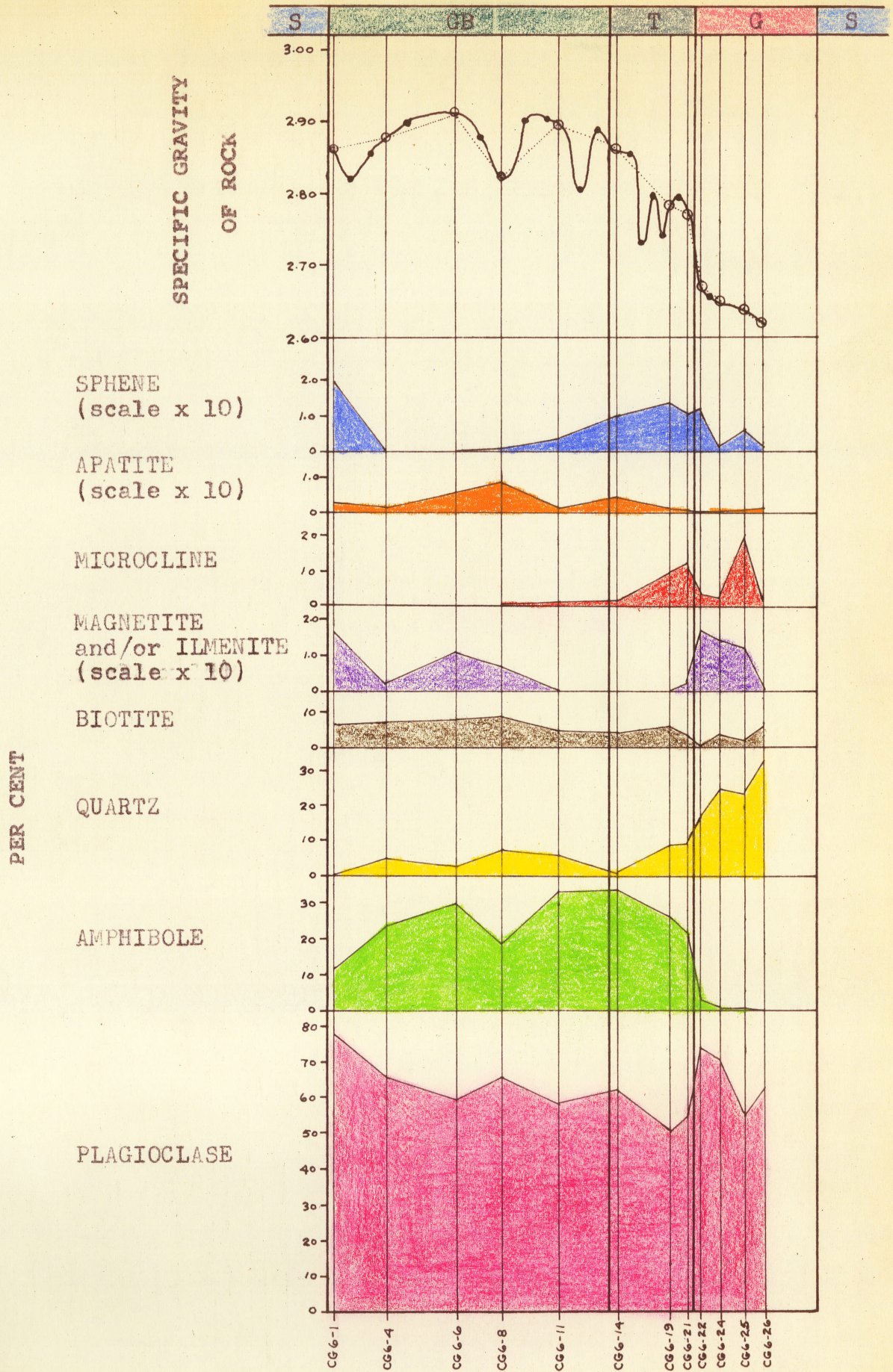


Figure 14. Plot of modal analyses, traverse CG 6.

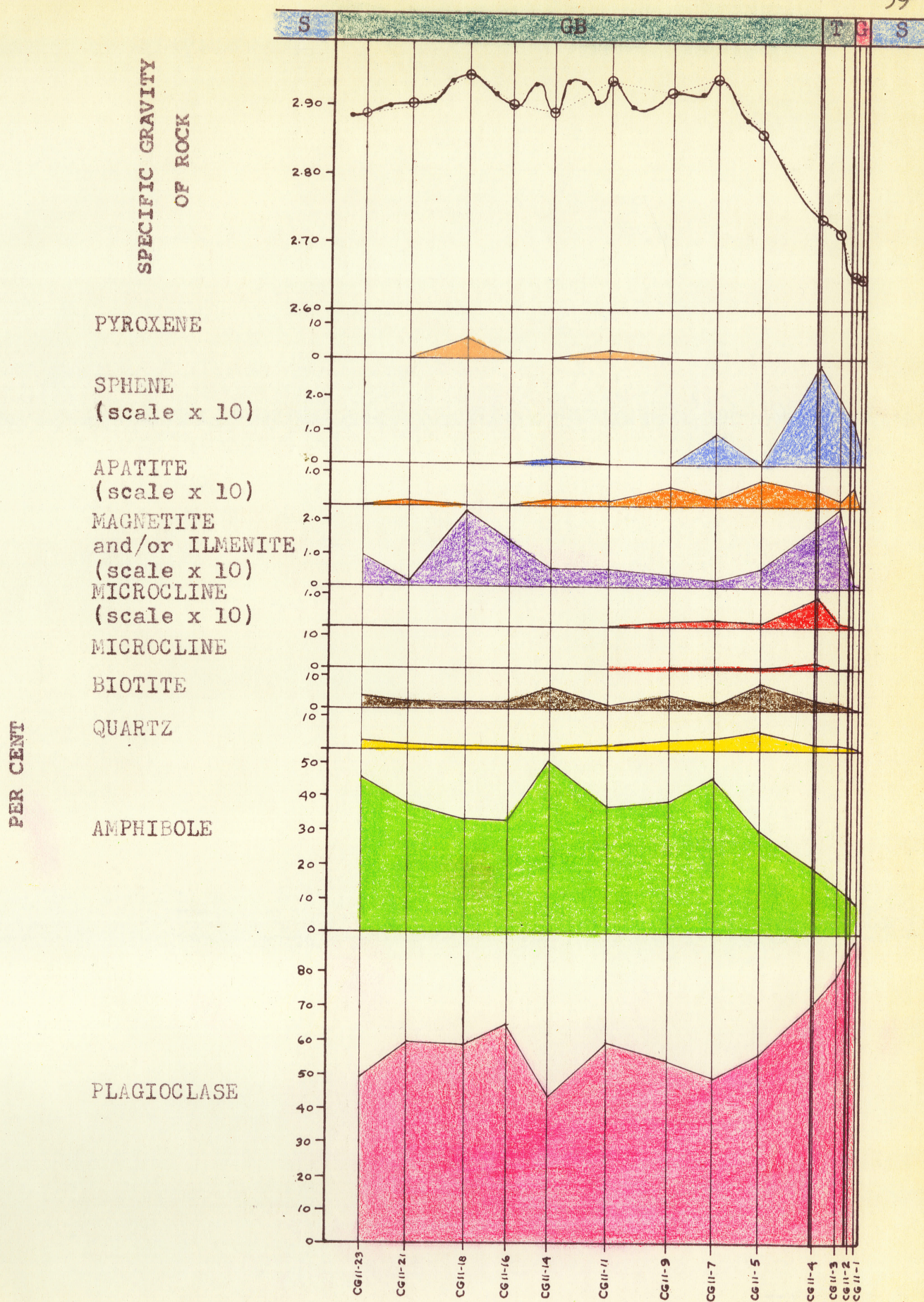


Figure 15 . Plot of modal analyses, traverse CG 11.

from the diagrams. This is due to the fact that amphibole is the dominant mineral of high specific gravity.

Quartz

In the case of traverses CG 2 and CG 6, quartz content is highest near the top of the granite zone. However, on traverse CG 11, the maximum quartz content is found in the gabbro zone; the transition and granite zones contain little quartz.

Biotite

The gabbro and transition zones have a higher biotite content than the granite zone.

Microcline

Microcline first appears near the middle of the gabbro zone, reaches its highest concentration in the transition and granite zones, then rapidly decreases to almost zero near the top of the intrusion. The highest microcline content was found on traverse CG 2 near the extreme southeast end of the main intrusion, where the maximum accumulation of late differentiates has occurred. The granite and transition zones become thinner toward the northwest, and maximum microcline content decreases rapidly.

Opaque oxides

Crystallization of the opaque oxides was apparently rhythmic or irregular, and two or three crystallization peaks appear on each traverse. In general one peak appears in the gabbro zone, and another near or at the transition zone - granite zone boundary. Concentrations of opaque iron oxides which apparently correspond to that at the transition zone - granite zone boundary are found in the Sudbury intrusion (Collins, 1934), the Lynn Lake Gabbro (Emslie, 1961, p.35), and the Tow Lake Gabbro (Hunter, 1958, p.18).

Apatite

Maximum apatite content is found near the top of the gabbro zone. A similar maximum in P_2O_5 content may be noted in the silica variation diagram, figure 16.

Concentrations of apatite are common to many differentiated gabbroic intrusions. In the well-known Sudbury intrusion, a similar concentration of apatite occurs near the top of the norite zone. Hunter (1958, p.10, p.19), in his study of the Tow Lake Gabbro, found a sharp peak in apatite content in the "B" or intermediate gabbro. A similar concentration of apatite occurs in the upper zone of the Lynn Lake Gabbro (Emslie, 1961, p.35).

Sphene

A pronounced concentration of sphene occurs in the transition zone, and a similar maximum TiO_2 content is evident in the silica variation diagram. In his study of the Lynn Lake Gabbro, Emslie (1961, p.46) states that sphene is limited almost entirely to the upper zone.

Discussion of mineralogical variation and petrogenesis

Mineralogical variation across the intrusion and particularly the distribution of quartz, opaque oxides, microcline, apatite, and sphene show remarkable similarity to the distribution found in other differentiated intrusions.

Plagioclase, clinopyroxene, orthopyroxene, minor biotite, and possibly some amphibole were the first minerals to crystallize from the primary undifferentiated magma. As the water content of progressive liquid differentiates became higher and temperature decreased, the pyroxenes were altered to various hornblende amphiboles, and hornblende began to crystallize directly from the magma. Formation of plagioclase continued until crystallization of the intrusion was complete. Crystallization of opaque oxides was irregular in the gabbro zone, reaching one or more peaks. Formation of apatite became pronounced when about half the magma had crystallized. The maximum accumulation of apatite occurred

near the top of the gabbro zone. Apatite then decreased gradually to almost zero in the granitic rocks due to impoverishment of the residual differentiate in P_2O_5 . As apatite crystallization reached its maximum, the rate of crystallization of sphene increased rapidly, reached a pronounced peak in the transition zone, then decreased.

By the time formation of the transition rocks was virtually complete, the remaining magma must have become depleted in magnesium and impoverished in calcium and to a lesser extent in iron. As a result, the formation of hornblende became almost negligible. Plagioclase composition changed abruptly from approximately An_{23} to An_{13} . This resulted in the relatively sharp boundary between hornblende-rich transition rocks and hornblende-poor granite. Most of the remaining opaque minerals crystallized at about this time, and a pronounced peak in opaque oxide content is evident.

Quartz is found in small quantities throughout the gabbro and transition zones. With the exception of traverse CG 11, quartz content is highest near or at the top of the granite zone, where it becomes as great as thirty per cent. However, on traverse CG 11, the maximum quartz content is found in the gabbro zone, and the transition and granite zones contain little quartz. This may be due to floating of

albite crystals to the top of the magma chamber, where they were trapped by irregularities in the upper surface, which prevented their migration to the uppermost southeast portion of the intrusion. A more plausible explanation is filter pressing and migration of the late silica-rich differentiate from its albite crystal mush before crystallization of quartz began. Such filter pressing would be the result of downslope settling of crystal mush and consequent displacement of the remaining fluid to the higher southeast end of the main intrusion. This is confirmed by the progressive increase in quartz and microcline content of rocks of traverses CG 11, CG 6, and CG 2, respectively.

Crystallization of microcline began in the upper portion of the gabbro zone, and reached its maximum in the transition or lower granite zone. Microcline is absent or present in negligible quantities at the top of the granite zone.

Chemical analyses and related data

Eight specimens considered to be representative of normal variation in the intrusion were chosen for chemical analysis. Unfortunately, it was necessary to choose these specimens before any thin sections were available, and as a result, the analyses do not include specimens of pyroxene

gabbro, chilled gabbro, or of granite formed by crystallization of the latest magmatic differentiate. It is therefore unlikely that the available analyses represent the maximum compositional variation. From figure 14 it is obvious that the analyzed specimen highest in SiO_2 (CG 6-25) is not the most silicic rock found in the intrusion.

Chemical analyses, molecular norms, and modes of chemically analyzed specimens are listed in table 3. Average compositions of igneous rocks, after Daly (1933), are given in table 4. Chemical composition of the three gabbro zone specimens is intermediate between Daly's average gabbro and average diorite. The transition zone rocks vary between diorite and granodiorite, and those from the granite zone are similar to Daly's average granite. All three zones are relatively rich in alumina and soda, poor in magnesia and potash, and slightly deficient in lime as compared to Daly's average rocks.

A. Silica variation diagram

Figure 16 is a silica variation diagram for the Granville Lake intrusion. The trends of the major oxides are consistent with what would be expected in a differentiated intrusion. Alumina, lime, magnesia, ferrous iron, and total iron show a generally consistent decrease with increasing

TABLE 3: Analyses of the Granville Lake Gabbro

	Gabbro Zone CG 10-5 K. Ramlal -analyst	Gabbro Zone CG 15-17 K. Ramlal -analyst	Gabbro Zone CG 9-25 K. Ramlal -analyst	Transition Zone CG 2-14 K. Ramlal -analyst
SiO ₂	49.6	51.2	52.9	53.7
Al ₂ O ₃	21.1	20.1	18.5	18.2
Fe ₂ O ₃	3.5	2.9	4.9	4.51
FeO	5.8	6.0	4.7	5.12
MgO	4.9	4.7	3.1	3.1
CaO	9.1	9.3	6.6	6.0
Na ₂ O	3.23	2.87	5.36	5.7
K ₂ O	0.82	0.48	1.18	1.85
TiO ₂	0.80	1.06	1.19	0.90
P ₂ O ₅	0.17	0.15	0.34	0.24
MnO	0.11	0.13	0.02	0.07
CO ₂	tr	nil	0.10	nil
H ₂ O ⁺ } H ₂ O ⁻ }	0.47	0.69	0.73	0.65
	99.60	99.58	99.62	100.14
<u>Molecular Norm</u>				
q	-	3.4	0.3	-
c	-	-	-	-
or	5.0	3.0	7.5	11.0
ab	29.0	26.5	47.5	48.8
an	41.0 An ₄₂	41.0 An ₃₉	23.3 An ₃₃	18.5 An ₂₉
wo	-	2.0	2.6	-
en	9.3	13.4	8.8	0.1
di	3.2	-	-	7.6
fs	3.7	6.0	2.2	-
fo	2.6	-	-	4.2
fa	1.0	-	-	1.9
mt	3.8	3.0	5.1	4.7
hm	-	-	-	-
il	1.2	1.4	1.6	1.2
ap	0.3	0.3	0.8	0.5
cc	-	-	0.2	-
ne	-	-	-	1.3
<u>Mode</u>				
Plagioclase	51.7 (An ₃₉₋₆₃)	54.5 (An ₃₆₋₆₄₊)	67.9	61.6 (An ₂₆₋₃₁)
Amphibole	38.0	43.8	27.3	16.9
Quartz	0.3	0.2	0.8	3.6
Microcline	-	-	-	1.5
Biotite	4.3	0.1	1.7	15.0
Sphene	tr	0.2	1.6	0.6
Opaque oxides	0.3	1.1	0.4	0.3
Apatite	-	0.1	0.4	0.3
Chlorite	tr	-	0.5	-
Pyrite	-	tr	-	tr
Epidote	-	-	-	tr
Hematite	-	-	-	-

TABLE 3 (concluded)

	Transition Zone CG 10-23 A.M. MacKay D.F.G. Brown -analysts	Transition Zone CG 12-21 A.M. MacKay D.F.G. Brown -analysts	Granite Zone CG 6-22 K. Ramlal -analyst	Granite Zone CG 6-25 K. Ramlal -analyst
SiO ₂	55.93	62.15	67.0	70.3
Al ₂ O ₃	17.59	16.81	16.3	15.2
Fe ₂ O ₃	2.73	3.76	5.7	3.8
FeO	4.88	2.23	0.39	0.39
MgO	3.44	2.05	0.1	0.03
CaO	6.10	3.60	1.9	1.4
Na ₂ O	5.80	6.16	7.0	5.5
K ₂ O	1.04	0.97	1.2	3.3
TiO ₂	0.74	0.68	0.41	0.25
P ₂ O ₅	0.22	0.22	0.10	0.06
MnO	0.04	0.04	0.05	0.02
CO ₂	nil	nil	nil	nil
H ₂ O ⁺ }	0.80	1.18	0.42	0.35
H ₂ O ⁻ }				
	99.31	99.85	100.57	100.60
<u>Molecular Norm</u>				
q	1.3	11.0	20.7	20.9
c	-	-	2.3	0.4
or	5.5	6.0	7.5	19.5
ab	52.0	55.5	56.0	49.5
an	19.3 An ₂₇	15.0 An ₂₁	8.5 An ₁₃	6.0 An ₁₁
wo	3.8	0.6	-	-
en	9.6	5.6	0.4	0.2
di	-	-	-	-
fs	3.4	1.4	-	-
fo	-	-	-	-
fa	-	-	-	-
mt	3.2	1.6	0.3	0.3
hm	0.3	1.8	3.7	2.5
il	1.2	1.0	0.6	0.4
ap	0.5	0.5	0.3	0.3
cc	-	-	-	-
<u>Mode</u>				
Plagioclase	64.0(An ₂₄₋₅₆)	82.3(An ₂₆₋₃₃)	73.5(An ₁₀)	53.4(An ₁₀₋₁₃)
Amphibole	24.4	11.6	2.9	0.3
Quartz	0.5	1.9	16.5	23.4
Microcline	-	-	3.9	19.6
Biotite	7.9	1.5	-	1.5
Sphene	1.7	1.2	1.2	0.6
Opaque oxides	1.1	1.3	1.7	1.1
Apatite	0.4	0.3	tr	tr
Chlorite	tr	-	0.2	-
Pyrite	-	-	-	-
Epidote	-	tr	tr	-
Hematite	-	-	tr	tr

TABLE 4

Average compositions of igneous rocks (from Daly, 1933)

Weight per cent

	<u>Granite</u>	<u>Syenite</u>	<u>Grano- diorite</u>	<u>Quartz Diorite</u>	<u>Diorite</u>	<u>Diabase</u>	<u>Gabbro</u>	<u>Norite</u>
SiO ₂	70.18	60.19	65.01	61.59	56.77	50.48	48.24	50.39
Al ₂ O ₃	14.47	16.28	15.94	16.21	16.67	15.34	17.88	16.06
Fe ₂ O ₃	1.57	2.74	1.74	2.54	3.16	3.84	3.16	2.43
FeO	1.78	3.28	2.65	3.77	4.40	7.78	5.95	7.86
MgO	0.88	2.49	1.91	2.80	4.17	5.79	7.51	8.37
CaO	1.99	4.30	4.42	5.38	6.74	8.94	10.99	9.20
Na ₂ O	3.48	3.98	3.70	3.37	3.39	3.07	2.55	2.61
K ₂ O	4.11	4.49	2.75	2.10	2.12	0.97	0.89	0.79
TiO ₂	0.39	0.67	0.57	0.66	0.84	1.45	0.97	1.13
P ₂ O ₅	0.19	0.28	0.20	0.26	0.25	0.25	0.28	0.20
MnO	0.12	0.14	0.07	0.10	0.13	0.20	0.13	0.17
H ₂ O ⁺	0.84	1.16	1.04	1.22	1.36	1.89	1.45	0.79
H ₂ O ⁻								

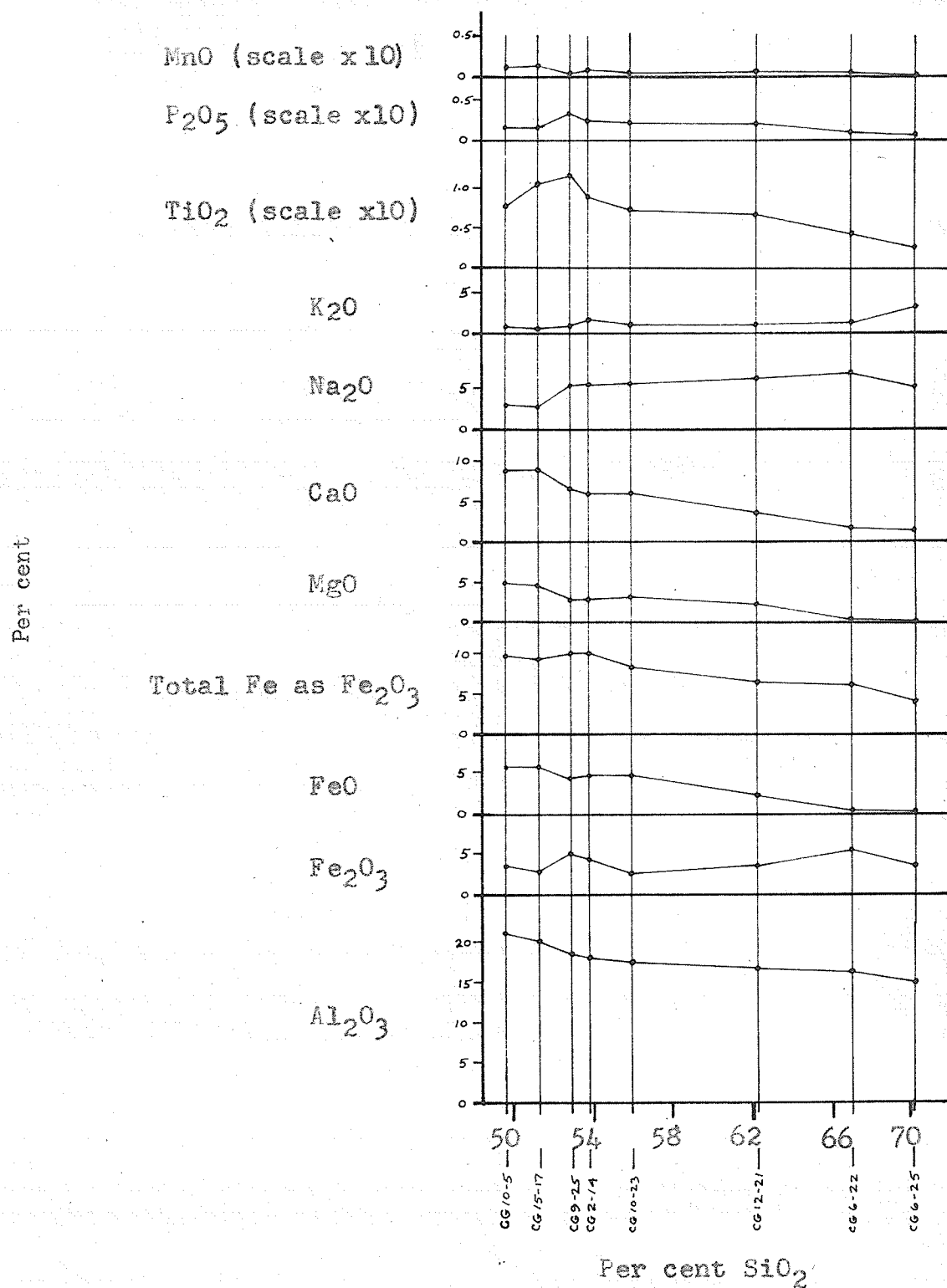


Figure 16. Silica variation diagram for the Granville Lake Gabbro.

silica content. Soda and potash show a general increase. The drop in soda and corresponding increase in potash in specimen CG 6-25 is due to the high microcline content of this rock. The trend of ferric oxide is irregular. Titania and P_2O_5 show peaks which may be similar to the maxima of apatite and sphene in the modal analysis diagrams.

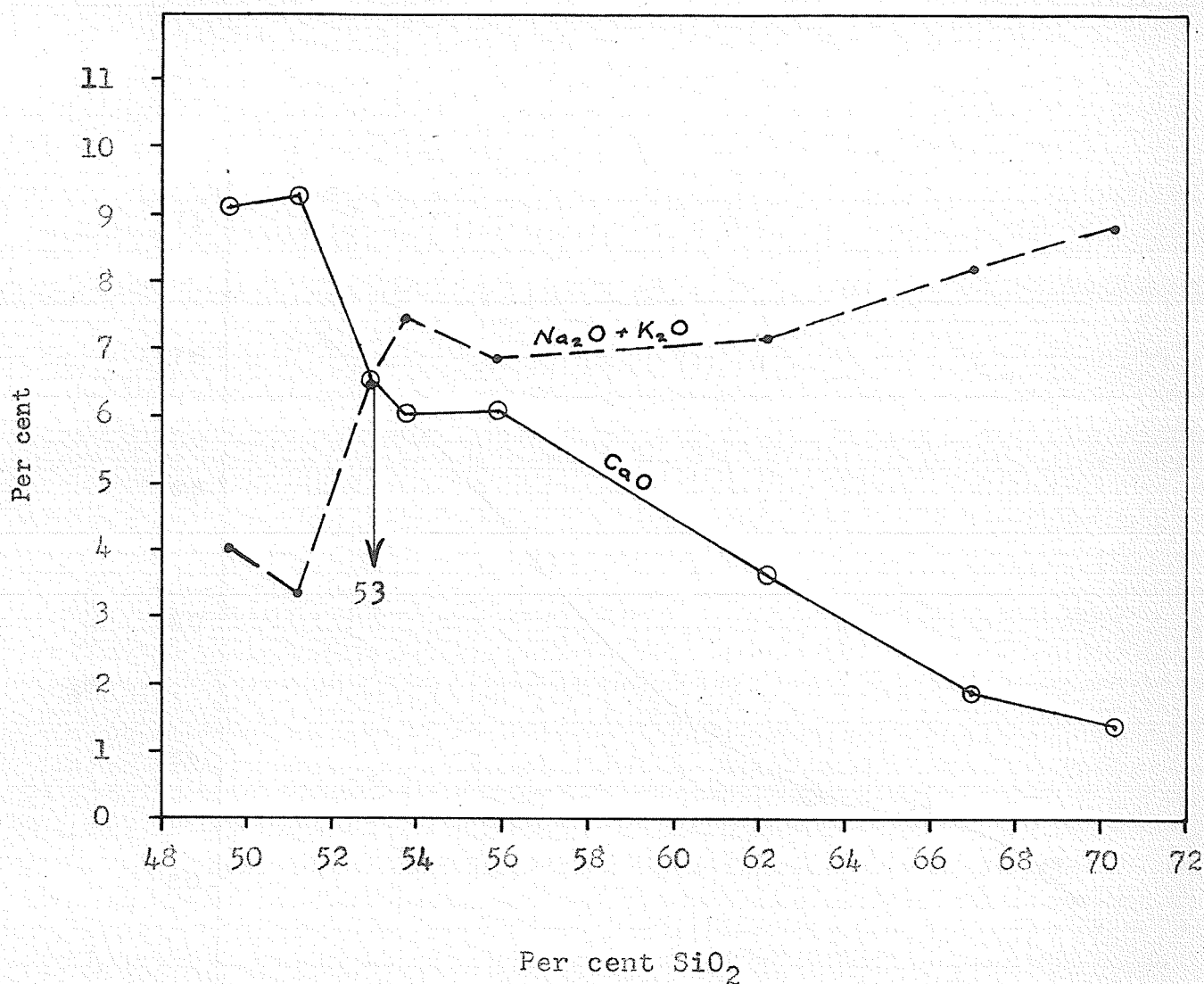
B. Alkali-lime index

Figure 17 is a plot of CaO and $(Na_2O + K_2O)$ against SiO_2 . These curves cross at a silica content of approximately 53 per cent. The value of the alkali-lime index is therefore 53, and corresponds to alkali-calcic in the Peacock classification (Peacock, 1931).

C. Relationship between silica content and specific gravity

Figure 18 is a plot of percentage silica against specific gravity for the chemically analyzed rock specimens. The relationship between these two variables is remarkable. All analyses fall on or almost on a smooth curve.

Silica content of a rock is a direct measure of its acid or basic nature, and should increase from base to top of a differentiated intrusion. Hence, the close relationship between silica content and specific gravity of



Peacock classification (Journal of Geology, 1931)-

-Alkalic < 51 < alkali-calcic < 56 < calc-alkalic < 61 < calcic -

Alkali-lime index of Granville Lake Gabbro = 53 = alkali-calcic.

Figure 17. Alkali-lime index of the Granville Lake Gabbro.

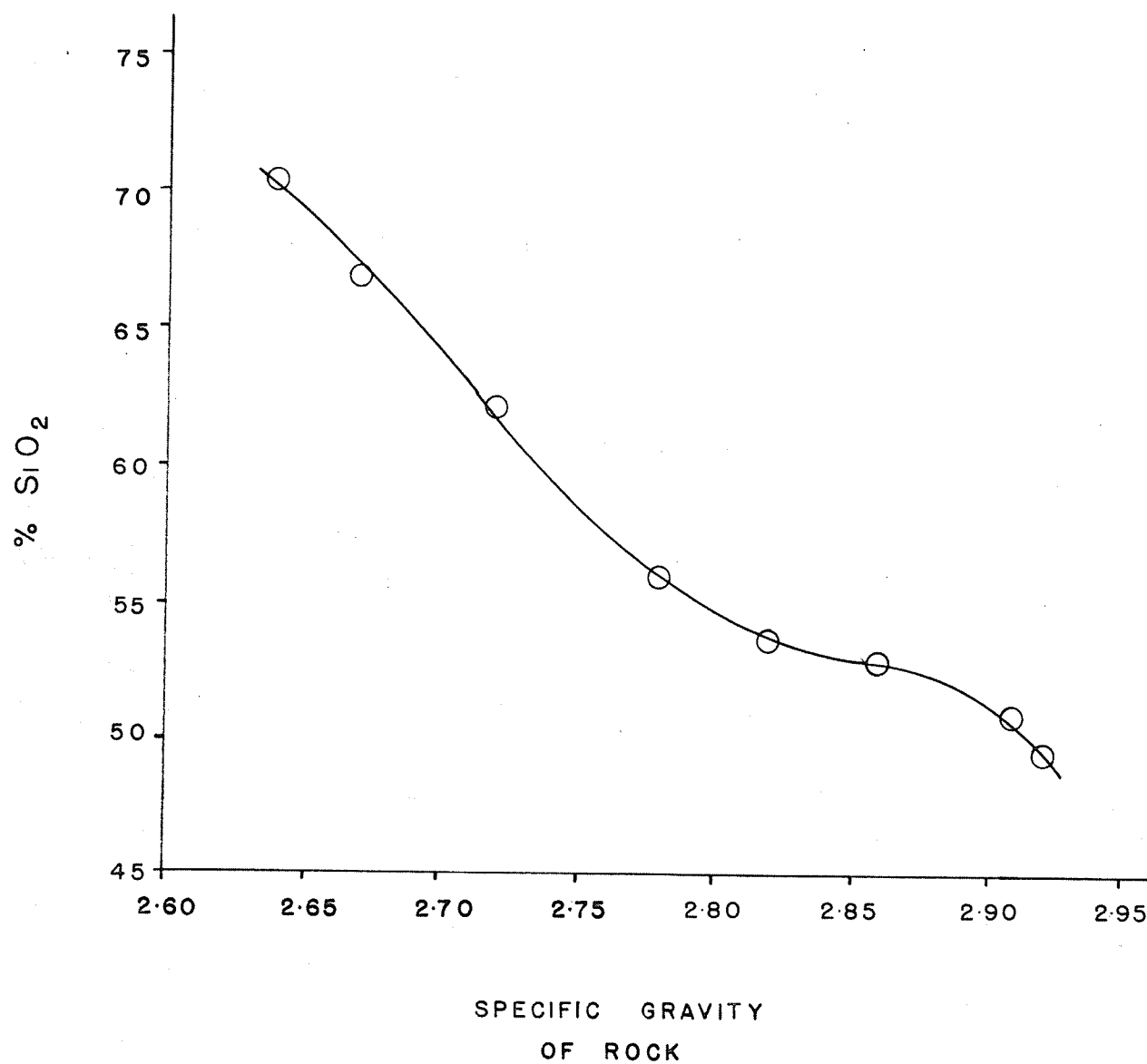
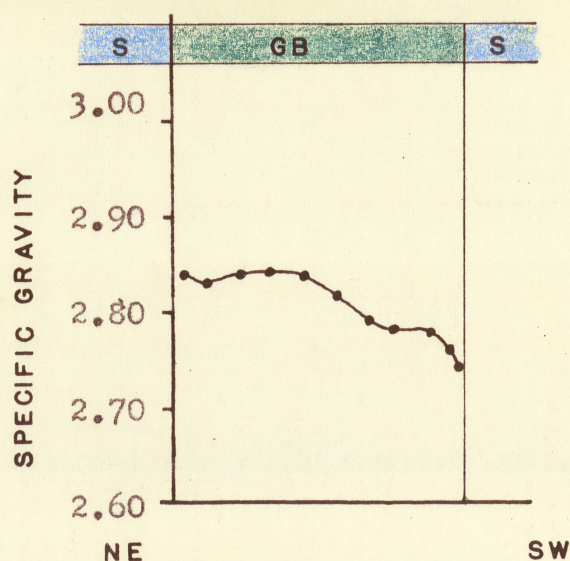
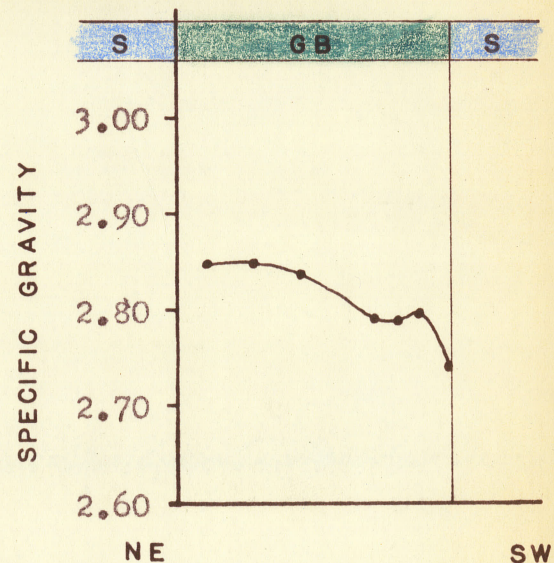
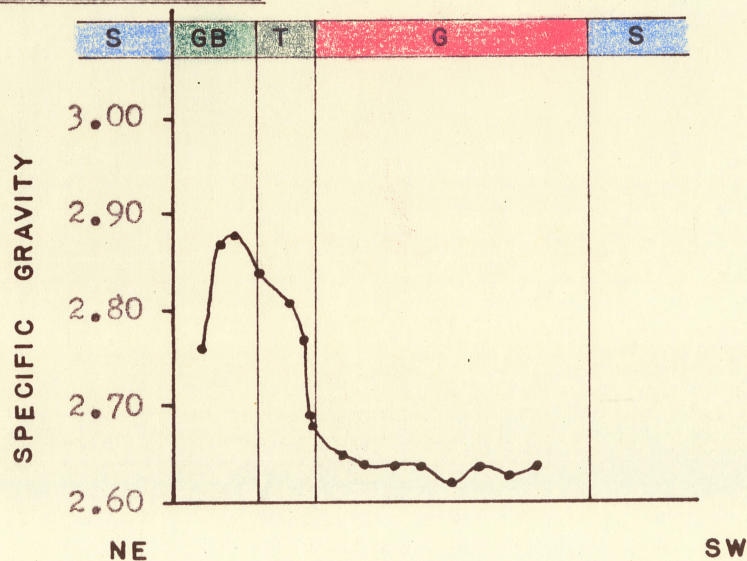


Figure 18. Relationship between silica content and specific gravity of chemically analyzed specimens, Granville Lake Gabbro.

specimens from the Granville Lake intrusion provides a valuable index to the differentiation of the intrusion. Specific gravity of any specimen is closely related to its silica content and provides therefore an easily determined index of differentiation. Approximately 450 specimens were collected in the field. Specific gravity was determined for each of these specimens, and specific gravity profiles plotted for each traverse. Figures 19 to 27 are specific gravity profiles across the Granville Lake intrusion. The various zones of the intrusion have been indicated at the top of each profile to permit comparison of specific gravity profiles to variation in rock type.

A typical traverse shows a relatively constant specific gravity in the gabbro zone, with a slightly lower value near the base of the intrusion. Commencing either in the upper part of the gabbro zone or in the transition zone, there is a relatively rapid but continuous decrease in specific gravity from perhaps 2.90 or 2.85, to about 2.70 or 2.65 at the place where the granite zone is reached. The decrease in specific gravity then becomes more gradual, and specific gravity becomes relatively constant at a value close to 2.62.

Differentiation of the satellite intrusion at the southeast end of the main intrusion was not recognized in

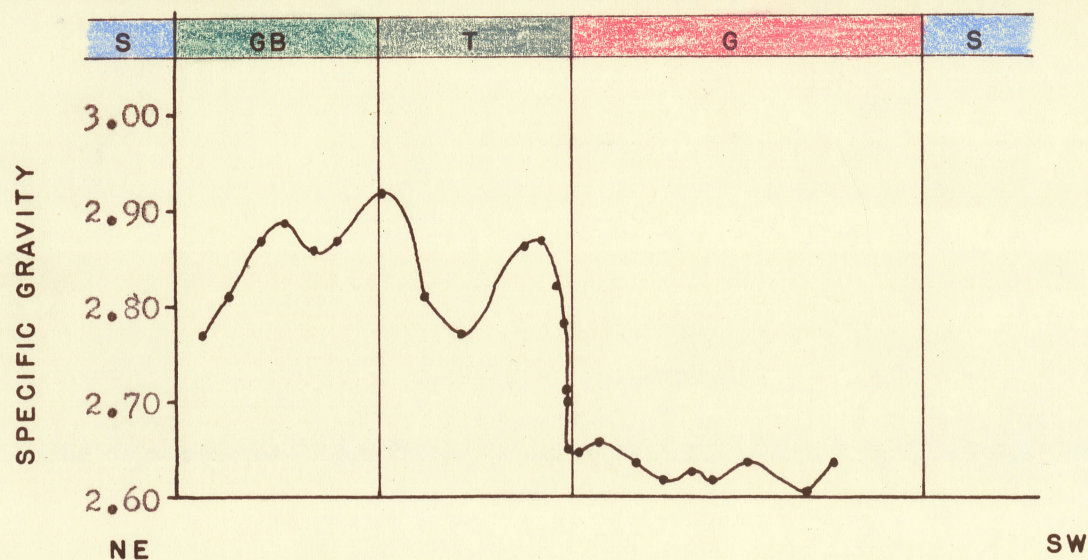
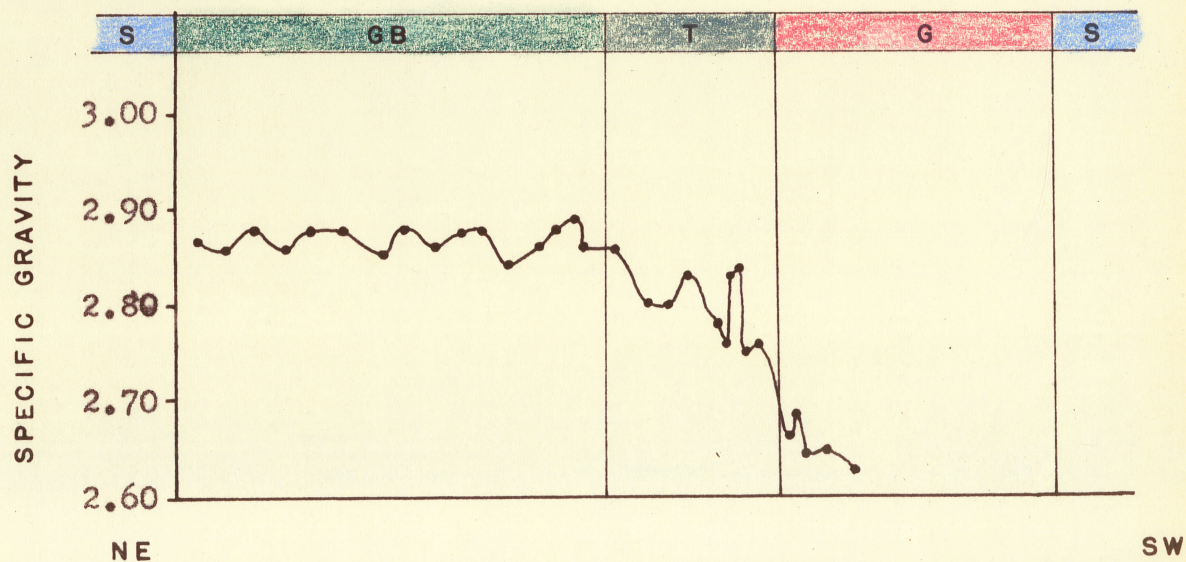
TRAVERSE C61-1123TRAVERSE C61-1096TRAVERSE CG 1LEGEND

S - Sediment GB - Gabbro T - Transition G - Granite

Horizontal Scale : 1 inch = $\frac{1}{4}$ mile

MILES
0 ——— 1/4

Figure 19. Specific gravity profiles across the Granville Lake Gabbro, traverses C61-1123, C61-1096, and CG 1.

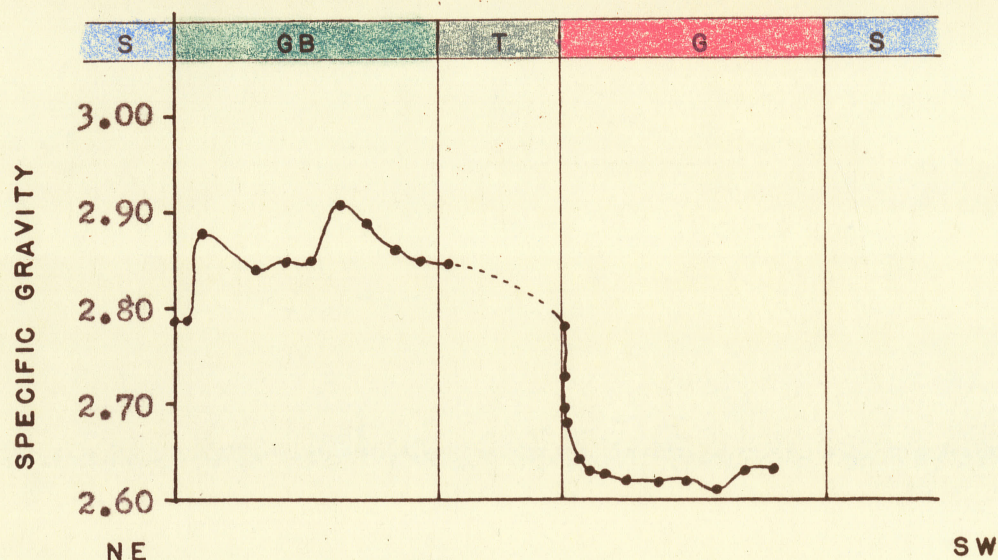
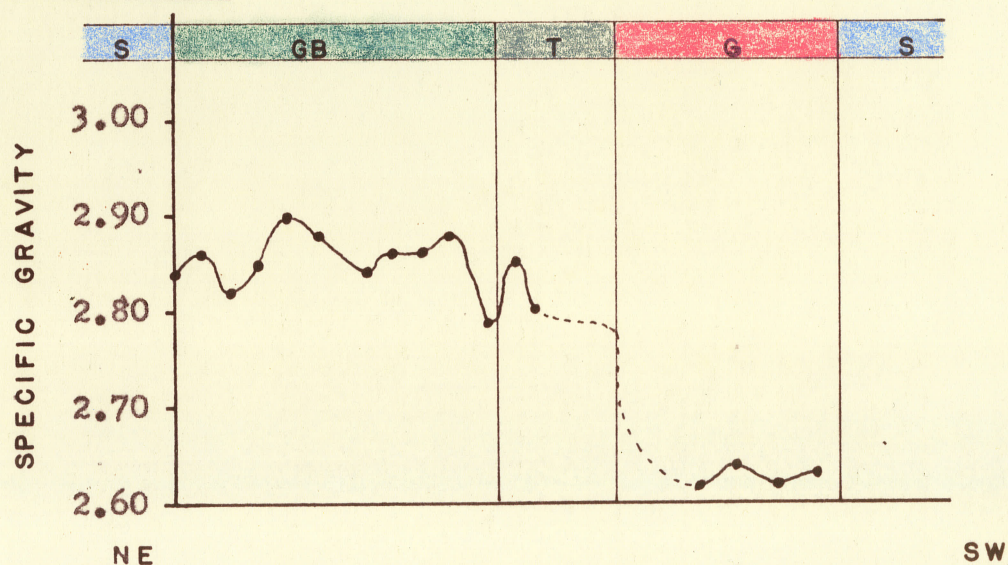
TRAVERSE CG 2TRAVERSE CG 3LEGEND

S - Sediment GB - Gabbro T - Transition G - Granite

Horizontal Scale : 1 inch = $\frac{1}{4}$ mile

MILES
0 1/4

Figure 20 . Specific gravity profiles across the Granville Lake Gabbro, traverses CG 2 and CG 3.

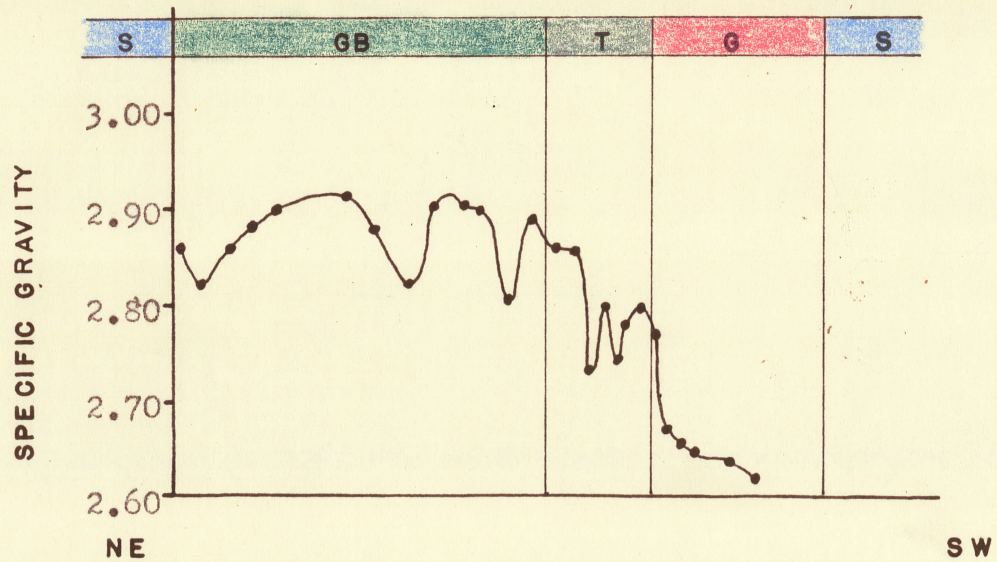
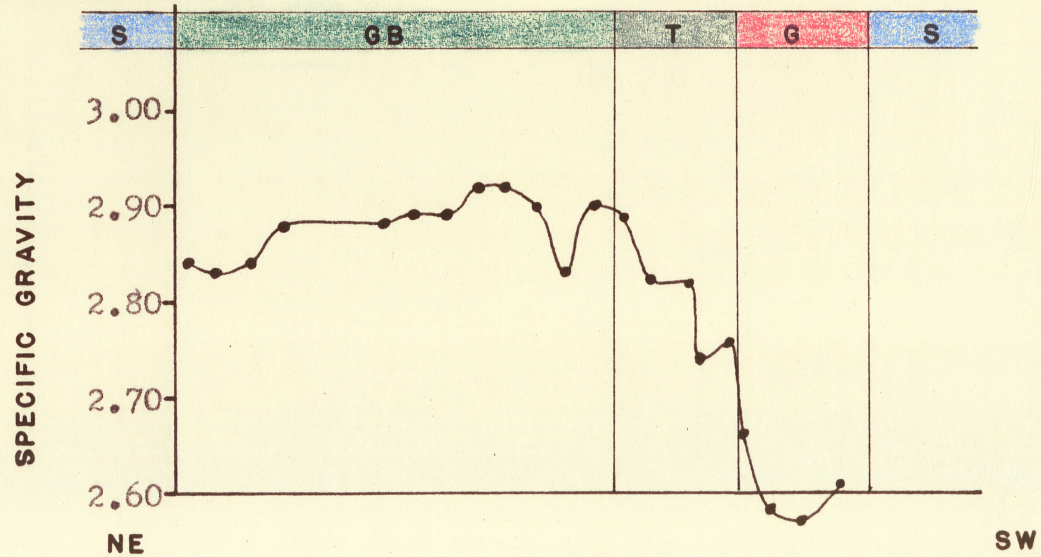
TRAVERSE CG 4TRAVERSE CG 5LEGEND

S - Sediment GB - Gabbro T - Transition G - Granite

Horizontal Scale : 1 inch = $\frac{1}{4}$ mile

MILES
0 1/4

Figure 21. Specific gravity profiles across the Granville Lake Gabbro, traverses CG 4 and CG 5.

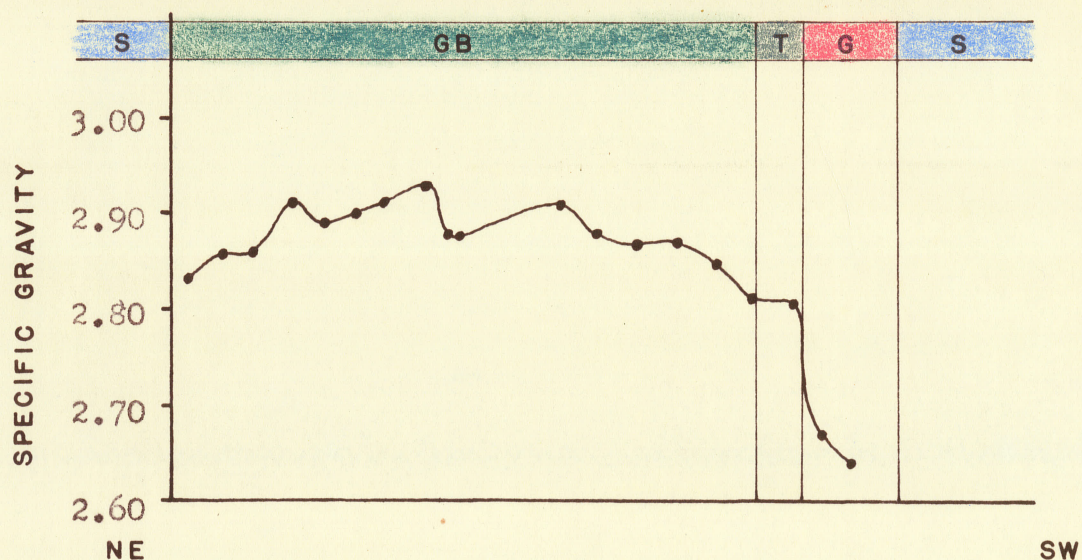
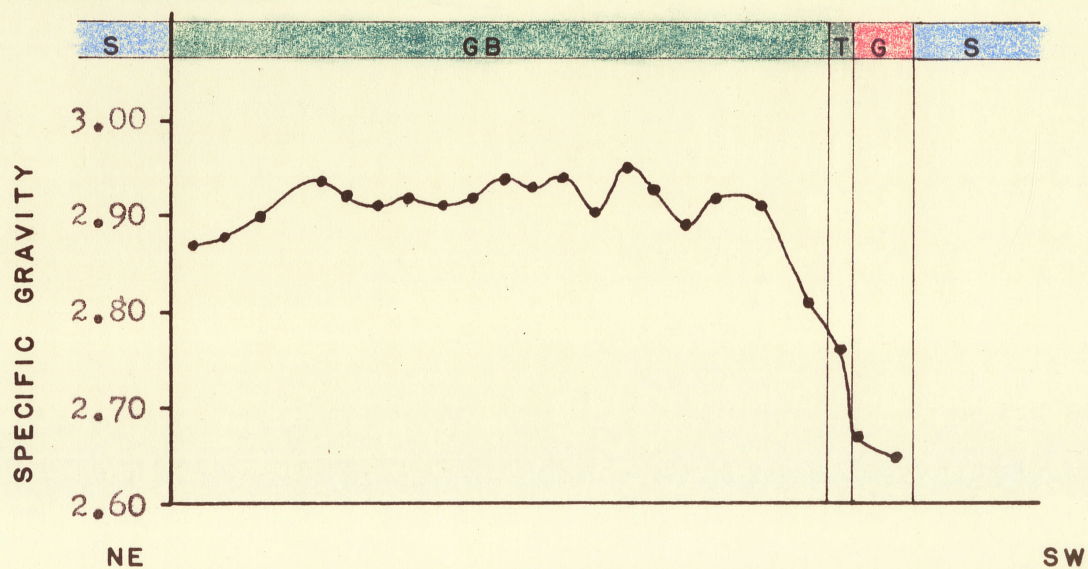
TRAVERSE CG 6TRAVERSE CG 7LEGEND

S - Sediment **GB** - Gabbro **T** - Transition **G** - Granite

Horizontal Scale : 1 inch = $\frac{1}{4}$ mile

MILES
0 $\frac{1}{4}$

Figure 22. Specific gravity profiles across the Granville Lake Gabbro, traverses CG 6 and CG 7.

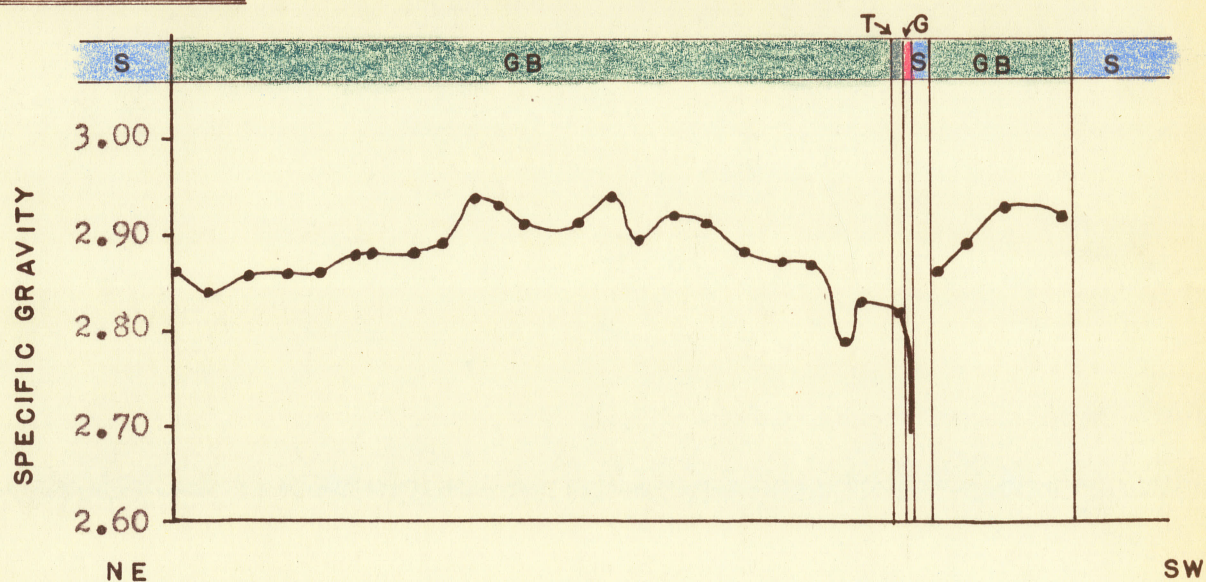
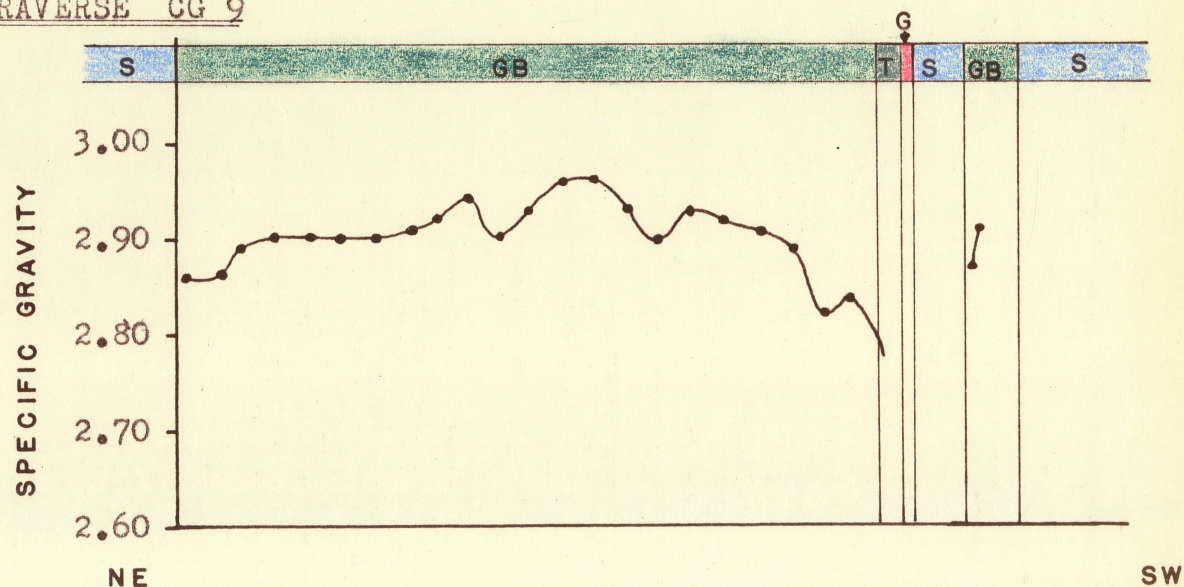
TRAVERSE CG 22TRAVERSE CG 23LEGEND

S - Sediment GB - Gabbro T - Transition G - Granite

Horizontal Scale : 1 inch = $\frac{1}{4}$ mile

MILES
0 ——— 1/4

Figure 23. Specific gravity profiles across the Granville Lake Gabbro, traverses CG 22 and CG 23.

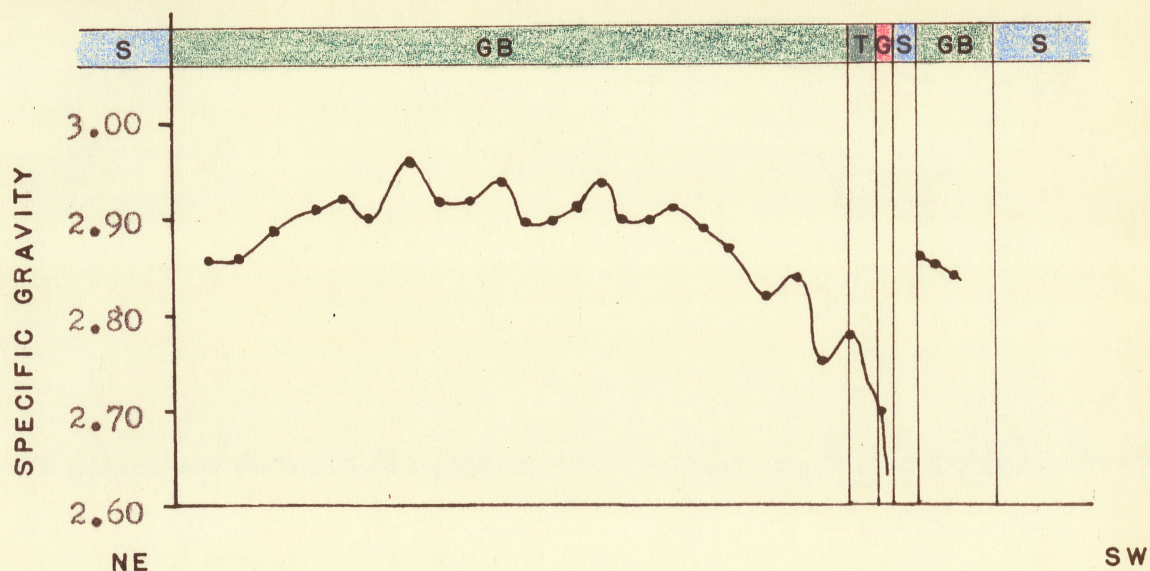
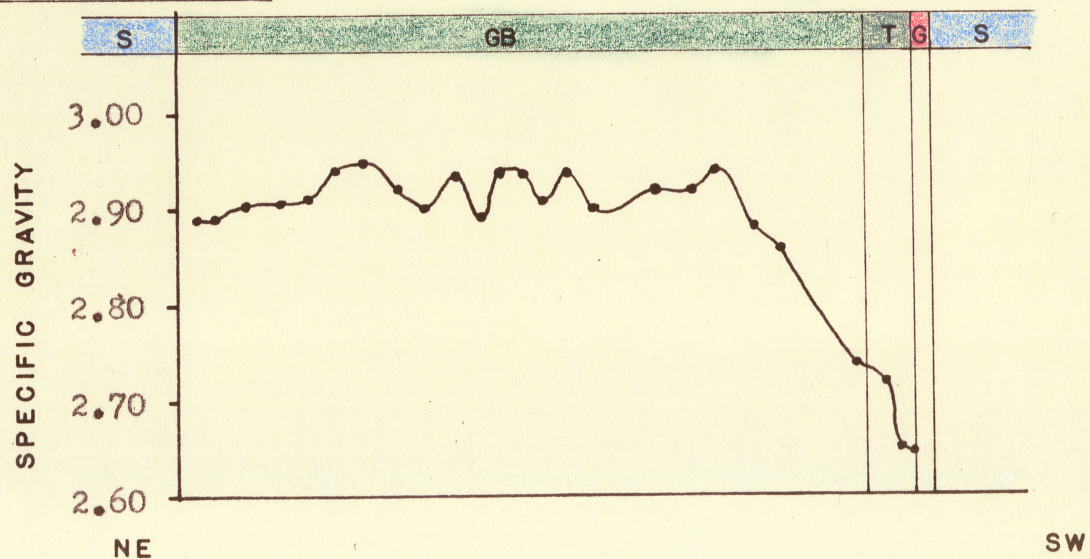
TRAVERSE CG 8TRAVERSE CG 9LEGEND

S - Sediment GB - Gabbro T - Transition G - Granite

Horizontal Scale : 1 inch = $\frac{1}{4}$ mile

MILES
0 1/4

Figure 24. Specific gravity profiles across the Granville Lake Gabbro, traverses CG 8 and CG 9.

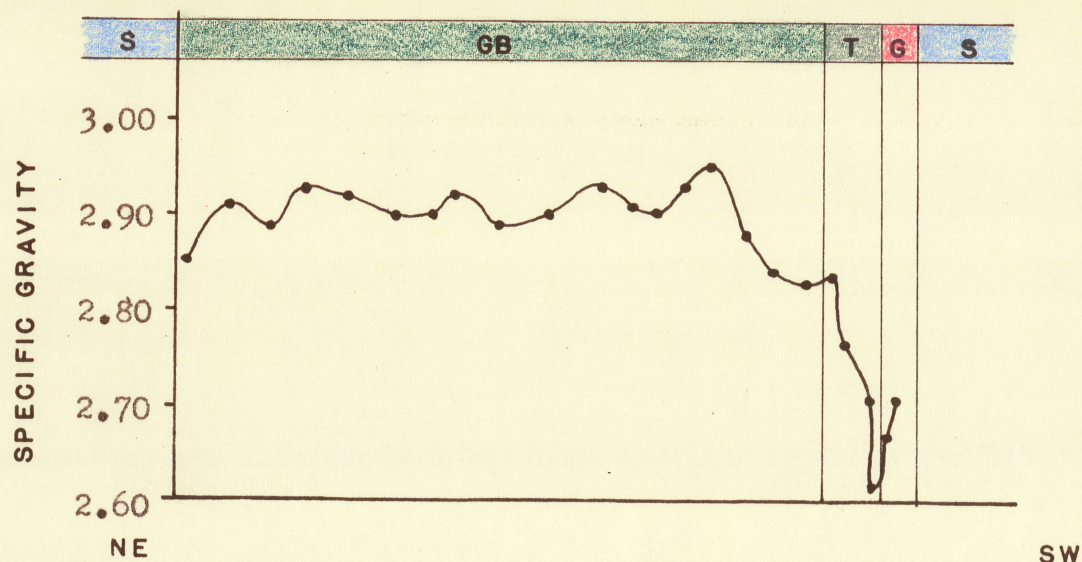
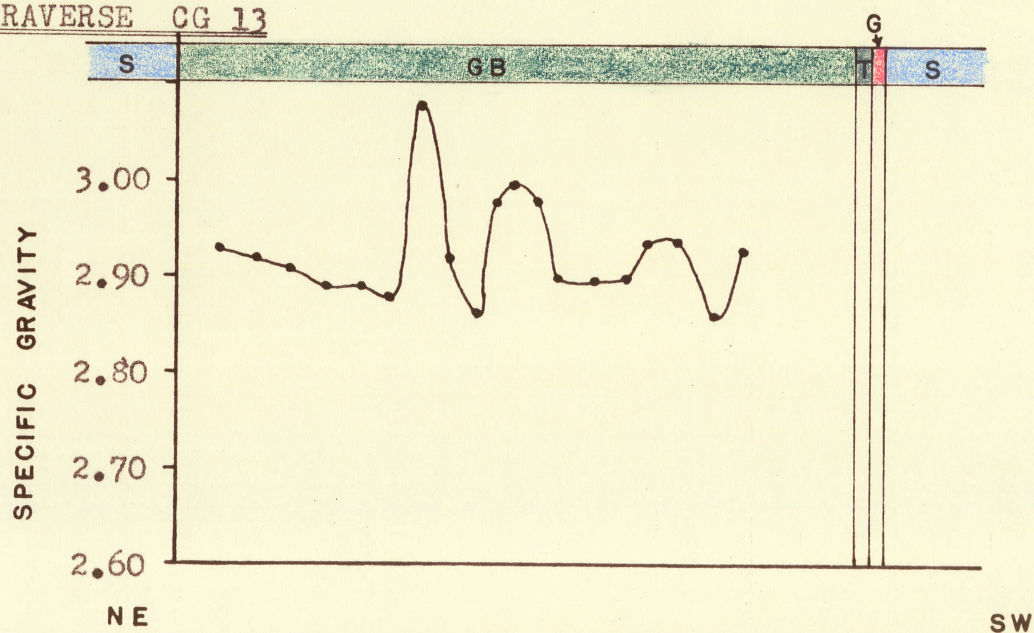
TRAVERSE CG 10TRAVERSE CG 11LEGEND

S - Sediment GB - Gabbro T - Transition G - Granite

Horizontal Scale : 1 inch = $\frac{1}{4}$ mile

MILES
0 1/4

Figure 25. Specific gravity profiles across the Granville Lake Gabbro, traverses CG10 and CG 11.

TRAVERSE CG 12TRAVERSE CG 13LEGEND

S - Sediment **GB** - Gabbro **T** - Transition **G** - Granite

Horizontal Scale : 1 inch = $\frac{1}{4}$ mile

MILES
0 $\frac{1}{4}$

Figure 26. Specific gravity profiles across the Granville Lake Gabbro, traverses CG12 and CG 13.

the field. However, the specific gravity profiles for traverses C 61-1123 and C 61-1096 indicate that the base of this intrusion has a specific gravity of about 2.85, which gradually decreases to a value of 2.72 at the top. Differentiation of the other satellite intrusions is not well developed, presumably because of their rather rapid loss of heat to the surrounding colder sediments, and consequent rapid crystallization.

Map 2 (in pocket) is a specific gravity contour map for the Granville Lake intrusion and should indicate variation in silica content. The upward tilt of the present southeast end of the intrusion during cooling is evident from this map. Rocks of highest specific gravity are concentrated near the northwest end of the intrusion.

Along the lower gabbro-sediment contact of the main intrusion, a zone of lower specific gravity is evident. This zone is believed to represent a "chill" zone which either crystallized relatively rapidly, or else cooled to an extremely viscous magma before the processes of differentiation began. Little evidence of chilling is visible in rocks from the base of the gabbro zone, with the exception of a possibly slightly smaller grain size. There is no evidence of chilling along the upper contact of the main intrusion. However, it is probable that if a chilled zone

were originally formed, it was soon remelted by upward dissipation of heat from the intrusion or disappeared by reaction with later granitic liquid. Emslie found a similar "chill" zone along the base of the Lynn Lake Gabbro, and this intrusion also lacked a chilled zone along its roof.

The specific gravity of the gabbro zone is remarkably uniform. This uniformity indicates that crystallization of plagioclase, pyroxene, and possibly amphibole began almost simultaneously, with the relative proportion of feldspar to the two ferromagnesian minerals remaining more or less constant until crystallization of the gabbro zone was almost complete. If one of these minerals had begun to crystallize before the other, then the specific gravity of the gabbro zone would not be so uniform, and a compositional banding would be evident in the field. There is a possibility that the rocks of lower specific gravity along the base of the intrusion indicate that crystallization of plagioclase was more rapid than crystallization of amphibole in the earliest stages of differentiation. The lower specific gravity of these rocks is in part due to a slightly high plagioclase and a slightly low amphibole content. This could be attributed either to chilling and crystallization without differentiation of primary magma, or else to enrichment of plagioclase in the earliest crystal differentiate

to form. Further evidence on the nature of this zone of low specific gravity is provided by plagioclase composition determinations as presented in figures 34 and 35.

If plagioclase were the first mineral to crystallize and settled to the base of the intrusion, it would be expected that the outer rims of zoned grains would have a relatively high content of the anorthite molecule in the immediate basal zone of the intrusion. A gradual decrease in anorthite content of the rims would be expected from base to top of the gabbro zone.

On the other hand, if undifferentiated primary magma were cooled relatively quickly near the base of the intrusion, and as a result became viscous enough so that little or no crystal settling with resultant separation of a more sodic differentiate could occur, it would be expected that rims of zoned plagioclase grains in this chilled zone would be more sodic than those formed by differentiation involving separation of a more sodic differentiate from rocks immediately above the chilled zone. Plagioclase composition determinations from traverses CG 6 and CG 11, the only traverses with sufficient determinations near the base of the intrusion, suggest that anorthite content of grain cores is identical near the base of the intrusion and higher up, but that grain rims near the base are more sodic than those

somewhat higher in the intrusion. This would indicate that the zone of lower specific gravity along the base has formed by relatively rapid cooling and crystallization of primary magma, rather than by differentiation and accumulation of early plagioclase crystals. This implies that the basal gabbro zone rocks are indicative of the primary magma composition. It is of interest to note that the average specific gravity of this basal zone is approximately 2.85 or 2.86, whereas the average specific gravity of the 448 specimens collected from the Granville Lake Gabbro is 2.84. It is probable that the zone of lower specific gravity represents a chilled zone.

D. Differentiation in the satellite intrusions

Differentiation in the satellite intrusions is evident only in the satellite at the southeast end of the main intrusion. Satellite intrusions are all chilled and finer grained than the main intrusion, and the southeast satellite is no exception. As a result, differentiation in this satellite is not as pronounced as that of the main body. The uppermost rocks are fine grained, and intermediate between those of the transition and granite zones of the main intrusion.

E. Indices of differentiation

The value of the ratio $\frac{K_2O + Na_2O}{CaO + K_2O + Na_2O}$ is commonly used as an index of differentiation, and is known as the felsic index. Similarly, the value of the ratio $\frac{FeO + Fe_2O_3}{MgO + FeO + Fe_2O_3}$ is commonly used for the same purpose, and is known as the mafic index. The ratio $\frac{MgO}{MgO + SiO_2}$ is also used as a mafic index of differentiation.

Figures 28, 29, and 30 illustrate the relationship between specific gravity and the respective differentiation indices for the Granville Lake intrusion. These diagrams confirm the usefulness of specific gravity in determining the degree of fractionation or index of differentiation of any specimen.

Colour index was determined from modal analyses. Because of the complete lack of rhythmic banding in the Granville Lake intrusion, colour index can probably be used as a rough index of differentiation. Figure 31 shows the relationship between colour index and rock specific gravity for the intrusion.

Figure 32 is a plot of the percentage of plagioclase, amphibole (hornblende), and quartz plus microcline, for

TABLE 5

Specific gravity and differentiation indices of chemically analyzed
specimens from the Granville Lake Gabbro

	<u>CG 10-5</u>	<u>CG 15-17</u>	<u>CG 9-25</u>	<u>CG 2-14</u>	<u>CG 10-23</u>	<u>CG 12-21</u>	<u>CG 6-22</u>	<u>CG 6-25</u>
Specific gravity of specimen	2.92	2.91	2.86	2.82	2.78	2.71	2.67	2.64
$\frac{K_2O + Na_2O}{CaO + K_2O + Na_2O}$	.308	.265	.496	.557	.528	.664	.814	.862
$\frac{FeO + Fe_2O_3}{FeO + Fe_2O_3 + MgO}$	.653	.655	.755	.757	.689	.747	.985	.993
$\frac{MgO}{MgO + SiO_2}$	.090	.084	.055	.054	.058	.032	.0015	.0004

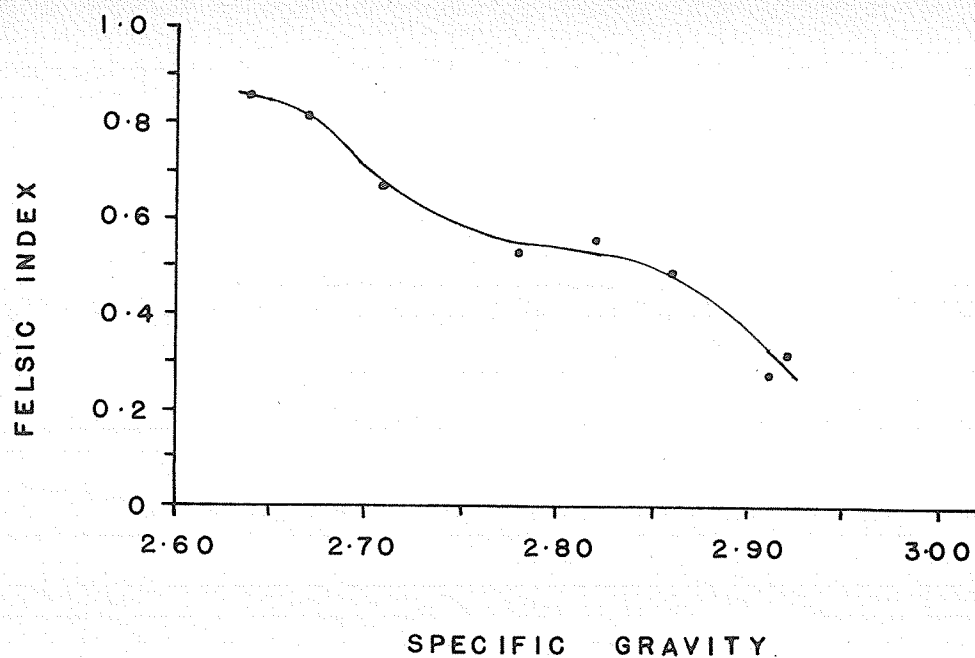


Figure 28. Relationship between the felsic index $\frac{K_2O + Na_2O}{CaO + K_2O + Na_2O}$ and specific gravity of analyzed specimens of the Granville Lake Gabbro.

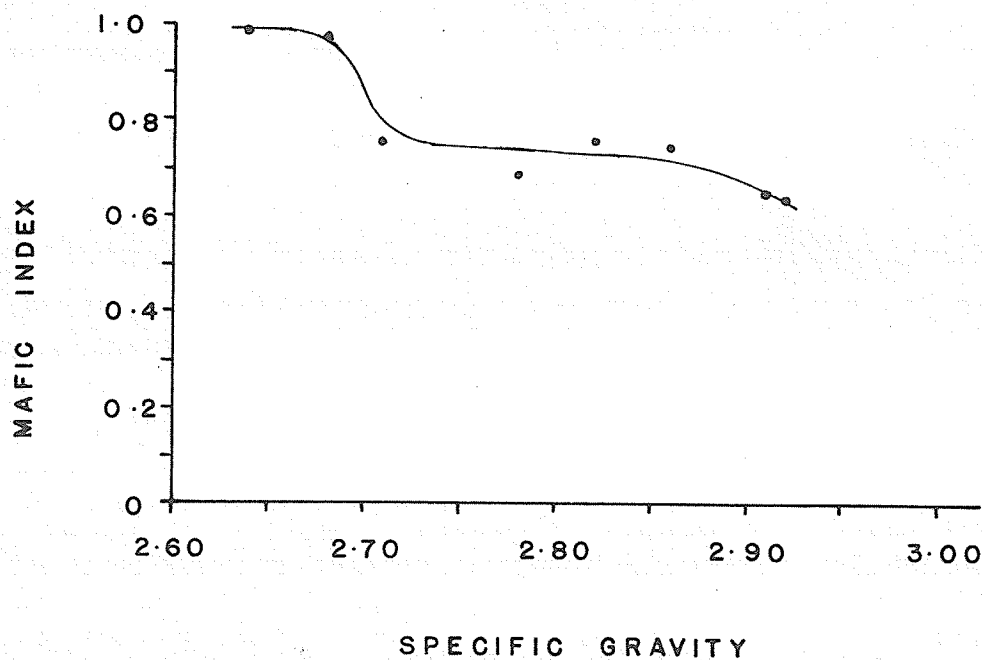


Figure 29. Relationship between the mafic index $\frac{FeO + Fe_2O_3}{FeO + Fe_2O_3 + MgO}$ and specific gravity of analyzed specimens of the Granville Lake Gabbro.

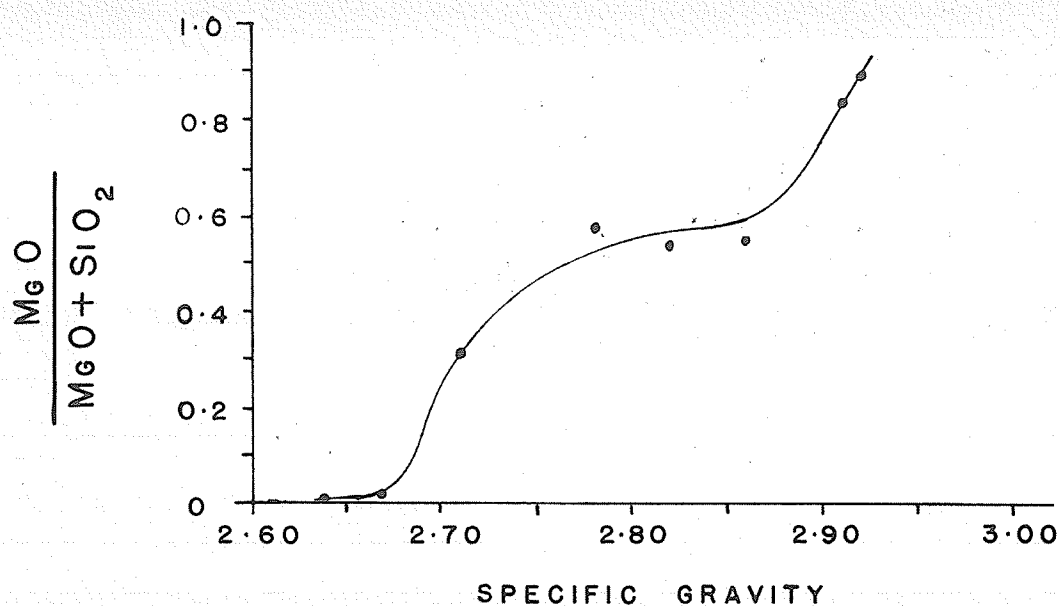


Figure 30. Relationship between the mafic index $\frac{\text{MgO}}{\text{MgO} + \text{SiO}_2}$ and specific gravity of specimens of the Granville Lake Gabbro.

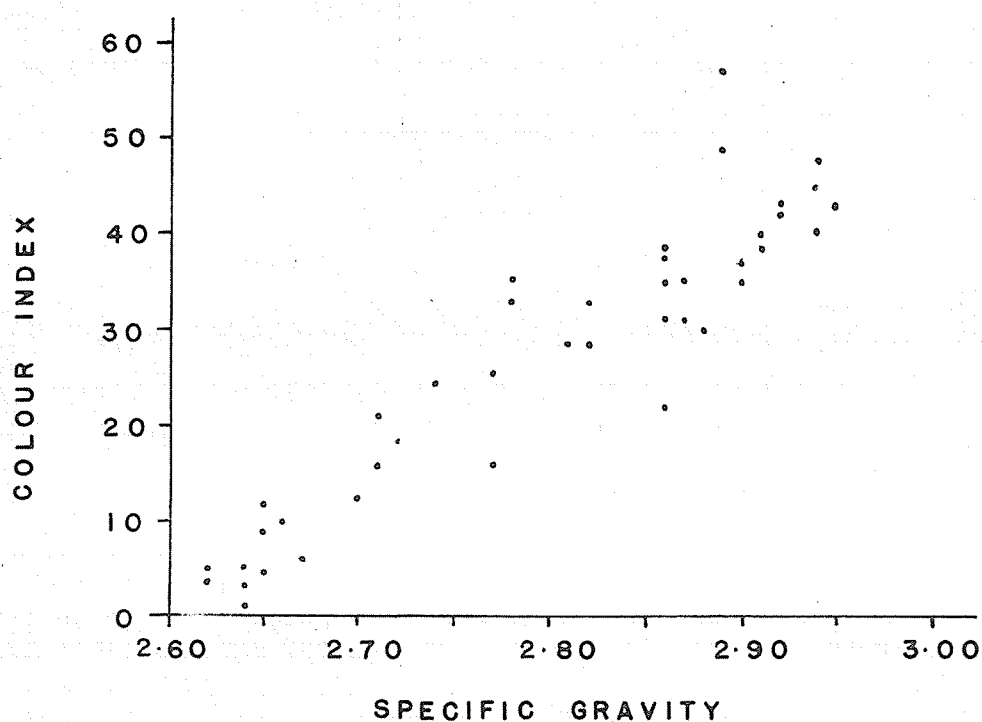


Figure 31. Relationship between colour index and specific gravity of specimens of the Granville Lake Gabbro.

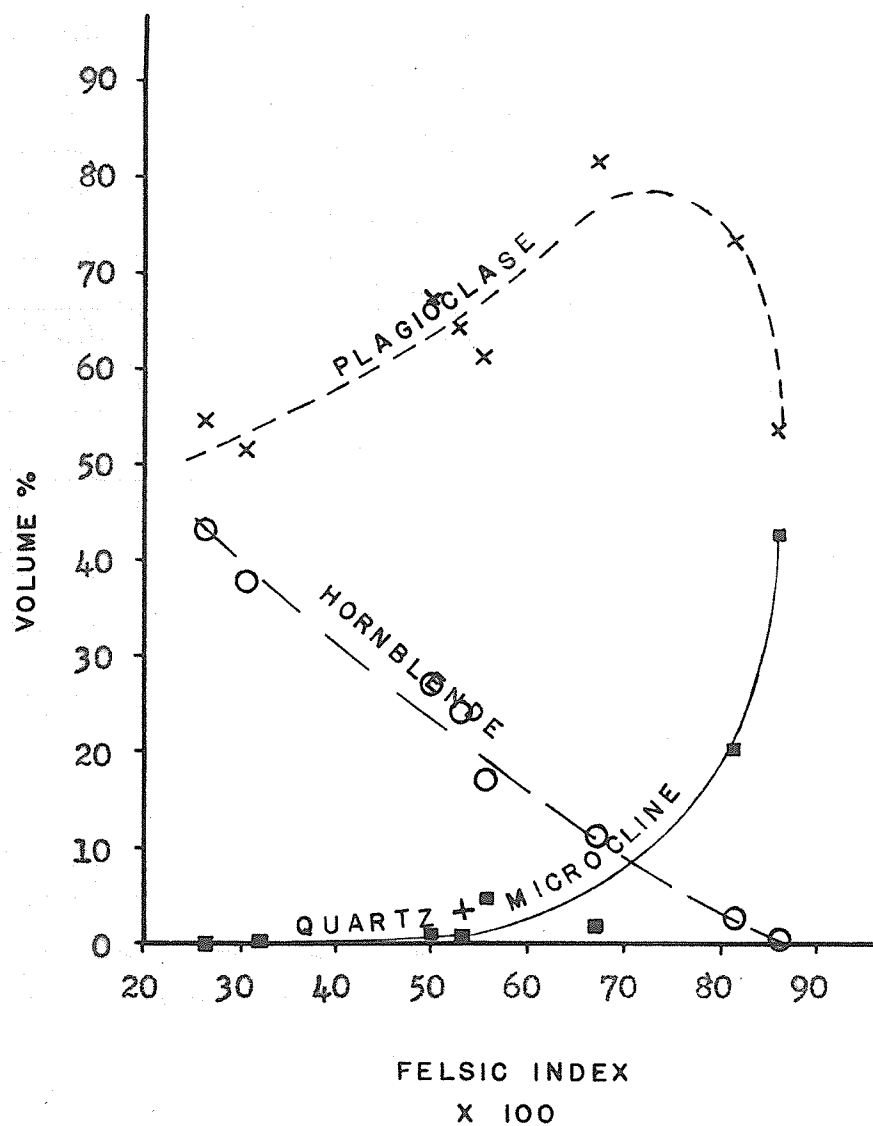


Figure 32. Volume % of the minerals plotted against the felsic index $\frac{K_2O + Na_2O}{CaO + K_2O + Na_2O}$, Granville Lake Gabbro.

chemically analyzed specimens of the Granville Lake Gabbro. Amphibole decreases regularly, and quartz plus microcline increase regularly with increasing felsic index. Plagioclase content increases at first, but decreases sharply in the two granite specimens; this corresponds to the sudden increase in quartz plus microcline.

Variation in plagioclase composition

Plagioclase composition was determined for twenty-six specimens using the universal stage, by determination of the maximum extinction angle on (010). Compositions are listed in table 1. Because of the strong zoning, it is possible that more calcic plagioclase may exist in any specimen of the transition zone and particularly the gabbro zone. It is doubtful, however, that any major error has been incurred. The location of each specimen for which a determination was made is shown in figure 33. Figures 34 and 35 illustrate the variation in plagioclase composition on traverses CG 23, 11, 2, and 6. It was not possible to determine the composition of the plagioclase in each thin section for these traverses. In some specimens saussuritization prevented composition determination. It was impossible to determine the maximum compositional range of the zoned plagioclase in many sections with any degree of assurance, because the sections contained an insufficient number of suitable plagioclase grains.

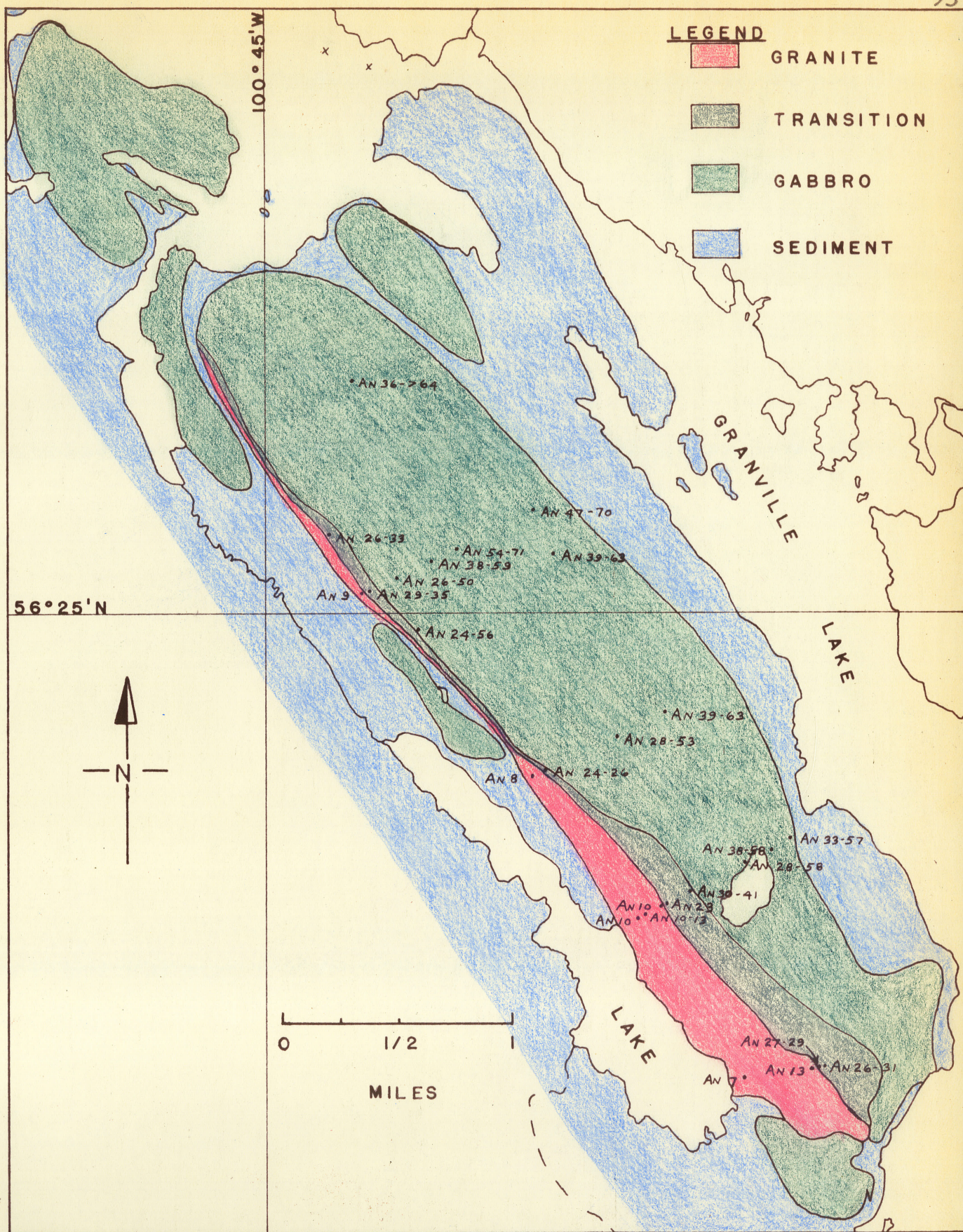
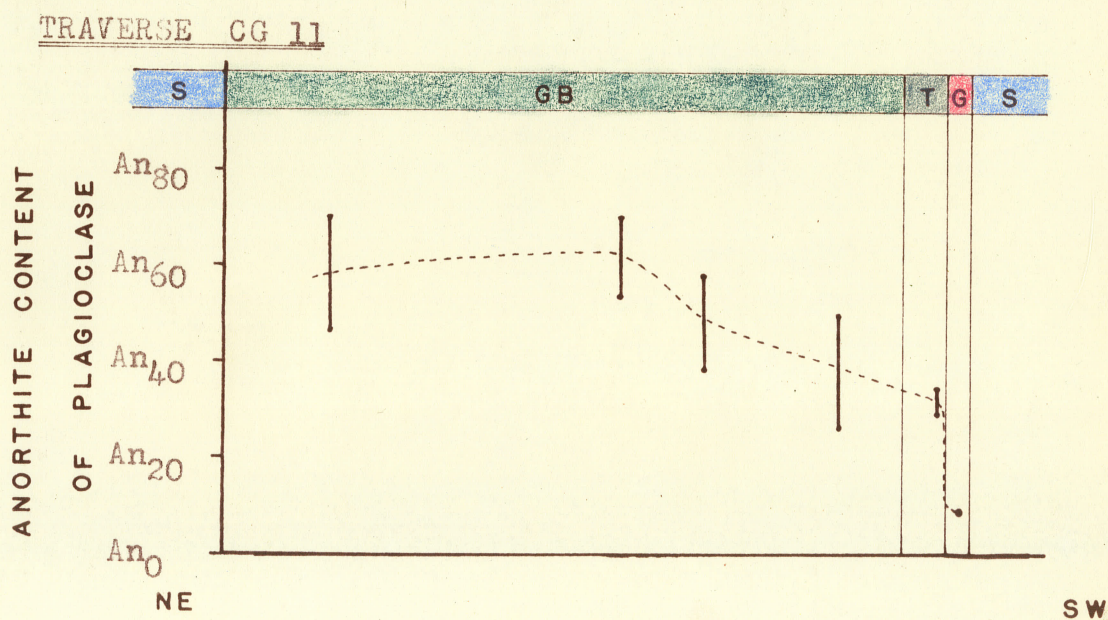
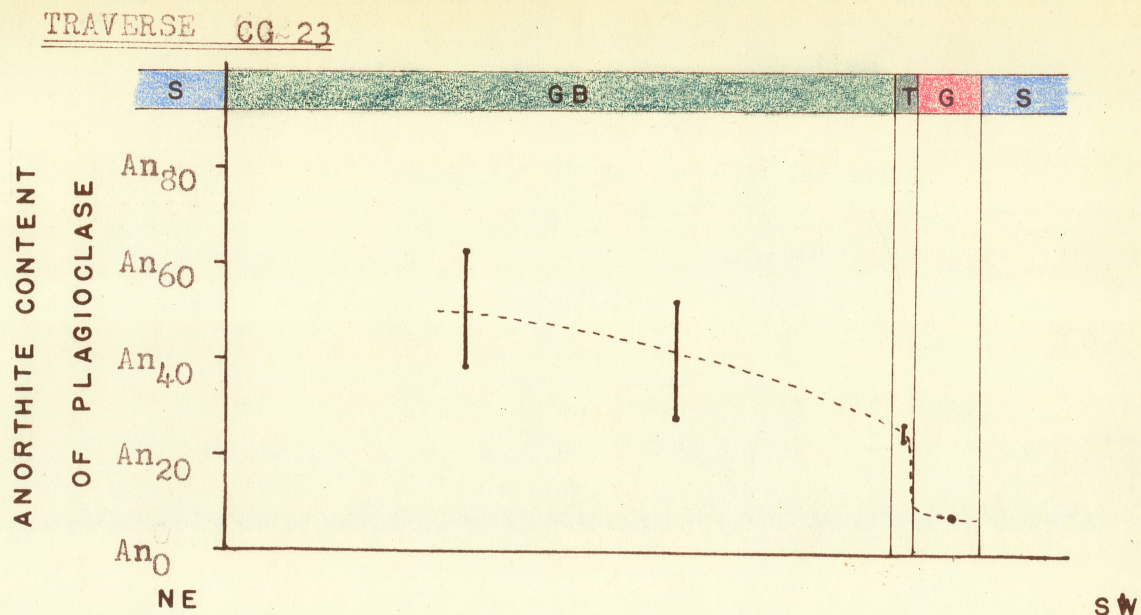


Figure 33. Plagioclase composition; Granville Lake Gabbro.



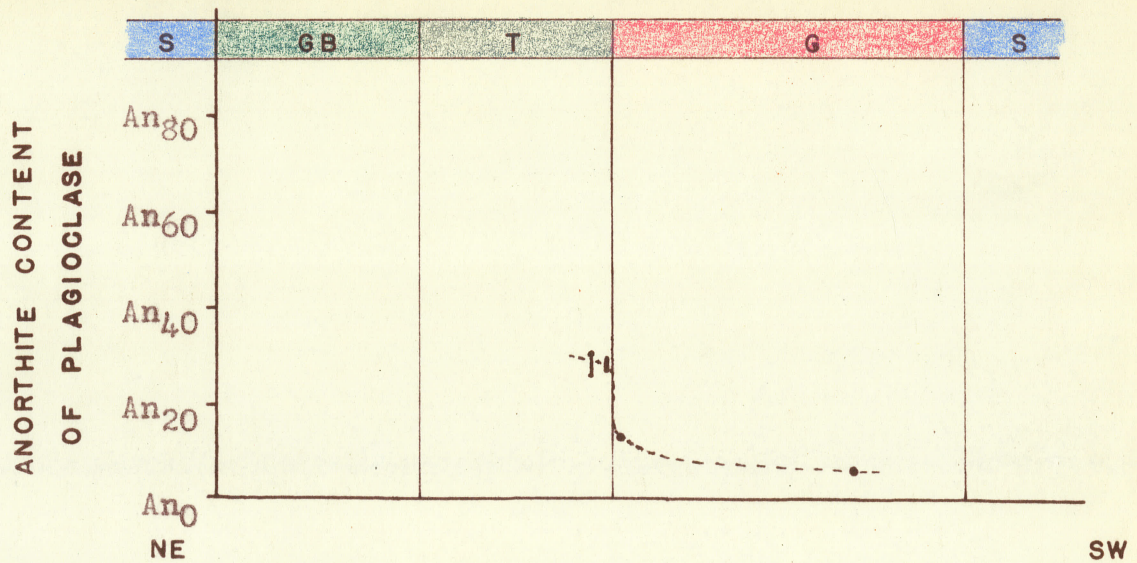
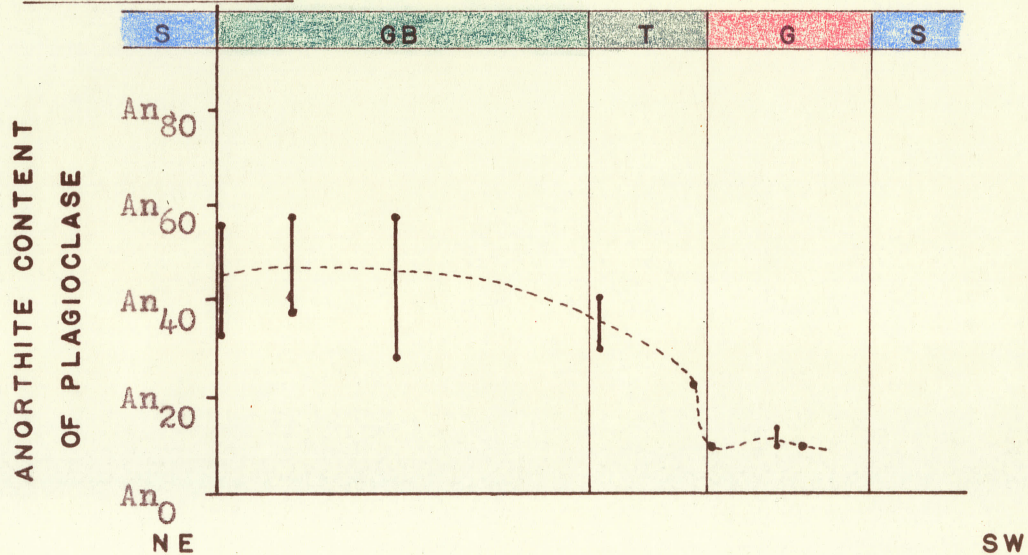
LEGEND

S - Sediment GB - Gabbro T - Transition G - Granite

Horizontal Scale : 1 inch = $\frac{1}{4}$ mile

MILES
0 1/4

Figure 34. Variation in anorthite content of plagioclase across the Granville Lake Gabbro, traverses CG 23 and CG 11.

TRAVERSE CG 2TRAVERSE CG 6LEGEND

S - Sediment GB - Gabbro T - Transition G - Granite

Horizontal Scale : 1 inch = $\frac{1}{4}$ mile

MILES
0 ——— 1/4

Figure 35. Variation in anorthite content of plagioclase across the Granville Lake Gabbro, traverses CG 2 and CG 6.

Doubtful determinations are not included in the table or illustrations.

Plagioclase composition is relatively constant on any one traverse in the lower one-half to two-thirds of the gabbro zone. Anorthite content gradually decreases through the upper portion of the gabbro zone and the transition zone, with a sharp decrease at the boundary between the transition and granite zones. A gap in the plagioclase composition range is evident at this boundary; plagioclases between An_{23} and An_{13} were not found. This may be an actual gap, or it may be due to lack of a sufficient number of closely spaced thin sections from the transition and granite zones immediately adjacent to the boundary. Optical data on plagioclases presented by Collins (1934) indicates that a compositional gap of An_{25} to An_{12} ^{may} exist between the transition and micropegmatite zones of the Sudbury intrusion. Similarly, for the Skaergaard intrusion, Wager and Deer (1939) report a normative plagioclase composition of An_{20} in specimen 3047 (hedenbergite granophyre), and of An_9 in specimen 3058 (transgressive acid granophyre) the next differentiate to have formed, with no plagioclase between these compositions. These are normative rather than optical compositions. Table III (Wager and Deer, pp.68-69) shows that normative plagioclase compositions for the Skaergaard rocks are closely related to the actual compositions. The normative and

modal analyses correspond closely in the hedenbergite granophyre, and it is therefore probable that the actual plagioclase composition is virtually the same as the normative composition. Plagioclase is the only mineral in the acid granophyre to incorporate the soda and lime indicated by the analysis; therefore the normative plagioclase composition must represent actual plagioclase composition. The sharp change in plagioclase composition observed between the transition and granite zones of the Granville Lake intrusion is apparently not unique.

Anorthite content of plagioclase generally increases in the gabbro zone of the Granville Lake Gabbro, proceeding from southeast to northwest (figure 33). This corresponds to the general increase in specific gravity which is evident in the specific gravity contour map (map 2).

The relationship between plagioclase composition and rock specific gravity is illustrated in figure 36. An abrupt change in anorthite content of plagioclase from approximately An_{23} to An_{13} is evident over the small specific gravity range of 2.71 to 2.68; this change is the compositional gap found at the transition zone - granite zone boundary. It may be determined from the curve illustrating the relationship between silica content and specific gravity (figure 18) that specific gravities of 2.71 and 2.68 correspond to

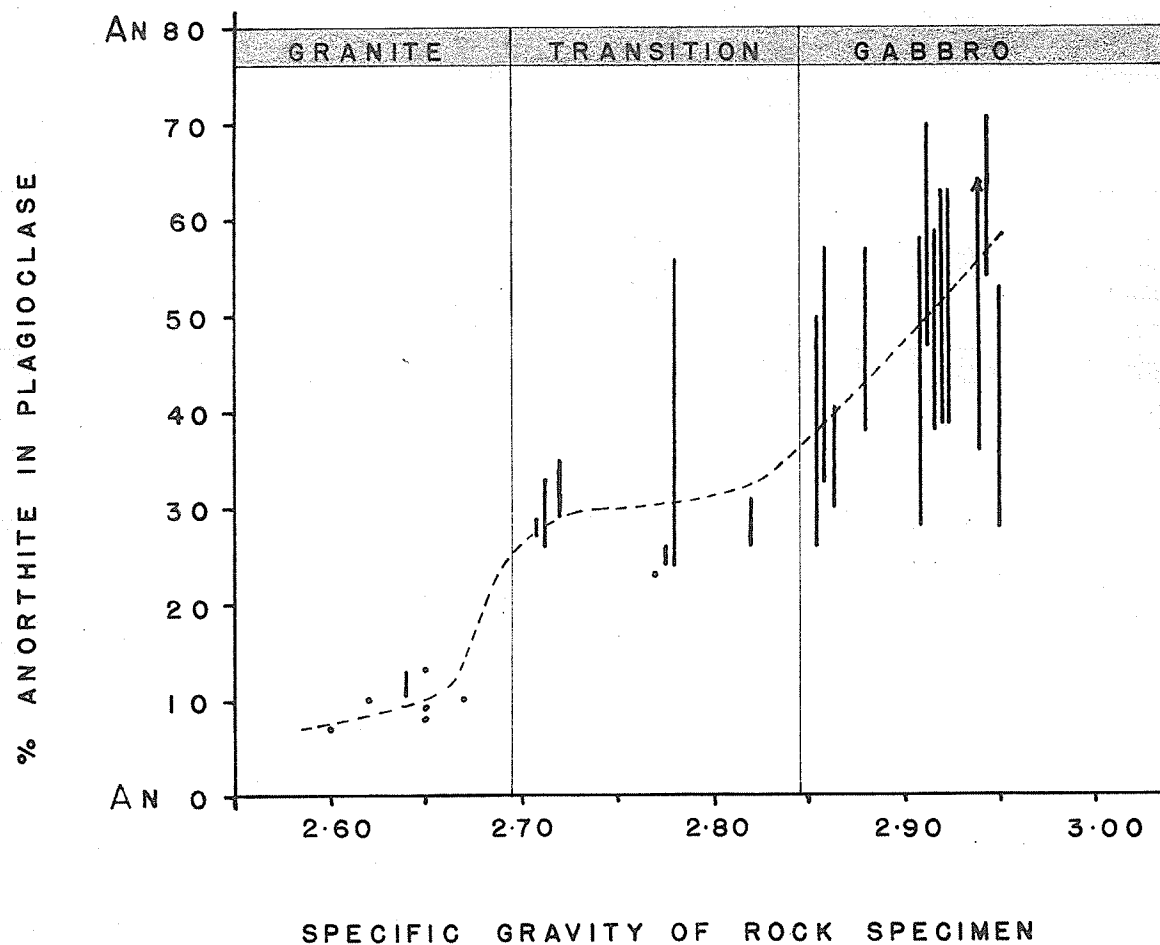


Figure 36. Plagioclase composition or range in composition plotted against specific gravity of rock specimen, Granville Lake Gabbro. The figure also indicates variation in rock type with specific gravity.

SiO₂ contents of 63 and 66 per cent respectively. In other words, at this boundary a change in silica content from 63 per cent in the transition zone to 66 per cent in the granite zone is accompanied by an abnormally sharp decrease in anorthite content of plagioclase from approximately An₂₃ to An₁₃. The cause is unknown.

Origin of the granitic and transitional phases of the intrusion

Differentiation in place of an original gabbroic magma seems to be the most probable explanation of all the features of the Granville Lake Gabbro. However, consideration must be given to all possible origins for the various zones of the intrusion. These are as follows:

- (1) Upward flow of heat from gabbro magma caused fusion of enclosing Sickle rocks to form the granite zone; the transition zone represents a mixture of the two liquids.
- (2) Crystallization of the gabbro zone gave rise to late granitizing fluids, which escaped upwards, altered the top portion of the gabbro zone to form the transition zone, and granitized the Sickle rocks immediately above the intrusion to form the granite zone.
- (3) The intrusion is multiple; the earlier formed rocks (either granite or gabbro) have been altered after

consolidation by interaction with the later magma to form the transition zone.

- (4) The intrusion is multiple; granite was intruded along the gabbro-sediment contact while the gabbro was still a crystal mush; the transition zone is the result of mixing of granite magma and gabbro crystal mush. Conversely, gabbro magma may have been intruded along a contact between Sickle rocks and partially consolidated granite.
- (5) The intrusion is differentiated, the three zones being formed by fractional crystallization of a gabbroic parent magma.

Each theory is discussed below.

- (1) The first theory, that granite was produced by fusion of greywacke, is subject to serious criticism. Field study revealed little evidence of any melting of the greywacke. Also, the Sickle greywacke which has been intruded by the Granville Lake Gabbro is considerably poorer in alkalies and silica, and richer in lime, magnesia, and iron oxides than is the granite. Simple fusion of greywacke could not, therefore, have produced a suitable granitic melt. Selective fusion of the silica and alkali rich minerals prior to the more basic minerals could have produced a suitable liquid, but it is unlikely that this hypothetical liquid would have

migrated out of the greywacke to form a layer along one side of the gabbro intrusion. Selective fusion on a scale sufficient to produce the large amount of granitic material present would necessarily have resulted in a correspondingly large amount of basic residue. None was observed, and although exposure of the Sickie series is poor in the immediate vicinity of the intrusion, there is sufficient outcrop to permit the conclusion that there is no such residue.

In those few places where the greywacke is exposed within a very short distance of the granite-greywacke contact there is no indication of melting or partial melting. Also, heat flow from a magma body must radiate outwards in all directions. Therefore fusion, if any, would be expected to occur on all sides of the intrusion, not only along the top. Little evidence of fusion was found. Furthermore, gabbro-sediment contacts along the edges of the smaller intrusions show no evidence of fusion, the contacts being knife sharp.

It is concluded that sediment fusion, if any, was minor, and that the granite was not produced by fusion of sedimentary rocks along the upper surface of hot gabbro magma.

(2) The second theory proposes granitization of Sickie greywacke and alteration of gabbro to transition rocks by

late fluids escaping upward from the crystallizing gabbro magma. These fluids would represent a late granitic residue contained in the crystal mush, with the basic constituents of the gabbro being incorporated in the crystals. Such a late residual fluid could not have reacted with gabbro to form transition rocks because the fluid would have been in equilibrium with the basic constituents of the crystals.

A granitizing fluid which could produce granite by reaction with the Sickle greywacke above the gabbro intrusion would have to be considerably richer in silica and alkalies than the resulting granite, because the actual granite zone rocks are richer in these constituents than the greywacke from which they would presumably have formed. If such a highly silicic and alkaline fluid had formed it could equally well have accumulated above the gabbro as a granitic differentiate.

No indication of extensive granitization of greywacke was seen in the field. One obviously granitized area occurs near the southeast end of the granite zone, but this is still a recognizable greywacke, having a fine grained sedimentary texture with phenocrysts or porphyroblasts of pink albite, quite distinct from the appearance of the granite. This area of granitized greywacke appears to be small, although

the granite-granitized greywacke contacts are covered by overburden, and it is completely engulfed by granite. It is probable that this greywacke was enclosed in granitic magma with which it reacted without melting, until it reached equilibrium.

The contact between the granite zone and the Sickie series is not exposed. Outcrops of granite and sedimentary rocks occur within 40 feet where exposure is best. In one place near the southeast end of the granite zone (approximately 500 feet south of the location of specimen CG 2-4), a small outcrop of light grey greywacke or impure quartzite about 60 feet west of the last granite outcrop contains scattered 1/8-inch phenocrysts or porphyroblasts of pink plagioclase. These are identical to the "phenocrysts" in the more extensive area of granitized greywacke mentioned above. The next outcrop, about 50 feet further west from the granite, is normal greywacke. No other evidence of granitization was observed.

Such minor granitization of greywacke is probably the result of interaction between granite magma and the greywacke with which it was in immediate contact, and does not represent the extensive granitization which would have taken place if the granite zone were formed by granitization of overlying greywacke.

It is unlikely that granitization played a significant part in formation of the rocks of the granite zone.

(3) The first multiple injection hypothesis proposes injection of either granite or gabbro magma along the edge of an earlier granite or gabbro intrusion which had completely crystallized. Injection of gabbro magma along a granite-sediment contact might cause refusion of granite, with mixing of gabbro magma and remelted granite resulting in the transition rocks. There are two objections to this. If the gabbro were hot enough to cause such extensive remelting, it is unlikely that the granite-transition zone contact would be as relatively sharp as it is, with no apparent metamorphism of the unmelted granite.

Specific gravity studies indicate apparent incomplete differentiation of the small southeast satellite intrusion, yet there is no granite along the top contact of this satellite, and no evidence that there ever was any. Hence refusion of earlier granite by later gabbroic magma does not seem to explain at least the southeast satellite intrusion.

The foregoing objections may be raised to the converse theory that granitic magma was injected along a gabbro-sediment contact. In addition, a granitic magma would not be hot enough to cause remelting of gabbro. Formation of transition rocks by metasomatism or granitization of gabbro is

unlikely. The gabbro-sediment and granite-sediment contacts of the intrusion are completely concordant in the plane of exposure (the topographic surface). It is likely that the concordance continues to at least a reasonable depth. In the one place where the granite zone - transition zone contact is almost knife-sharp, it dips steeply to the southwest, and is parallel to the plane of the intrusion. There is no evidence to indicate a significantly larger volume of granite at depth than that indicated at surface. Therefore it is unlikely that such a relatively small amount of granitic magma could have caused granitization or metasomatic alteration of gabbro for distances as great as 1/4 mile, the maximum width of the transition zone.

(4) Intrusion of granite along a gabbro-sediment contact while the gabbro was in the form of a crystal mush is improbable. Formation of the intrusive body in this manner requires that an extremely delicate, and therefore unlikely, relationship must have existed; the gabbro would have to have been hot enough and fluid enough to react and partially mingle with the granitic magma, yet firm enough so that extensive or complete intermixing or crosscutting by large bodies of granite did not occur. Injection of the granite would, of necessity, have to have been extremely gentle. The few short, vague granitic dykes found in transition

rocks within a few feet of the granite-transition contact, while consistent with such a mode of formation, can equally well be ascribed to minor injection of early differentiated crystal mush by later and more granitic differentiates.

(5) Finally, there is the possibility of differentiation in place of an original gabbroic magma. Differentiation is common to many other gabbroic and doleritic intrusions throughout the world, and therefore would seem to be a probable explanation of the features of the Granville Lake intrusion.

Differentiation in place would explain all the features of the intrusion which were noted in the field. The relatively sharp contact between the transitional and granitic phases is not inconsistent with this theory; many other differentiated intrusions have relatively sharp phase boundaries.

Differentiation is strongly supported by petrographic studies, mineralogical and chemical data, and the variation across the intrusion of specific gravity and plagioclase composition. Differentiation is the only adequate explanation of the specific gravity variation across the southeast satellite intrusion.

It is concluded that the Granville Lake intrusion originated by differentiation in place of an original gabbroic magma.

Geologic history of the Granville Lake Gabbro

The Granville Lake Gabbro was intruded as a concordant almost horizontal sill-like mass in well-bedded arkosic greywackes of the Sickie series. It remained in a more or less horizontal position until crystallization was complete. Pronounced differentiation took place during cooling, resulting in the formation of a thick lower gabbro layer, a transitional diorite layer, and an upper granite layer. The granite and transitional layers are widest, and the gabbro layer narrowest near the southeast end of the intrusion. This indicates that the intrusion was not exactly horizontal at the time of crystallization, but had a slight upward tilt towards the present southeast end. As crystallization proceeded from the bottom up, there was presumably an accumulation of basic crystal mush down slope, and of successive dioritic and then granitic differentiates up slope. Later folding of the enclosing Sickie rocks tilted the intrusion to its present nearly vertical position.

THEORETICAL CONSIDERATIONS

Differentiation and iron enrichment in basaltic magma

Differentiation and the results of differentiation of basaltic magma have been the subject of a great deal of disagreement among geologists for many years. The major point of controversy has been whether or not the normal calc-alkaline series of igneous rocks can be derived from a primary basalt magma by fractional crystallization, or some other process of differentiation.

Bowen (1928) contended that the result of the process of differentiation of a basaltic magma would be the production of the normal calc-alkaline series of igneous rocks. He reached this conclusion by experimental investigation of simple silicate systems in the laboratory, and from evidence obtained by field studies of rocks.

Bowen believed that normal processes of differentiation would result in a continuous decrease, in successive rocks of a differentiated series, of magnesia, lime, and iron oxides, and a continuous increase in silica and alkalies, resulting in the production of iron-poor dioritic and granitic residual magmas.

Bowen's view have been questioned by Fenner (1929), who considers that the normal calc-alkaline series of igneous

rocks is not produced by fractional crystallization of basalt. Fenner favours enrichment of iron oxides in the final residual liquid produced by fractional crystallization, and believes that residual liquids remain highly ferriferous right up to the time of complete crystallization. He concludes that the result of fractional crystallization of a basaltic magma is to produce a final liquid rich in iron oxides and alkalies, and poor in silica, magnesia, and lime.

Bowen, Schairer, and Willemms (1930) agree that iron oxides should be enriched relative to magnesia in a series of rocks formed by fractional crystallization, and state that almost all calc-alkaline series of rocks will show this enrichment. Similarly alkali feldspar should be enriched relative to calcic feldspar.

Fenner (1931) claims that the enrichment of iron oxides should predominate over the enrichment of alkalies and silica; Bowen held the opposite view.

Wager and Deer (1939), in their well-known study of the differentiated Skaergaard intrusion, show that in the Skaergaard magma, the differentiation trend was strongly toward iron enrichment, which continued until the magma was 95 per cent crystallized. At this point there was a sharp change in the differentiation trend, and the remaining 5 per

cent of the magma crystallized to produce a residual liquid rich in silica and alkalies, but poor in iron.

Wager and Deer have constructed a number of ingenious diagrams to demonstrate the differentiation trend of the Skaergaard magma, and to permit comparison with the rocks of the calc-alkaline series, as well as with the differentiation trends of other presumably differentiated series. The differentiation trend is best illustrated by a triangular diagram with variables FeO, MgO, and $(\text{Na}_2\text{O} + \text{K}_2\text{O})$. Figure 37a is a plot of the differentiation trends of the Skaergaard intrusion and the Granville Lake Gabbro, and also of the calc-alkaline series of igneous rocks, after Daly (1933). This diagram and its implications will be more fully discussed.

On the basis of their diagrams, Wager and Deer claim that iron enrichment, shown by the differentiation trend of the Skaergaard intrusion, is typical of the average differentiated basaltic magma.

However, differentiation of the Skaergaard magma has resulted in the production of unusual ferrogabbros, containing as high as thirty per cent iron oxides. Similar ferrogabbros are rare elsewhere. These workers (p.313) consider that

..... the rarity of ferrogabbros is not due to their production from a magma of unusual compo-

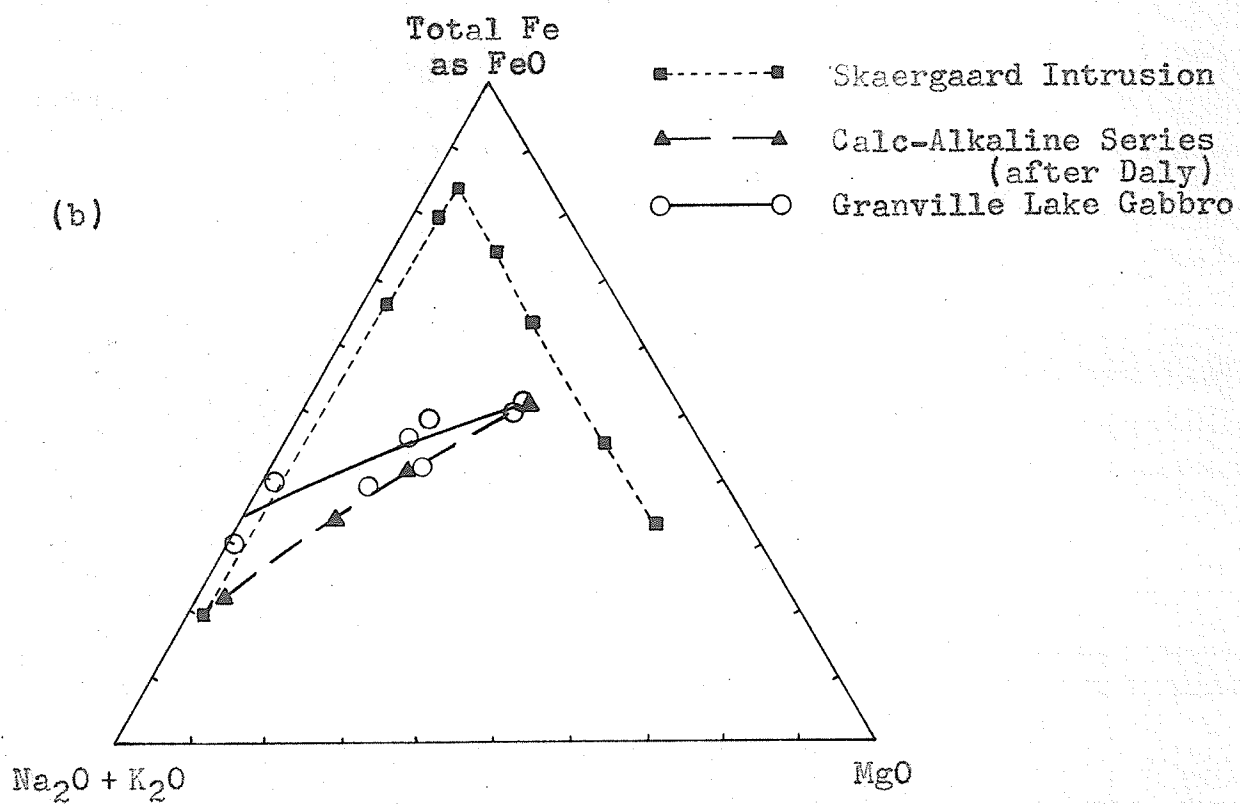
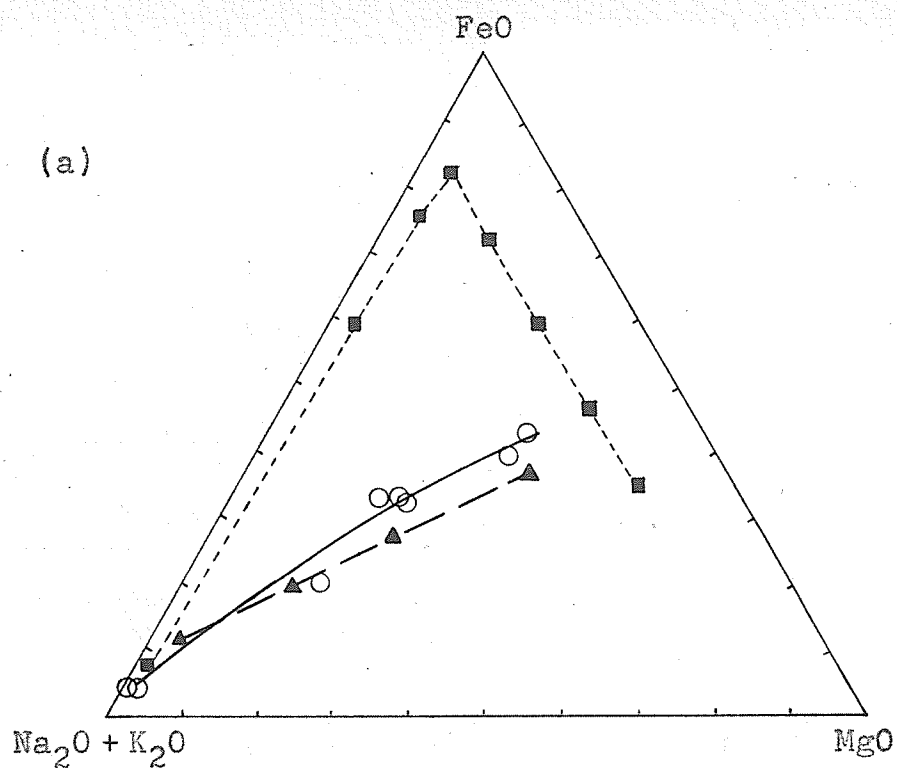


Figure 37. Differentiation trend of the Granville Lake Gabbro.

sition but because uninterrupted, strong fractionation of basic magma, such as took place in the Skaergaard intrusion, is rare. The normal calc-alkaline series of igneous rocks, which is often regarded as resulting from fractional crystallization of basalt, is not the sequence shown by the Skaergaard differentiation; thus we consider some other process as well as, or in place of, fractional crystallization has been responsible for it.

They also suggest (pp.314-315) that the linear relationship of the calc-alkaline series shown on the $\text{FeO} - \text{MgO} - (\text{Na}_2\text{O} + \text{K}_2\text{O})$ diagram

..... may be interpreted as due to mixture of granite and basalt in various proportions

although they do admit that such a linear relationship might, by chance, have been the result of crystal fractionation, and does not in itself indicate that the rocks are mixtures. However, the fact that the crystallization of basaltic magmas from other examples considered by Wager and Deer appears to follow the Skaergaard trend, is taken by them to support the theory that the calc-alkaline series is essentially the result of mixing and hybridization between the two end materials, granite and basalt.

It is concluded by Wager and Deer (p.335) that

The trend of the Skaergaard magma during differentiation is believed to be essentially the trend which would be followed by average basalt (magma) if subjected to the same degree of crystal fractionation From the evidence of the Skaergaard intrusion it appears that crystal fractionation of basalt magma leads to

the ferrogabbros and not to intermediate rocks of the calc-alkaline series.

However, it appears that Wager and Deer have not considered all the factors governing the differentiation of basaltic magma. This subject will be discussed later.

Edwards (1942), in his study of the Tasmanian dolerites, states that the trend toward the enrichment of iron relative to magnesia is strongly marked in those rocks. This is shown by the $\text{FeO} - \text{MgO} - (\text{Na}_2\text{O} + \text{K}_2\text{O})$ plot for analyses of the Tasmanian dolerites, figure 38d.

However, a study of Edwards' analyses soon indicates that there was little, if any, absolute enrichment of iron oxides in the magma as differentiation proceeded. The iron oxide enrichment is only relative to magnesia, and actual percentage of iron oxides changes very little from base to top of the differentiated Tasmanian dolerites.

This relatively constant iron oxide content across the individual dolerite sills should be contrasted to the variation in iron oxide content across the Skaergaard intrusion, as shown by the analyses of Wager and Deer (1939, Table XXXXI). The Skaergaard analyses indicate a gradual increase in total iron oxides (FeO and Fe_2O_3 behave similarly) from 11 per cent at the lowest exposure, up to a maximum of over 30 per cent about two-thirds of the way from

this point to the top, then a gradual decrease to 10 per cent in the rocks near the top of the series. This variation represents an absolute enrichment of iron during the majority of the crystallization of the magma.

Edwards (p.605) also believes that enrichment of iron oxides relative to magnesia

..... is so characteristic of basalts in general that it may be regarded as the normal trend in differentiation of basaltic magmas.

He considers it possible that differentiation of basaltic magma taking place in a magma chamber of batholithic proportions, could result in the production of rocks of the calc-alkaline series, by sinking of heavier iron silicate crystals faster than lighter alkali silicates. However, he concurs with Wager and Deer that the great majority of the calc-alkaline series of igneous rocks can be only the result of mixing of acid and basic material.

Walker and Poldervaart (1949, pp.657-661) have constructed nine $\text{FeO} - \text{MgO} - (\text{Na}_2\text{O} + \text{K}_2\text{O})$ diagrams, with the object of comparing the differentiation trends of various intrusions to that of the Skaergaard intrusion, and to the calc-alkaline series of igneous rocks. They find that iron enrichment is the normal trend of differentiation during the greater part of the crystallization of basaltic magma.

However, they consider it likely that the calc-alkaline suite might be produced by fractionation of basic magma.

An examination of analyses of four of these nine examples, for the Palisade diabase (Walker, 1940), the Karroo dolerites (Walker and Poldervaart, 1949), the Insizwa intrusion (Scholtz, 1936), and including the Tasmanian dolerites (Edwards, 1942) also indicates a relatively constant iron oxide content for each of these differentiated intrusions, with iron oxide enrichment only relative to magnesia. There is no absolute enrichment in iron. These intrusions should also be contrasted to the pronounced absolute iron enrichment of the Skaergaard rocks. It would, in fact, appear that the Skaergaard intrusion is rather unusual in this regard.

Nevertheless, it should be noted that all the above intrusions do show a pronounced decrease in magnesia from bottom to top of each, and hence an enrichment of iron oxides relative to magnesia in progressive differentiates.

It was not possible to check the other five cases for iron enrichment in successive differentiates, because the original analyses had not been classified as to their relative positions in the intrusions.

In view of the fact that successive rocks of the Skaergaard intrusion show a pronounced absolute increase in

total iron oxide content, which none of the other differentiated series do, the writer does not believe that the Skaergaard intrusion represents typical differentiation of basaltic magma, contrary to the opinion of Wager and Deer.

Consider again figure 37a, which is an $\text{FeO} - \text{MgO} - (\text{Na}_2\text{O} + \text{K}_2\text{O})$ diagram, the type proposed by Wager and Deer, and used by many workers since that time. This diagram shows the differentiation trends of the Skaergaard magma, and the Granville Lake Gabbro. It also shows the plot of the calc-alkaline series of igneous rocks (average basalt, andesite, dacite, and rhyolite of Daly, 1933).

Wager and Deer, and many other geologists, have compared trends of analyses of various differentiated series to the differentiation trend of the Skaergaard magma, and to the plot of the calc-alkaline series.

There is a possible fallacy in such comparisons. The differentiation trend shown for the Skaergaard intrusion is the trend of hypothetical magma compositions which were calculated by Wager and Deer. It is not the differentiation trend followed by the actual rock analyses, which need not necessarily be identical to that of the hypothetical magma. However, the writer has found that the actual rock analyses in fact followed the differentiation trend of Wager and

Deer's hypothetical magma fairly closely. It is of interest that successive analyses from bottom to top of the Skaergaard intrusion do not follow this trend in order. In other words, a rock may fall closer to the MgO end of the trend than another taken from lower in the intrusion. This may be a result of the layered nature of the intrusion.

Similarly, the calc-alkaline trend is for average basalt, andesite, dacite, and rhyolite, which represent frozen magma compositions. They are, however, the most suitable because the average analyses of gabbro, diorite, granodiorite, and granite would include analyses of rocks produced by granitization and similar processes. In spite of this possible complication, it is found that the average gabbro, diorite, granodiorite, and granite analyses follow closely the trend of the frozen magma compositions.

Strictly speaking, rock compositions should not be compared to magma compositions. In the case of the Skaergaard intrusion and the calc-alkaline series, the close correspondence would indicate that no great error has been incurred thereby.

Figure 37a shows that the differentiation trend of the Granville Lake Gabbro is almost identical to the trend of the calc-alkaline series. The Granville Lake intrusion

does not show absolute or relative FeO enrichment, as is characteristic of the Skaergaard rocks, but instead, both FeO and MgO decrease with a simultaneous increase in $(\text{Na}_2\text{O} + \text{K}_2\text{O})$.

Analyses of the Granville Lake Gabbro indicate a comparatively high Fe_2O_3 content. It was thought that any iron enrichment might not be evident in the standard FeO - MgO - $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ diagram, because of this. Figure 37b is a triangular plot of (total iron as FeO) - MgO - $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ for the Skaergaard intrusion, the Granville Lake Gabbro, and the calc-alkaline series. No such iron enrichment is present, and the Granville Lake differentiation trend still corresponds closely to that of the calc-alkaline series.

Figures 38a to 38h are comparisons of differentiation trends of several well known differentiated intrusions to the Skaergaard differentiation trend, and to the trend of the calc-alkaline series. These have been taken, with addition of a few new analyses, from Walker and Poldervaart (1949). The analyses represented on these diagrams are from:

- a. Insizwa intrusion (Scholtz, 1936)
- b. Karroo dolerites (all available analyses as listed by Walker and Poldervaart, 1949)
- c. Palisade sill (Walker, 1940)
- d. Tasmanian dolerites (Edwards, 1942; McDougall, 1962)

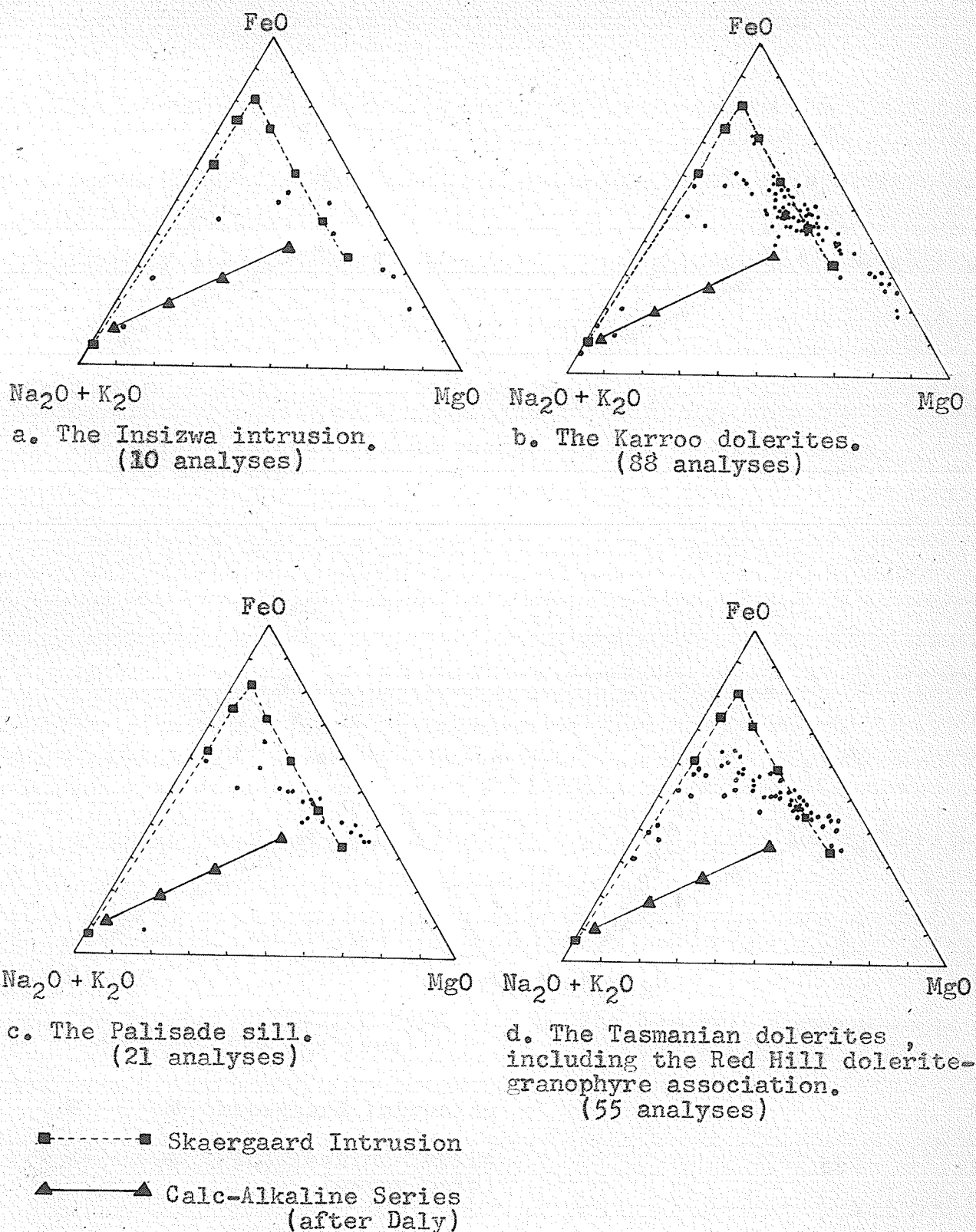
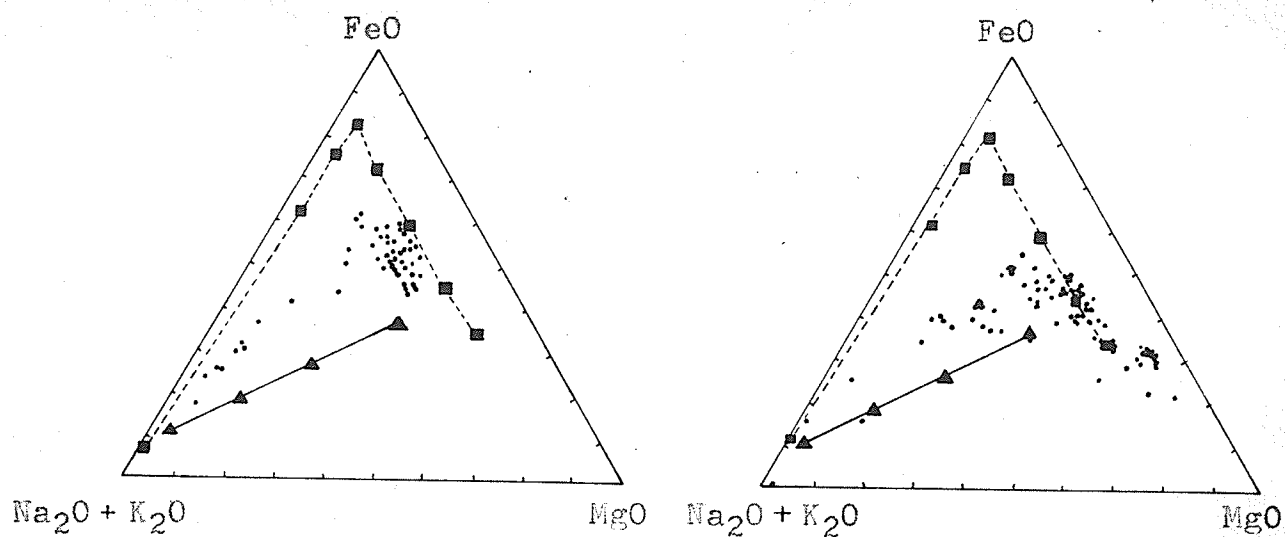
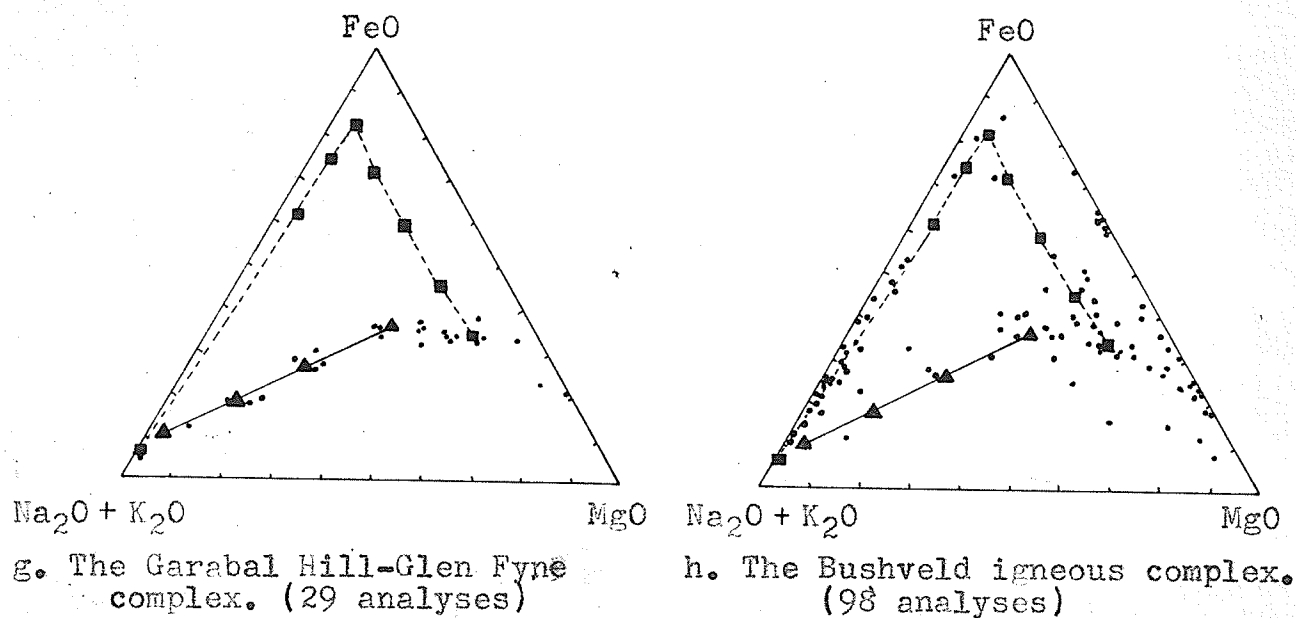


Figure 38. FeO-MgO-($\text{Na}_2\text{O} + \text{K}_2\text{O}$) diagrams, showing differentiation trends of several differentiated intrusions, compared to the differentiation trend of the Skaergaard Intrusion, and to the plot of Daly's calc-alkaline series.



e. The Whin sill and related rocks. (55 analyses) f. The Hawaiian lavas. (96 analyses)



g. The Garabal Hill-Glen Fyne complex. (29 analyses)

h. The Bushveld igneous complex. (98 analyses)

■-----■ Skaergaard Intrusion
 ▲-----▲ Calc-Alkaline Series
 (after Daly)

Figure 38 (continued).

- e. Whin sill and related rocks (Day, 1928; Holmes and Harwood, 1928, 1929; Tomkeieff, 1929; Smythe, 1930; Walker, 1935)
- f. Hawaiian lavas (Washington, 1923 I to IV; Washington and Keyes, 1926, 1928)
- g. Garabal Hill - Glen Fyne complex (Nockolds, 1941)
- h. Bushveld igneous complex (Hall, 1938; Nel, 1940)

Figures 38a to 38d (Insizwa intrusion, Karroo dolerites, Palisade sill, and Tasmanian dolerites, respectively) all show a pronounced enrichment of iron relative to magnesia during the majority of the period of crystallization, followed by later depletion in iron and enrichment in alkalis.

Figures 38e and 38f (Whin sill and Hawaiian lavas, respectively) show a less pronounced enrichment of iron relative to magnesia, followed by a more pronounced longer period of enrichment in alkalis. These intrusions apparently represent a transition to the calc-alkaline series.

Figure 38g (The Garabal Hill - Glen Fyne complex) shows only minor enrichment of iron relative to magnesia in the early stages of crystallization, then follows the calc-alkaline trend toward increasing alkalis. Nockolds (1941, p.508) concludes that differentiation is the only process which can explain the rock associations found in the complex.

Figure 38h (the Bushveld igneous complex) appears to show two trends of differentiation, one displaying enrichment in iron, the other following the trend of the calc-alkaline series.

It appears that differentiation of basaltic magma can result in any gradation between two main trends, which are:

Type I: A differentiation trend consisting of pronounced enrichment of iron relative to magnesia until late stages of crystallization, followed by a decrease in iron and enrichment of alkalies.

Type II: A differentiation trend which essentially follows the trend of the calc-alkaline series of igneous rocks, with continuous enrichment in alkalies.

It also appears that type I is generally predominant, unless the great bulk of igneous rocks comprising the calc-alkaline series is considered to have formed by differentiation, in which case type I is definitely subordinate. The Skaergaard intrusion illustrates the best development of type I. The Granville Lake Gabbro is an excellent example of type II, and its differentiation trend follows closely the trend of the normal calc-alkaline series of igneous rocks.

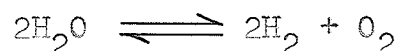
The calc-alkaline series trend followed by the differentiation of the Granville Lake Gabbro would indicate that differentiation of basaltic magma of the tholeiitic type can result in the formation of normal rocks of the calc-alkaline type. Hence, it is at least conceivable that contrary to the conclusions of Wager and Deer, Edwards, Fenner, and others, differentiation of basaltic magma could have produced the great bulk of the rocks of the calc-alkaline series, provided that it was possible for the more basic differentiates to accumulate at great depths where they are not exposed. This might be the case if crystallization differentiation has taken place in large bodies of batholithic size.

The influence of the partial pressure of oxygen on crystallization differentiation

Osborn (1959) has shown that the partial pressure of oxygen (pO_2) acting during the fractional crystallization of a silicate liquid which contains iron oxide can have a profound effect on the course of crystallization. The manner of change of oxygen pressure during fractional crystallization and differentiation of basaltic magmas is the chief control determining whether liquids move toward higher silica and lower iron oxide content (calc-alkaline trend), or toward higher iron oxide content with little change in

silica content (tholeiitic trend). The former occurs where pO_2 remains about constant, or increases, and this entails addition of oxygen to the system. The latter occurs in a closed system where pO_2 decreases during crystallization.

A high water content in basaltic magmas during differentiation is probably the principal factor causing constant or increasing pO_2 . The equation governing the dissociation of water is:



At temperatures and pressures prevailing at the surface of the earth, the pO_2 produced by this reaction is negligible. However, with increasing temperature and pressure, the pO_2 due to this reaction increases until it becomes a significant factor in contributing to the total pO_2 in the magma. After consideration of the factors which would control the proportion of pO_2 contributed to the total pO_2 by water in the magma, Osborn concludes that if water pressure is appreciable, the total pO_2 in the magma will remain about constant or will increase as a magma crystallizes. Probably only a few per cent of water vapour is required in the original magma at the start of crystallization.

In a closed system where the magma is essentially dry, then pO_2 will decrease rapidly as crystallization proceeds. The Skaergaard intrusion is considered to represent

a closed system with little or no water contained in the magma. This has led to an increase in the iron oxide content, and little change in the silica content, until the very last stages of crystallization, with the resultant production of the uncommon ferrogabbros plus a small amount of felsic residue, typical of this type.

Where pO_2 remains relatively constant, or even increases as crystallization proceeds, a continuous increase in the silica content results, with a continuous decrease in iron oxide. Hence, in this case, the normal calc-alkaline series of igneous rocks develops by fractional crystallization of basaltic magma. Such rocks are more typical of the differentiates found in the orogenic belts, where the necessary water is provided by the intruded geosynclinal sediments. Osborn considers the olivine basalt to dacite series of lavas of the Cascade orogenic belt to be an example of this type.

The effect of the partial pressure of oxygen on the crystallization of the Granville Lake Gabbro

Let us now reconsider the differentiation trend of the Granville Lake Gabbro, as illustrated by figures 37a and 37b, the triangular plots of the oxides $FeO - MgO - (Na_2O + K_2O)$ and $(total\ Fe\ as\ FeO) - MgO - (Na_2O + K_2O)$, respectively.

Differentiation trends for the Skaergaard intrusion illustrated in these diagrams show a pronounced continuous increase in iron oxide content until the late stages of crystallization, when enrichment in the felsic constituents became predominant. However, the trend indicated for the Granville Lake Gabbro is similar to that of Daly's calc-alkaline series in both diagrams. This is particularly so in figure 37a, the $\text{FeO} - \text{MgO} - (\text{Na}_2\text{O} + \text{K}_2\text{O})$ diagram, which is the type commonly used to determine and compare differentiation trends. In both diagrams the Granville Lake Gabbro shows no increase in relative iron oxide content, but rather a continuous decrease in iron oxides throughout crystallization.

Rocks of the Granville Lake Gabbro appear to be fairly normal, and relatively typical of those of the calc-alkaline series, both in hand specimen and in thin section. They are not the ferrogabbro-granophyre association typical of differentiated basic intrusions such as the Skaergaard intrusion.

The relative rarity of pyroxene, and the high hornblende content of the gabbroic portion of the Granville Lake intrusion may be a result of deuteric alteration of magmatic pyroxene, or possibly of direct crystallization of magmatic hornblende. Either case would suggest a relatively high

water content in the primary magma. Similarly, scapolite is a common alteration product of plagioclase in the gabbro and transition zones. Moorhouse (1959) considers scapolite in basic rocks to have formed by hydrothermal alteration of calcic plagioclase. In the case of the Granville Lake intrusion, scapolite alteration was probably caused by the action of deuteritic fluids resulting from a wet magma.

It appears that the Granville Lake intrusion crystallized under a high partial pressure of oxygen, perhaps caused by a high water content. After considering the conclusions of Osborn, the calc-alkaline trend followed by the Granville Lake Gabbro, and the nature of the rocks comprising the intrusion, the writer believes that the magma which differentiated in place to form the Granville Lake Gabbro was not dry, but contained an appreciable amount of water. This water may have been dissolved in the magma prior to its emplacement, or may have been introduced from nearby sediments. The similarity of the differentiation trend of the intrusion to the trend of the calc-alkaline series, rather than the enrichment in iron oxides shown by the Skaergaard intrusion and so many other differentiated intrusions, may be related to its high water content.

The effect of water on the ratio $\text{FeO}:\text{Fe}_2\text{O}_3$ in a magma

Kennedy (1948) states that the ratio of ferrous to ferric oxide (the ratio of FeO to Fe_2O_3) in a rock melt

depends upon the partial pressure of oxygen (pO_2) with which the magma is in equilibrium. The reaction involved is:



It has already been shown that pO_2 is influenced by any water contained in the melt according to the reaction governing the dissociation of water:



If the magma contains water, then the water contributes to the partial pressure of oxygen according to equation 2, and as a result, in accordance with the law of mass action, equation 1 is driven to the left; that is, ferrous iron (FeO) is converted to ferric iron (Fe_2O_3) until the equation

$$K = \frac{(FeO)^4 O_2}{(Fe_2O_3)^2}$$

is satisfied. Hence, the effect of water on a silicate magma is to increase the content of ferric iron (Fe_2O_3) at the expense of ferrous iron (FeO).

Therefore, in dry magmas it would be expected that the FeO to Fe_2O_3 ratio would be high, and in wet magmas it would be low. Conversely, magmas in which the ratio of FeO to Fe_2O_3 was high must have been relatively dry, and those in which the ratio was low must have been relatively wet.

These conclusions should hold for rocks produced by crystallization of such magmas.

Significance of the $\text{FeO}:\text{Fe}_2\text{O}_3$ ratio for the Granville Lake Gabbro

Table 6 gives the value of $\text{FeO}/\text{Fe}_2\text{O}_3$ for a representative selection of rock analyses for the Skaergaard intrusion (every second analysis from Wager and Deer, 1939, table XXXXI). In general, the value of $\text{FeO}/\text{Fe}_2\text{O}_3$ ranges from approximately four to thirteen. Only in the upper border group, the latest rocks to crystallize, does this ratio reach a value as low as two. In contrast, the maximum value of $\text{FeO}/\text{Fe}_2\text{O}_3$ for the Granville Lake Gabbro is 2.1 (table 7). This value is considerably exceeded in the great majority of the Skaergaard rocks. The contrast suggests that the Skaergaard magma was probably dry, and the Granville Lake magma wet.

The value of $\text{FeO}/\text{Fe}_2\text{O}_3$ for the Granville Lake Gabbro rocks ranges from a high of 2.1 to a low of 0.1. It is of interest to compute the average value of $\text{FeO}/\text{Fe}_2\text{O}_3$ for the intrusion. This was done by taking numerical averages of the available $\text{FeO}/\text{Fe}_2\text{O}_3$ ratios (table 7) of chemically analyzed specimens, for each of the three zones of the main intrusion. A planimeter measurement of the surface area of each zone was presumed to give an approximation of the

TABLE 6

Value of $\text{FeO}/\text{Fe}_2\text{O}_3$ ratios for the Skaergaard intrusion
(every second analysis, Wager and Deer, 1939, table XXXXI)

<u>Specimen</u>	<u>% FeO</u>	<u>%Fe₂O₃</u>	<u>FeO</u> <u>Fe₂O₃</u>	<u>Rock type</u>	<u>Height above</u> <u>imaginary</u> <u>datum plane</u>
3050	8.17	4.13	2.0	Upper border group	3250 metres
2275	8.13	1.96	4.2	Marginal border group	
1837	9.12	0.71	12.8		
1682	10.52	2.69	3.9		
1724	8.87	1.16	7.7	Chilled marginal gabbro	
4136	7.47	2.18	3.4	Unlaminated layered series	2750
4139	23.77	5.78	4.1		2600
4142	26.63	4.05	6.6	Layered series	2500
1907	16.66	3.75	4.5		1800
3661	14.86	3.41	4.4		1200
4077	10.44	1.52	6.9		500
4087	9.29	2.09	4.5	Transitional	0

TABLE 7

Value of $\text{FeO}/\text{Fe}_2\text{O}_3$ ratios for the Granville Lake Gabbro

<u>Specimen</u>	<u>%FeO</u>	<u>%Fe₂O₃</u>	<u>FeO/Fe₂O₃</u>	<u>Zone</u>
CG 6-25	0.39	3.8	0.1	Granite zone
CG 6-22	0.39	5.7	0.1	
CG 12-21	2.23	3.76	0.6	Transition zone
CG 10-23	4.88	2.73	1.8	
CG 2-14	5.12	4.51	1.1	
CG 15-17	6.0	2.9	2.1	Gabbro zone
CG 10- 5	5.8	3.5	1.7	
CG 9-25	4.7	4.9	1.0	

relative volume percentage that each zone comprises of the entire main intrusion. The relative areas of gabbro, transition, and granite zone rocks at the present erosion surface do not necessarily represent the actual relative volumes of the three types which formed by differentiation; however, a good cross section of the intrusion is exposed, and it is probable that relative areas are fairly representative of the relative volumes of each zone. Allowance was made for the lower specific gravities of the granite and transition zone rocks as compared to the average specific gravity of the gabbro zone. The average specific gravity of the granite zone is 2.64, the transition zone 2.79, and the gabbro zone 2.88. The area of the granite zone was multiplied by $2.64/2.88$, and of the transition zone $2.79/2.88$, before a value of $\text{FeO}/\text{Fe}_2\text{O}_3$ was computed for the entire main intrusion. The calculation follows:

Average value of $\text{FeO}/\text{Fe}_2\text{O}_3$:

$$\text{gabbro zone} = \frac{2.1 + 1.7 + 1.0}{3} = 1.6$$

$$\text{transition zone} = \frac{0.6 + 1.8 + 1.1}{3} = 1.2$$

$$\text{granite zone} = \frac{0.1 + 0.1}{2} = 0.1$$

Average specific gravity of each zone (main intrusion):

gabbro zone 2.88 (271 specimens)

transition zone 2.79 (47 specimens)

granite zone 2.64 (57 specimens)

Surface areas, main intrusion (planimeter measurements):

gabbro zone 3.13 miles² = 76.5% of main intrusion

transition zone 0.40 miles² = 9.5% of main intrusion

granite zone 0.58 miles² = 14.0% of main intrusion

Hence, average value of $\text{FeO}/\text{Fe}_2\text{O}_3$ for the main intrusion is

(converting all zones to equivalent areas of gabbro):

$$\begin{aligned} & \left(\frac{76.5}{100} \times \frac{2.88}{2.88} \times 1.6 \right) + \left(\frac{9.5}{100} \times \frac{2.79}{2.88} \times 1.2 \right) \\ & + \left(\frac{14.0}{100} \times \frac{2.64}{2.88} \times 0.1 \right) = 1.3 \end{aligned}$$

The validity of this calculated value is open to argument. The average $\text{FeO}/\text{Fe}_2\text{O}_3$ values for the individual zones are only approximate. Relative surface areas do not necessarily represent actual relative volumes. However, it is believed that the value obtained (1.3) is an approximation of the true value of $\text{FeO}/\text{Fe}_2\text{O}_3$ for the intrusion, and hence the uncrystallized Granville Lake magma.

It is of further interest to calculate the value of $\text{FeO}/\text{Fe}_2\text{O}_3$ for some of the various intrusions illustrated in figure 38. Compositions for the undifferentiated magmas which formed the Karroo dolerites, the Tasmanian dolerites, the Whin Sill dolerite, the Palisade diabase, and the Skaergaard intrusion have been proposed by the workers studying

these intrusions. The values of $\text{FeO}/\text{Fe}_2\text{O}_3$ for these intrusions are shown in table 8.

In four of the five examples, the value of $\text{FeO}/\text{Fe}_2\text{O}_3$ is considerably larger than that of the Granville Lake Gabbro. In the fifth example, the Whin Sill dolerite, the average is 2.2, which is also greater than the 1.3 of the Granville Lake intrusion.

These examples were the only studies sufficiently complete for this purpose found in the geological literature; other studies did not include a proposed original undifferentiated magma composition.

In none of the 88 Karroo dolerite analyses of Walker and Poldervaart does the percentage of Fe_2O_3 exceed or equal that of FeO (Walker and Poldervaart, 1949, table 15, p.646). The Palisade diabase analyses (Walker, 1940) are similar in this respect to those of the Karroo dolerites. In the 36 available analyses of the Skaergaard rocks, Fe_2O_3 exceeds FeO in only one sample (Wager and Deer, 1939, table XXXXI; Wager, 1960, p.370, p.389). This is a late transgressive rock, that is, a very late differentiate of the original magma, and might be expected to have a relatively high water content at such a late stage of differentiation. In the Tasmanian dolerites, only the rare latest differentiates

TABLE 8

Value of $\text{FeO}/\text{Fe}_2\text{O}_3$ ratios for original undifferentiated
magmas of various differentiated intrusions

	<u>%FeO</u>	<u>%Fe₂O₃</u>	<u>FeO/Fe₂O₃</u>
Average Karroo dolerite (Walker and Poldervaart, 1949, p.667)	9.3	1.2	7.7
Average undifferentiated Tas- manian dolerite (Edwards, 1942, p.465)	8.3	0.5	16.5
Average Whin Sill dolerite (Holmes and Harwood, 1928, p.539)	8.7	4.0	2.2
Average undifferentiated Pali- sade diabase (Walker, 1940, p.1081)	9.3	1.0	9.3
Original undifferentiated Skaergaard magma (Wager, 1960, p.375)	8.44	1.32	6.4
Probable undifferentiated magma of the Granville Lake intrusion			1.3

have an Fe_2O_3 content equal to or exceeding that of FeO (Edwards, 1942; McDougall, 1962).

However, in the case of the Granville Lake Gabbro, the content of Fe_2O_3 is greater than or essentially equal to that of FeO in five analyses out of eight. The maximum value of $\text{FeO}/\text{Fe}_2\text{O}_3$ is 2.1, which is considerably lower than that of nearly all the available analyses of the Skaergaard rocks. Similarly, the calculated value of $\text{FeO}/\text{Fe}_2\text{O}_3$ for the undifferentiated Granville Lake magma is invariably lower than that of the undifferentiated magmas for the five examples of differentiated intrusions which are readily available from the literature. Reconsidering Kennedy's results (Kennedy, 1948), it is apparent that all five examples have probably formed by crystallization of relatively dry magmas, and hence have a high FeO and a low Fe_2O_3 content. The Granville Lake Gabbro, with a relatively high content of Fe_2O_3 as compared to FeO, was apparently formed by crystallization of a wet magma. This is further evidence for a wet magma, which had been inferred previously from other evidence.

Silica content of the primary magma

The silica content of the primary undifferentiated Granville Lake magma was computed in a manner similar to

that by which the $\text{FeO}/\text{Fe}_2\text{O}_3$ value was computed. The calculation follows:

Average per cent SiO_2

$$\text{gabbro zone} = \frac{51.2 + 49.6 + 52.9}{3} = 51.2\%$$

$$\text{transition zone} = \frac{53.7 + 55.9 + 62.2}{3} = 57.3\%$$

$$\text{granite zone} = \frac{67.0 + 70.3}{2} = 68.7\%$$

Average specific gravity of each zone:

$$\text{gabbro zone} \quad 2.88$$

$$\text{transition zone} \quad 2.79$$

$$\text{granite zone} \quad 2.64$$

Surface areas:

$$\text{gabbro zone} = 3.13 \text{ miles}^2 = 76.5\% \text{ of main intrusion}$$

$$\text{transition zone} = 0.40 \text{ miles}^2 = 9.5\% \text{ of main intrusion}$$

$$\text{granite zone} = 0.58 \text{ miles}^2 = 14.0\% \text{ of main intrusion}$$

Average SiO_2 content of the main intrusion:

$$\begin{aligned} & (51.2\% \times \frac{76.5}{100} \times \frac{2.88}{2.88}) + (57.3\% \times \frac{9.5}{100} \times \frac{2.79}{2.88}) \\ & + (68.7\% \times \frac{14.5}{100} \times \frac{2.64}{2.88}) = 53.9\% \end{aligned}$$

The result is subject to the same criticisms as the value of $\text{FeO}/\text{Fe}_2\text{O}_3$ computed in the previous section. However average silica content may be calculated by a different method. A total of 448 specimens was collected from the intrusion, and these have an average specific gravity of

2.84. From figure 18 (relationship between SiO_2 content and specific gravity), it may be determined that a specific gravity of 2.84 corresponds to a silica content of 53.8 per cent. This is almost identical to the value 53.9 per cent calculated by the first method, and tends to verify that value.

The validity of comparing results obtained by these two methods is open to question, because the same eight analyses were used in both cases. If one or more of these analyses is not typical of the intrusion, then both results are incorrect. However, the exceptional regularity of the curve in figure 18 would indicate that none of the analyses is particularly atypical. It is reasonable to assume that the average silica content of the presently exposed surface of the intrusion is close to 54 per cent. If the present surface is assumed to be representative of the entire intrusion, including that portion already removed by erosion and that concealed at depth, the undifferentiated magma had a silica content of 54 per cent, and was intermediate between Daly's average gabbro and average diorite (table 4). This is only slightly more silicic than the average of the gabbro zone analyses. The average specific gravity of the basal "chill" zone in the main intrusion is 2.85 or 2.86, almost identical to the average specific gravity of 2.84 for the entire

Granville Lake intrusion. Such a close correspondence indicates that the present erosion surface is essentially representative of the entire intrusion, and confirms the values calculated for the average $\text{FeO}:\text{Fe}_2\text{O}_3$ ratio and average SiO_2 content of the primary magma.

A comparison between the silica content of a specimen of chilled gabbro from one of the satellite intrusions and that calculated for the original magma would be of considerable interest. Unfortunately, such an analysis is not available to the writer at the present time.

ECONOMIC POSSIBILITIES OF THE GRANVILLE LAKE GABBRO

The association of copper-nickel sulphides with basic and ultrabasic rocks is well known. Differentiated basic intrusions present a particularly favourable environment for the accumulation of copper and nickel sulphides in the form of chalcopyrite and pentlandite, in association with pyrrhotite. The Sudbury, Ontario intrusion and its associated orebodies is probably the best known intrusion of this type. Two others are the ultrabasic sill at Rankin Inlet, Northwest Territories, and the Lynn Lake Gabbro. The apparent origin of the orebodies in these intrusions was that, at the same time as, or soon after the commencement of crystallization of the parent gabbroic magma, a sulphide liquid phase separated to form immiscible droplets in the magma. Because of their high specific gravity, these droplets sank through the magma to the floor of the intrusion. Where sufficient immiscible sulphide liquid separated from the parent magma, the sulphide content became great enough to form orebodies at the base of the intrusion. Where the base of the intrusion sloped downward, the sulphide liquid flowed down slope, and pools accumulated in depressions to form massive sulphide orebodies. Sulphide droplets were also trapped in the crystal mush, to form disseminated grains of pyrrhotite, chalcopyrite, pentlandite, and other minerals.

In view of the favourable environment provided by differentiation of basic magma, and also the economic significance of the nickel-copper orebodies of the Lynn Lake intrusion, it would seem possible that similar sulphide accumulations might be found in the Granville Lake Gabbro.

In the field, rare tiny specks of pyrite were observed in the gabbro and transition zones of the main intrusion. In addition, minor copper sulphides were observed in the satellite intrusion which is located at the northwest end of the main intrusion, between the granite zone and the east shore of the narrow mile-and-a-half long inlet of Granville Lake. This is the same intrusion from which specimens CG 15-1 and CG 15-3 were obtained. The one copper sulphide occurrence noted by the author is at the northwest end of this intrusion. It consists of a few 1/8 inch veinlets of mixed bornite and chalcopyrite along chloritic fractures in gabbro, immediately adjacent to the western gabbro-sediment contact. A similar occurrence, not seen by the writer, is reported near the southeast end of this same satellite intrusion. It is the opinion of the writer that the veinlets are of hydrothermal origin, deposited at some time after the consolidation of the intrusion. They are of no economic value.

Not one grain of chalcopyrite, pentlandite, or pyrrhotite was noted in the main intrusion, either in the

field, or in a later careful examination of all rock specimens. The main intrusion is extremely well exposed, particularly along its base where sulphide accumulations might be expected. In contrast to this, the Lynn Lake Gabbro contains disseminated grains of pyrrhotite and chalcopyrite throughout the intrusion.

The excellent exposure of the intrusion, and the apparent complete lack of copper or nickel bearing sulphides, would seem to preclude the possibility of occurrence of any economic copper-nickel sulphide accumulations in the vicinity of the present exposed surface of the intrusion. Field and petrologic evidence has indicated that the intrusion was slightly tilted at the time of crystallization. There is a possibility that more basic rocks exist at depth, but this is unlikely. In view of the absence of copper-nickel bearing sulphides along the five mile length of the main intrusion, any sulphide bodies which might exist would be expected to occur at depths which would make exploration and development prohibitively expensive, if not impossible.

SUMMARY AND CONCLUSIONS

The Granville Lake Gabbro is a strongly differentiated layered intrusion which consists of a large main body and a number of smaller apparently undifferentiated satellites. The main intrusion originated as a homogeneous gabbroic magma, which crystallized in a nearly horizontal position with the present southeast end being slightly higher. Differentiation was effected by crystal settling. The zones of the main intrusion, commencing from the base, are:

1. A gabbro zone which is predominantly gabbro close to diorite in composition, with lesser diorite and relatively minor quartz gabbro and quartz diorite. Specific gravity studies indicate a chilled zone at the base of the gabbro zone, but there is no evidence of chilling along the upper contact of the main intrusion.
2. A transition zone which varies in composition from diorite to quartz diorite and minor granodiorite.
3. A granite zone consisting of albite-microcline granite, albite granite, and minor albite syenite.

Mineralogical and chemical variation across the intrusion is consistent with differentiation of a gabbroic magma, and similar in many respects to other differentiated intrusions. The specific gravity of rocks of the intrusion is closely related to their silica content, and provides an easily determined index of differentiation. The undifferentiated Granville Lake magma is inferred to have had a silica content of 54 per cent. This value is confirmed by the average specific gravity of the basal chilled zone, which would indicate that the present erosion surface is essentially representative of the entire intrusion.

The intrusion does not show evidence of significant regional metamorphism, but late deuteric alteration has resulted in almost complete alteration of primary pyroxenes to amphiboles. Contact metamorphism of the enclosing Sickie sediments is minor and is confined to a zone a few feet in width. A one-quarter mile wide foliated zone in these sediments was formed by stresses induced in the sediments during later folding, with the intrusion acting as a rigid and unyielding mass.

Specific gravity studies indicate that the southeast satellite intrusion is partially differentiated. There is no evidence of significant differentiation of any other satellite.

It is unlikely that any economic mineral deposits will be found in the Granville Lake Gabbro.

Two main trends for differentiation of basaltic magmas are evident. Differentiation can result in any gradation between the two types. The types are:

TYPE I: A differentiation trend consisting of pronounced enrichment of iron relative to magnesia until late stages of crystallization, followed by a decrease in iron and enrichment of alkalies.

TYPE II: A differentiation trend which essentially follows the trend of the calc-alkaline series of igneous rocks, with continuous enrichment in alkalies.

The partial pressure of oxygen (pO_2) acting in a magma affects the course of differentiation. Magmas in which pO_2 is low follow the type I differentiation trend, whereas those having a high pO_2 follow the type II or calc-alkaline trend. The principal factor causing constant or increasing pO_2 in a basaltic magma during differentiation is its water content, only a small percentage of water vapour in the original magma being required. The Granville Lake Gabbro follows the type II differentiation trend, and mineralogical and chemical evidence indicates that the magma was wet.

The effect of water on a silicate magma is to increase the content of ferric iron at the expense of ferrous

iron. In rocks produced by crystallization of dry magmas the ratio of ferrous iron to ferric iron will be high, whereas in those rocks produced by crystallization of wet magmas it will be low. The Karroo dolerites, Tasmanian dolerites, Whin Sill dolerite, Palisade diabase, and the Skaergaard intrusion all have relatively high $\text{FeO}:\text{Fe}_2\text{O}_3$ ratios, and are therefore presumed to have been dry. The Granville Lake Gabbro has a relatively low $\text{FeO}:\text{Fe}_2\text{O}_3$ ratio and the magma had a correspondingly high water content.

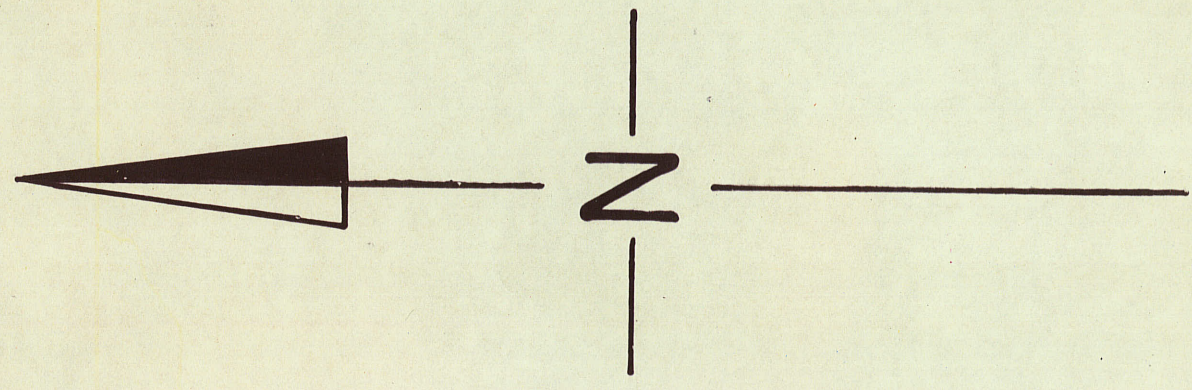
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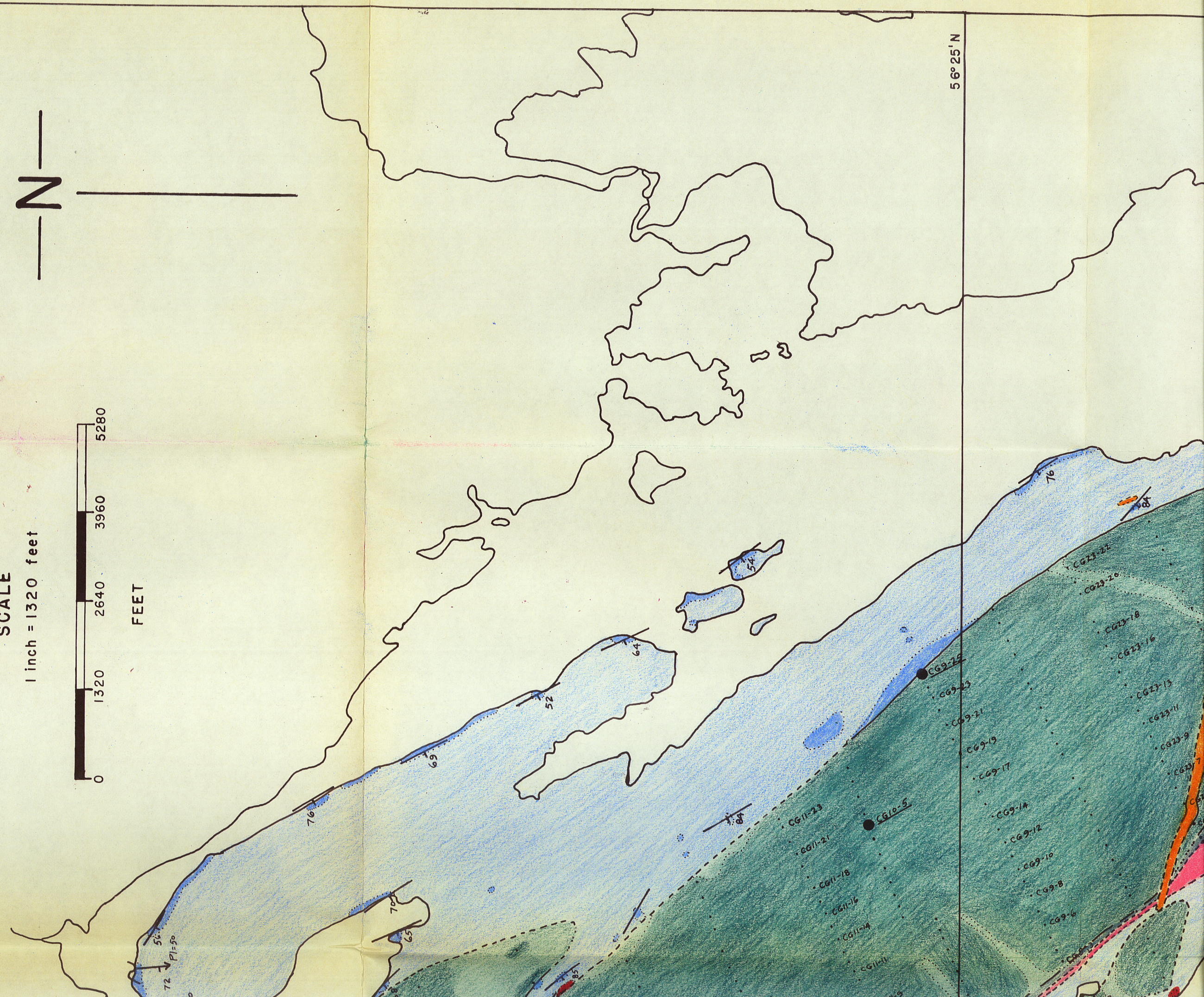
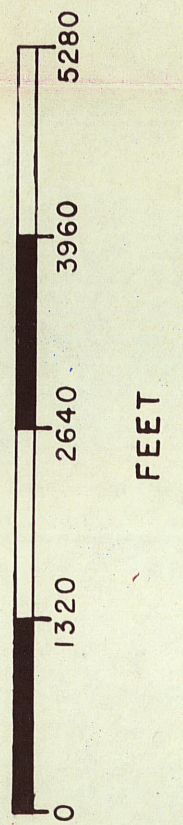
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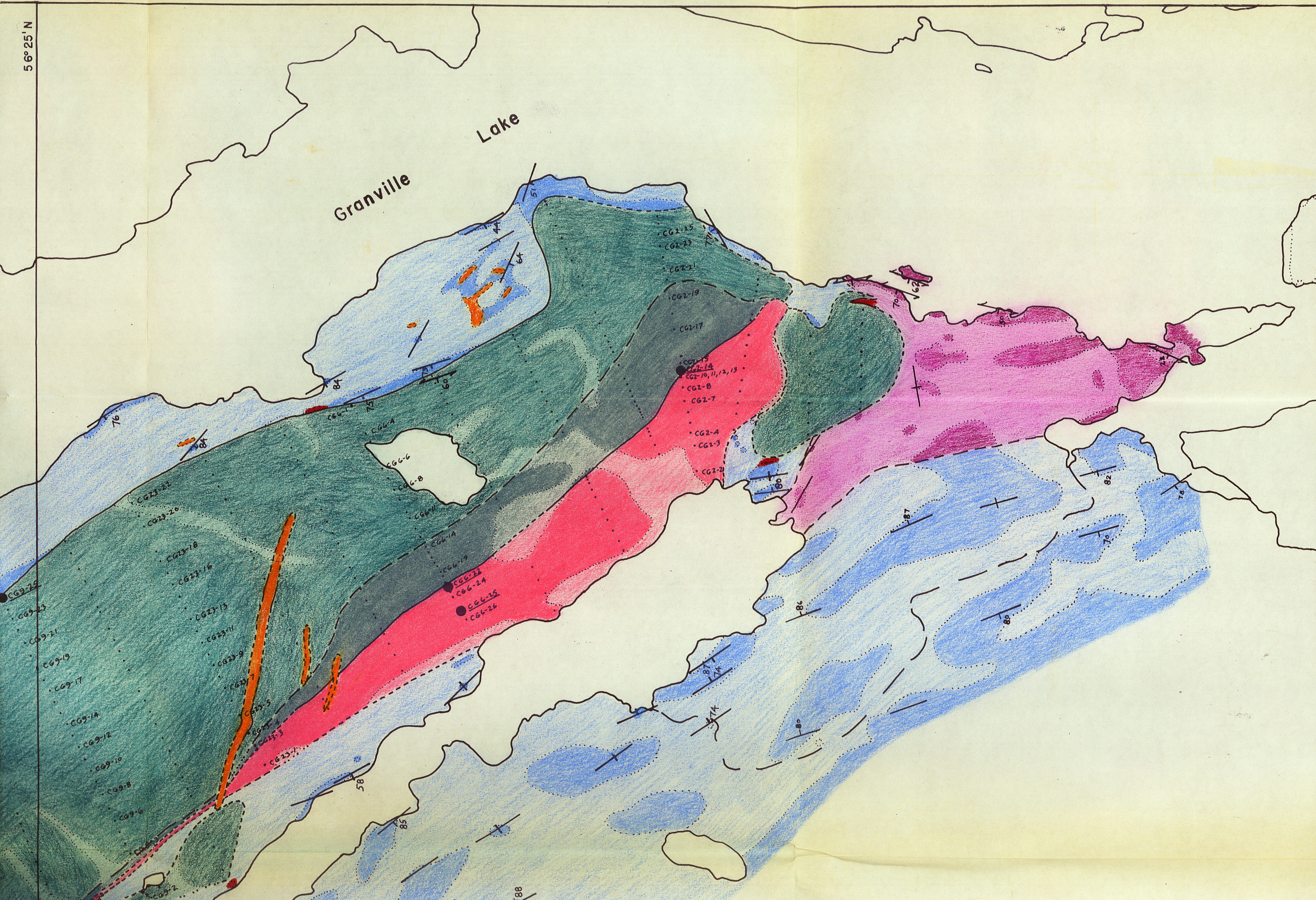


SCALE
1 inch = 1320 feet



56° 25' N

56°25'N





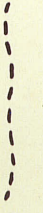
GRANVILLE LAKE GABBRO

GEOLOGY

LEGEND

- PRECAMBRIAN
-  PEGMATITE
 -  PEGMATITE-SCHIST-SEDIMENT COMPLEX — derived from Sickle greywacke
 -  GRANITE ZONE—albite-microcline granite, albite granite
 -  TRANSITION ZONE—diorite, quartz diorite, minor granodiorite
 -  GABBRO ZONE—gabbro to diorite, minor quartz gabbro and quartz diorite
 -  BRECCIATED GREYWACKE—cemented by pulverized rock, rarely by chilled gabbro
 -  SICKLE SERIES — well bedded greywacke

Geological Boundary

-  Defined - exposed, may be slightly gradational
-  Gradational - exact placement somewhat arbitrary
-  Assumed - probably accurately located, but not well exposed or not traversed
-  Indefinite - located from aerial photographs, occasionally inferred in the absence of outcrop

Sedimentary bedding

Schistosity, gneissosity

 Drag fold, plunge of axis 40°, dip of axial plane 67°

Location of specimen

 Location of specimen and thin section

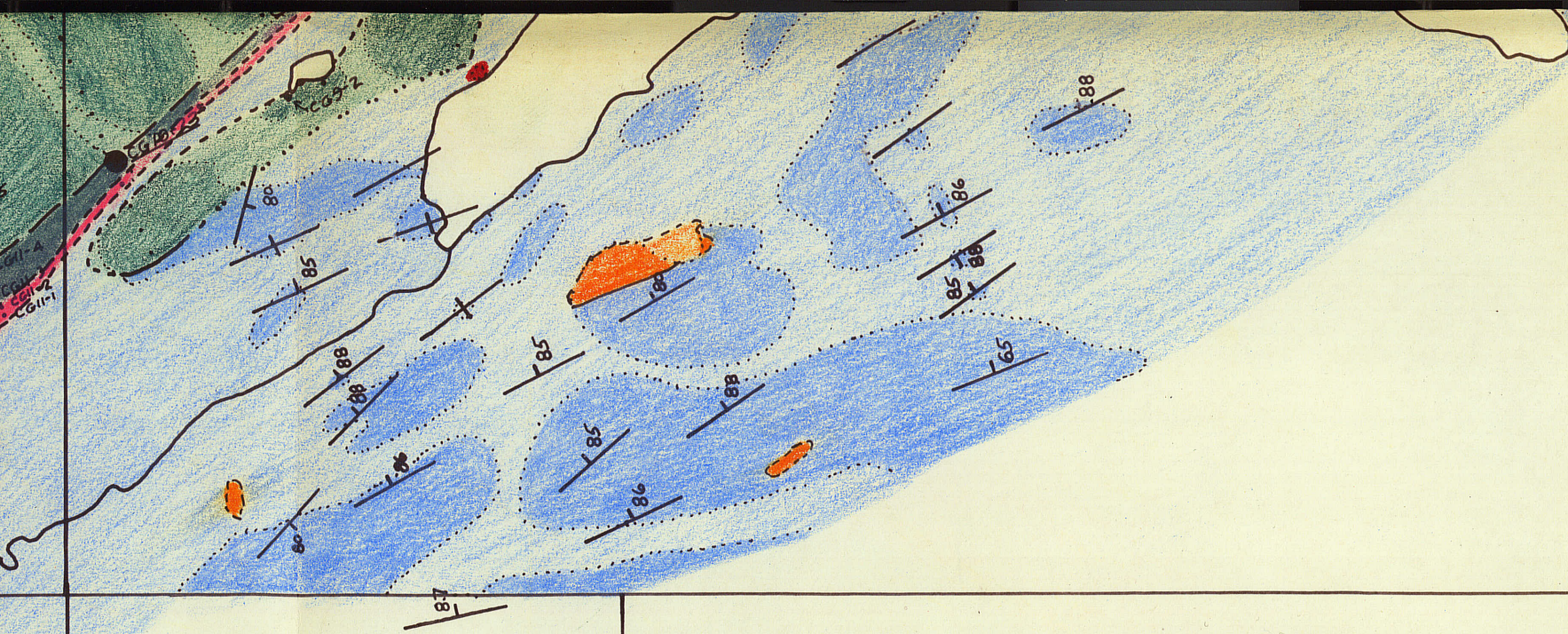
 Location of chemically analyzed specimen

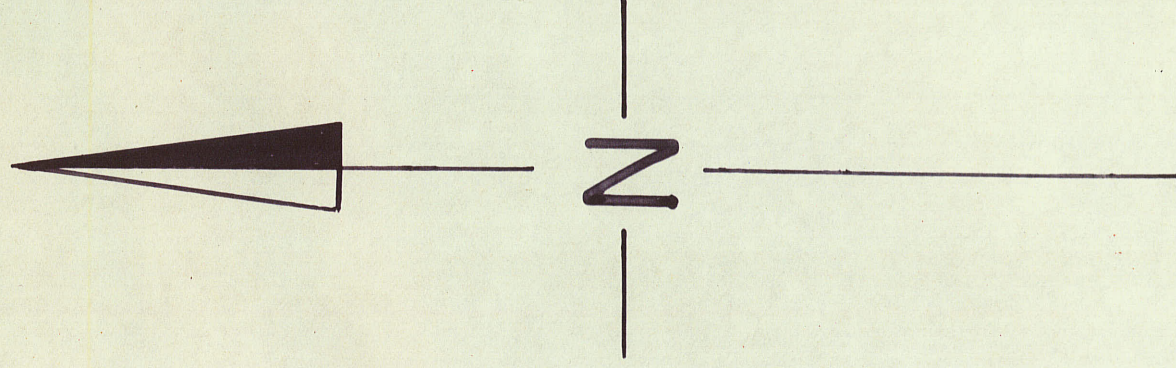
Area of outcrop



Geology by D.A.Cranstone, August 1961

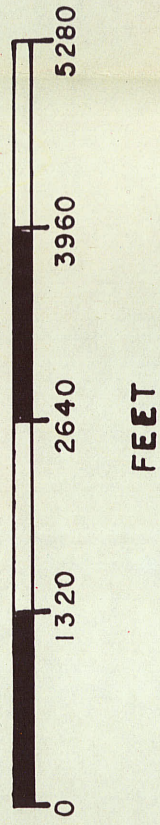
Base map by Manitoba Department of Mines and Natural Resources



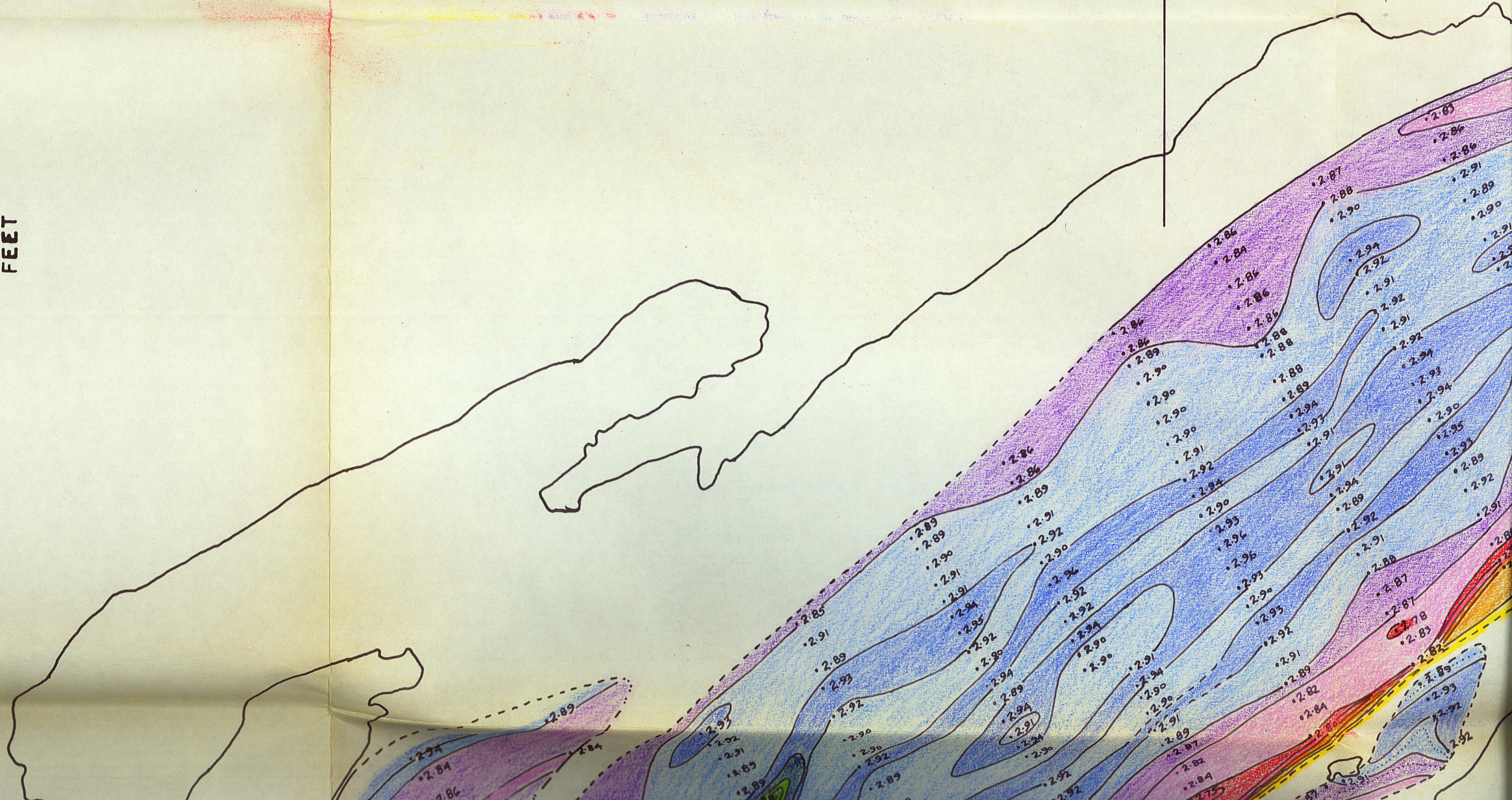


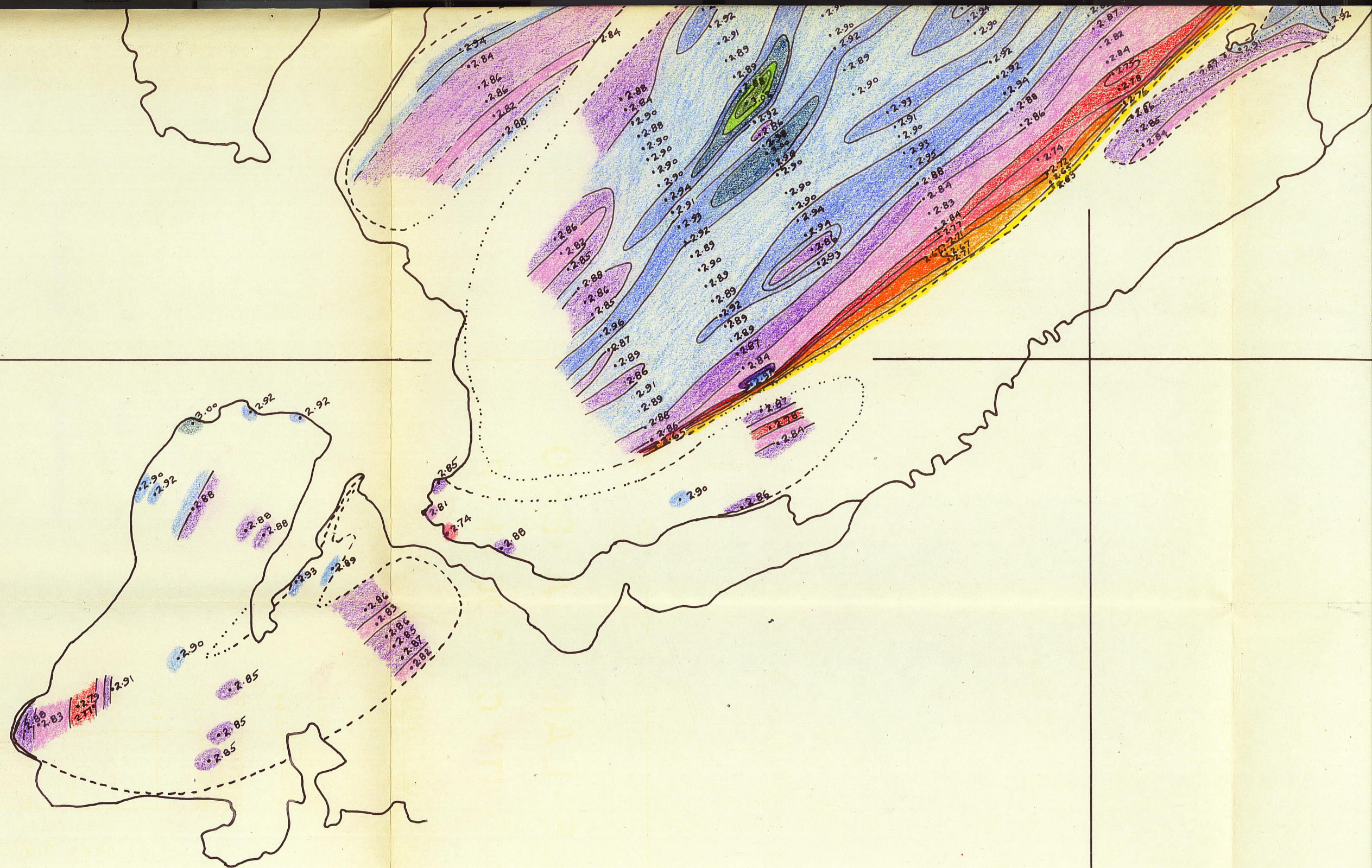
SCALE

1 inch = 1320 feet



56°25' N





100° 45' W

Specific Gravity	Color Description
3.08	Dark Green
3.04	Light Green
3.00	Dark Blue
2.96	Medium Blue
2.92	Light Blue
2.88	Dark Purple
2.84	Light Purple
2.80	Dark Red
2.76	Light Red
2.72	Dark Orange
2.68	Light Orange
2.64	Yellow
2.60	Light Yellow
2.56	Grey