STUDIES OF A SCAPOLITE-PYROXENE-GARNET GNEISS FROM THE CASCADE LAKES, KEENE, NEW YORK

by

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Abstract

During 1965 and 1966 field work in the Cascade Lakes area, Keene, New York, uncovered a scapolite-pyroxene- garnet granulite of limited areal extent. Petrographic studies were undertaken of this and several other rock types which were present in close association with the scapolite granulite. These rocks included gabbroic anorthosite, anorthosite, basaltic dike rocks, metamorphosed limestones, syenites, and granitic pegmatite.

The density of the gneiss is an unusual 3.26, and the mineralogy is indicative of high temperatures and pressures. Accessory mineralization consists of sphene, apatite and quartz; alteration products are primarily sericitic in nature.

The high pressure and temperature condition necessary to generate this assemblage is almost inherent in the environment of the Adirondack Precambrian, but the introduction of volatiles necessary to create scapolite seems associated with a pegmatite which is exposed near the granulite. Further contributions of volatiles (essentially carbon dioxide) could have been derived from the included limestones of the Grenville. Scapolitization of the gabbroic anorthosite is extensive near the pegmatite body, but is not a general feature of the area.

The gabbroic anorthosite contains numerous granulated zones of a linear character, and the foliation of the granulite is parallel to these crushed areas. If the presence of volatile constituents, susceptible structurally controlled zones, and intense temperature-pressure conditions can be demonstrated, it is perfectly possible to generate the scapolite-pyroxne-garnet assemblage. It is the writer's feeling that these conditions were prevalent and that the creation of the granulite was caused by introduction of late stage magmatic eminations into crushed zones during dynamic metamorphism.

Interest in the Grenville limestones of northern New York was apparently stimulated by a report to the Philadelphia Academy (1822) by A. E. Jessup and Dr. William Meade after they had travelled through the Champlain Region in 1810. (Kemp, 1895, p. 243)

The first published accounts dealing with the actual localities in Keene, New York which are pertainent to this thesis must be credited to Prof. E. Emmons, then of Williams College. The work which he did in the second district of New York was published by the state geological survey. The following comments are contained therein:

> "The primitive limestones are always coarse and crystalline, frequently friable and rapidly broken down...A handsome green variety which becomes a beautiful blue by exposure to the weather, occurs at Keene, at Long Pond."
>
> "I infer the igneous origin of the primitive limestones..."

The occurence still yields the fine specimens mentioned by Emmons, even 126 years after the submission of the report. (Emmons, 1839, pp. 196 & 202)*

By 1847 the economic potential of the area was recognized in the discovery of magnetic iron ore in the town of Keene. Mining commenced in 1872 and continued for about eight years. The best accounts of the operations are available in the report on the Tenth Census of New York according to Kemp (1921, p. 22). The Report of the State Geologist

* It should be noted that since the report was was written, the name Long Pond has been superceded by the name Cascade Lakes. The original name was derived because French explorers correctly mapped the waters as a single narrow lake. In 1830 a landslide split the lake in two and created the waterfalls for which they were later named.

for 1884 shows the area around the south side of the Cascade Lakes mapped as "Lower Laurentian iron ores" after the terminology then extant for the Precambrian. (Hall, 1885, map)

The Cascade Lakes area is agian mentioned in the Preliminary Report on the Geology of Essex County in 1894. (Kemp, 1894) The report deals with the body of iron ore found on the east flank of Cascade Mountain near Owl's Head; and does not touch upon the actual area of this thesis, but the following quote is useful since the occurences are so similar.

> "The little area upon the mountain at Cascadeville we did not explore beyond the iron mine. It afforded in the float beautiful diopside and several other minerals in a limestone. Emmons regarded it as a dike of limestone, but he then described a list of very characteristic contact minerals (pyroxene, idocrase, apatite, scapolite). The mass is doubtless a fragment caught up in anorthosite." (p.469)

This mention of scapolite was further enhanced in the report by the observation that scapolite is a common mineral in the "black schists" associated with iron ores. This association is found in other of the titaniferous iron ore deposits of the Adirondacks. (Stephenson, 1945, p. 24)

Another publication by Kemp (1895, pp. 241-262) presents further details on the metamorphosed limestones of the Cascade area. He describes a garnet granulite from the Owl's Head occurence of unusual composition. The rock was composed of garnet, feldspar, green augite, apatite, microperthite, and plagioclase. The pyroxene and garnet were notably intergrown, and pyroxene was notably associated with the oxide minerals.

An analysis of the limestone associated with this granulite gave the following composition after removal of the silicate fraction:

CaO	46.79%	Fe_2O_3, Al_2O_3	1.72%
MgO	5.15%		
CO_2	42.42%	H_2O	2.16%

Kemp used this data to infer that the original rock had been a slightly siliceous dolomite.

This paper also contains the best description of the Cascade Lake occurence found in the literature:

> "... a body of lean ore some 200 to 300 feet above the water alongside the first Cascade. From the ore body a narrow belt of crystalline calcite, from eight to ten feet across, extends from 1000 to 1500 feet and more to the south. It is thickly charged with very beautiful coccolite and black garnets. Emmons mentions scapolite also.... The Walls of the limestone are typically anorthosite." (Kemp, 1895, p. 260)

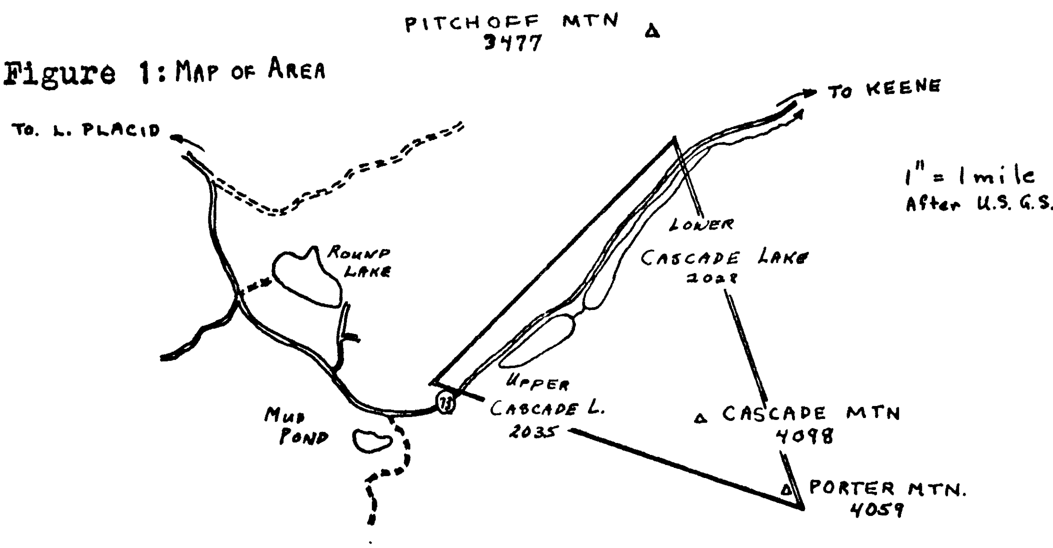
Kemp then expresses the view that the exposure is a vein, thus in one statement contradicting Emmons' arguements for an igneous origin, but also compromising his view that the similar body on Owl's Head is a contact feature.

The most comprehensive work available on the quadrangle is contained in State Museum bulletins 229 and 230. (Kemp, 1921) There is considerable discussion of the differant types of altered limestones and gneisses as well as a description of different reaction rims encountered in petrographic studies. (Roessler, 1921) The results of this report will be presented during the discussion of the problem which follows.

It should be noted that the brief historical summary of geologic work in the area of this thesis is by no means complete. It contains a summary of major publication and interest, but by no means represents the summation of references available. It is meant only as a set of introductory remarks, not as a literature guide for the reader.

Field work in the Cascade Lakes area was begun during July 1965 when several weeks of reconnaissance mapping were done in the northern part of the Mount Marcy Quadrangle.

Figure 1: Map of Area



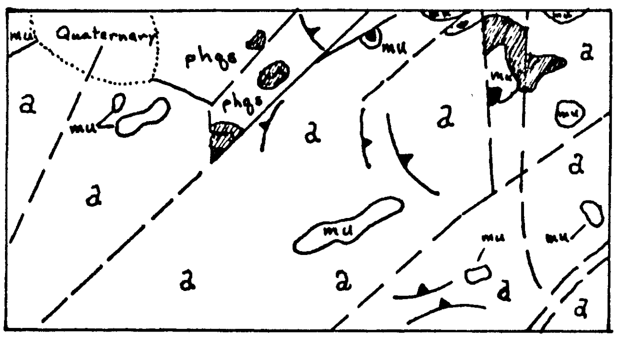
The area of investigation was confined primarily to the triangular area marked on the above sketch map. (figure 1)

The southern apex was marked by the summit of Porter Mountain; the eastern and western apices were more poorly defined. The field work was initially directed toward investigation of an included body of Grenville limestone from which interesting calcite-diopside specimens had been long noted. [redacted] Among samples collected during this reconnaissance were specimens of gneiss which were to change the orientation of this study; for petrographic analysis during October 1965 revealed that the sample was a pyroxene, garnet, scapolite, sphene assemblage. Due to the unusual mineralogy, further investigations were directed toward this rock type.

New field work in October 1965 was directed toward an examination of this rock type in situ, determination of its extent, relation to other rock types, and collection of samples. The completion of these objectives was hampered by snowfall and only two days were spent in these pursuits; many questions consequently remained unanswered.

Further attempts at field investigation were made in March of 1966 when several days were spent in studying the detailed geology of the area. Snow and ice hampered the study again, but considerable success was achieved. Due to the poor conditions, several days were devoted to investigation of roadcuts in the general area, and, in particular, to an outcrop in the Newcomb Quadrangle near the Hudson River. This outcrop of a scapolite-garnet-pyroxene rock was originally described by Balk (1932, p. 23); but since that date road construction had increased the outcrop area and provided fresh surfaces. Considerable valuable data was gained from this examination as will be discussed later in the text.

There are numerous rock types exposed in the northern area of the Mount Marcy Quadrangle. The geologic map of the State of New York (1961), reproduced in part below, shows five major mapable units.



After N.Y.S.G.S. 1961

Figure 1a: Geology of the Mount Marcy Quadrangle.

a = anorthosite
phgs = pyroxene-hornblende syenites
mu = undifferentiated metamorphic
//// = charnockites and metasediments
● = marbles

For large scale mapping, these units are quite satisfactory, but in more detailed work numerous other rocks which cannot be assigned to these major units are found. Reconnaissance quickly reveals pegmatite, skarn, granulites, dikes, etc. which are too local to be placed on any commercially available topographic map. (The best available is the U.S.G.S. sheet on a scale of 1:62,500.) Consequently a pace and compass map on the scale of one inch to fifty feet was made in the area of intense interest. Reconnaissance detailled some four square miles, but the area of final interest, as shown on the map, figure 1b, was of much smaller extent.

Reconnaissance of the area north of the lakes was confined to detailed examination of five road cuts along route 73. The major rock types noted included syenitic gneisses, charnockitic rocks and some assorted gneisses and granulites. Many of these rocks contain large rounded crystals of andesine-labradorite typical of anorthosite. There are definite bands which are richer in these large fragments, but their relation to the overall foliation is complex so that no simple inferences can be drawn. The syenites contained considerable garnet either as disseminated grains or in lumped aggregates with quartz and pyroxene. The entire suite with the exception of a biotite gneiss contains very low amounts of hydrous minerals. However, the biotite gneiss contains abundant micas in association with magnetite. All rock types showed some foliation, but the best orientations were obtained on the biotite gneiss (Strike N50°W, Dip 78°W). The suite is totally different from the anorthositic rocks exposed on the south side of the lakes.

That the lakes occupy a fault controlled valley is hardly questionable; there is no structural or petrographic continuity from the north to south sides of the lakes. Kemp (1921) mapped this fault about 100 feet above the north shore of the lake. The present author does not agree that the fault can be so located, as no outcrops of anorthosite were in evidence at the time of field investigation. It is entirely possible that post 1921 road construction has concealed outcrops which were closer to the lake level than those now available. Since the reasons for Kemp's location are not mentioned in his publications, and his field notes are unavailable to the writer, this question cannot be resolved satisfactorily. The presence of the fault, however, is beyond dispute.

On the south side of the lakes, the limestone outcrops were quickly discovered by tracing float. The magnetite and pegmatite mentioned by Kemp (1921) were also easily found. The major rock type was found to be gabbroic anorthosite which rapidly grades into the major anorthosite massif which comprises most of the quadrangle. This transformation is fairly rapid and poorly defined, taking place within the mile distance from the lake shore to the summit of Cascade Mountain. During the reconnaissance of the area a sample of pyroxene and garnet bearing gneiss was collected in the bed of the small stream draining the notch in Cascade Mountain between the two lakes. The material was local in extent, for no other exposures were found during the initial mapping.

A survey of the west flank of Cascade Mountain and the higher elevations of the west flank of Porter Mountain disclosed areas of rotten granulite, pegmatite (muscovite bearing), and some actually granitic rocks, although the major rock type remained anorthositic in character. Since no major rocks other than anorthosite and gabbroic anorthosite were encountered, emphasis was shifted to the Grenville inclusions and gneisses exposed in the drainage between the two lakes.

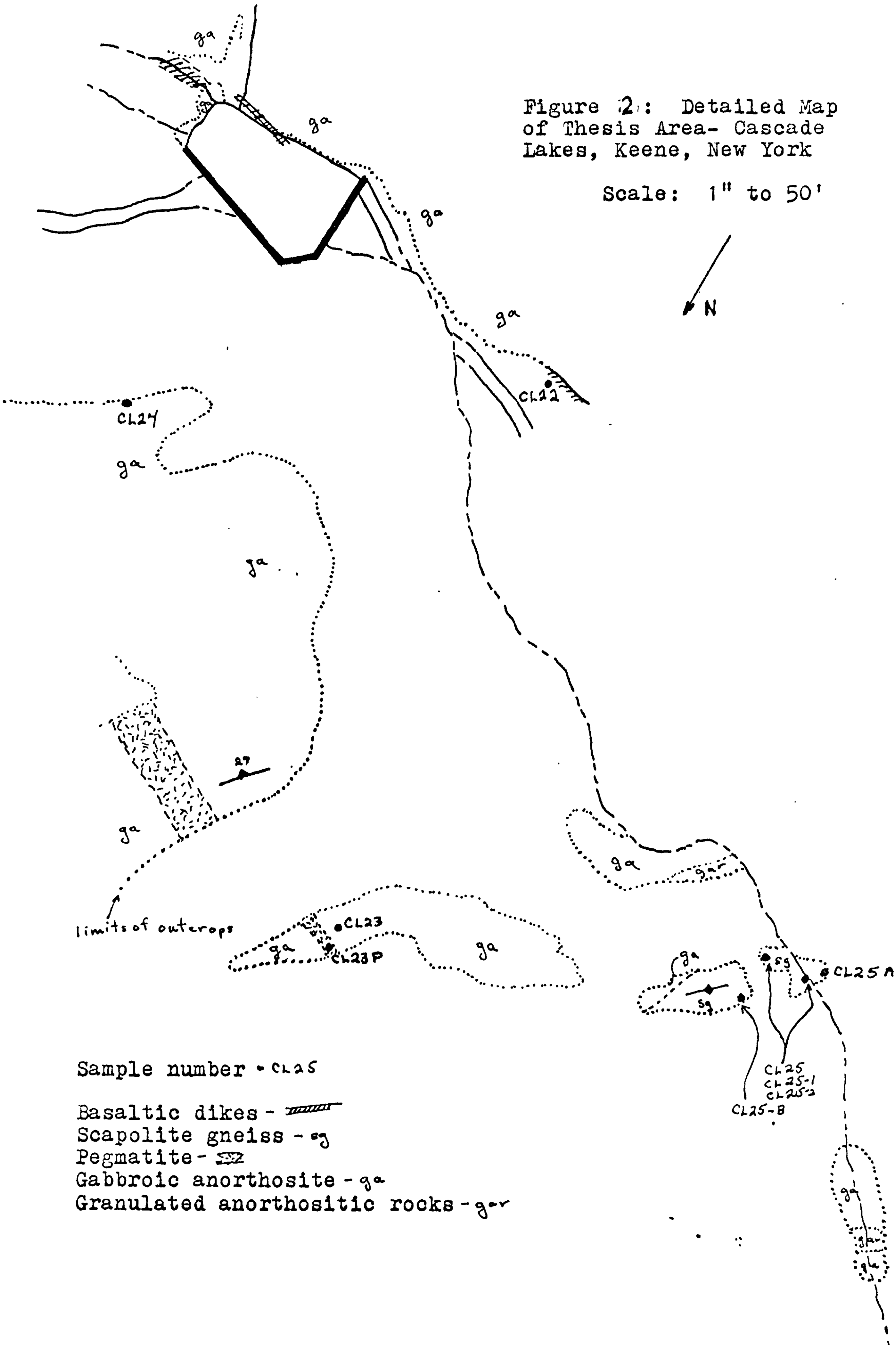
More detailled surveys of this area disclosed some highly altered, slickensided anorthosites associated with trap dikes of some few feet width near the small pond shown on the accompanying map (figure 2). The anorthosites of the area were generally gabbroic and highly variable in percentages of dark minerals (pyroxene, garnet, and magnetite). Grain size was also variable but was generally about five millimeters. The major portion of the north face of Cascade Mtn. could be classed as Whiteface anorthosite.

Several mineral occurences were noted during the summer. A crystal of magnetite of 3/4 inch length was found in a skarn near the Lower Lake. Irregular masses were also found in association with augite prisms surrounded by calcite reaction rims. The beautiful samples of pale green coccolite have already been noted in much literature (Kemp, 1921; Emmons, 1839; Kemp, 1895) and need no further commentary. Large clumps of pyroxene, quartz, and garnet were noted in several places and are especially well developed in the Marcy anorthosite on the summit of Cascade Mountain. Large pyroxene crystals of indefinite shape occur in the summit of Porter Mountain. Other minerals are not well developed except as rock-forming constituents.

Field investigations of October 1965 centered on the scapolite-pyroxene-garnet gneisses which had been discovered during the summer. Samples representing a cross-section of the gneiss were obtained and good samples showing variable grain size and mineralogy were also collected. The extent of the gneiss was left undetermined, but a general feeling for its extent and relation to other rocks was established.

Figure 2: Detailed Map of Thesis Area- Cascade Lakes, Keene, New York

Scale: 1" to 50'



Sample number • CL25

Basaltic dikes -

Scapolite gneiss - sg

Pegmatite -

Gabbroic anorthosite - ga

Granulated anorthositic rocks - gar

The studies of March 1966 met with weather difficulties, but the eastern and western boundaries of the gneiss were determined. It was found that the scapolite-pyroxene-garnet gneiss was gradational into a scapolite-pyroxene-magnetite granulite. The gabbroic anorthosite in the area of the gneisses and pegmatite had been found to be scapolitized, and was therefore reexamined; but no new information was forthcoming.

The outcrop of scapolite rock in the Newcomb Quadrangle was examined during March and was found to be fairly similar to the gneiss of the Cascade Lakes, though there were certain differences worthy of note: 1) The grains are much coarser in the Newcomb occurence, 2) micas and other hydrous minerals are present, and 3) scattered sulfides are present. Balk (1932, p. 23) describes the rock as a contact metamorphic effect in Grenville limestone resulting from intrusion of a syenite sill:

> Between presumeably normal grenville marble below (not visible in the road cut) and a syenite sill above, a road cut exposes some twenty feet of a medium-grained, well-foliated, lime-silicate rock. Megascopically, one can distinguish white quartzose, brown garnetiferous and green diopsidic layers. Under the microscope the rock is composed of scapolite, diopside, microcline, garnet, calcite and quartz. The scapolite is somewhat seriticized and chloriticized. Rows of gas bubbles in quartz grains pass without change in direction into adjacent scapolite grains, but are interrupted by secondary calcite. Where such lines pass through the diopside they cause fine cracks along which the crystals are serpentinized. The rock structure is typically crystalloblastic.

The present writer is somewhat skeptical of this mode of origin for the rock type. The present outcrop is considerably larger due to recent road construction and exposes the contact of the underlying Grenville marble with the scapolite rock. This contact is quite sharp; it exhibits little of the gradational character that would be expected in a system where extensive introduction of volatiles would most likely be necessary to create scapolite. The only variation in the scapolite rock as the contact is approached is a decline in the amount of garnet, but such local variations have been found in the midst of the gneiss at the Cascade Lakes at some distance from any contact. Consequently, the writer feels that there must have been original differences in composition to have allowed the scapolite rock to develop in contact with the Grenville marble. This view is supported by the lack of silicates in the marble (the only one is the magnesian mica phlogopite). It seems unreasonable to assume that a reasonable contact could have been maintained in a system with such variable compositions, unless original compositional differences were present.

The following section contains detailed descriptions of the major rock types in the thesis area. Those types of least importance receive only superficial treatment, and further information on them can be found in the appendices. All point count data and many subsidary features of the rocks are given in the tabulations in those appendices to avoid burdening the text with excess material which is unnecessary except for detailed reading.

Gabbroic anorthosite: (Samples CL7 and CL24 in Appendices) As can be seen by reference to figure 1b this is the major rock type in the thesis area from the standpoint of outcrop area. The samples examined throughout the area showed considerable variation in percentages of dark minerals which varied from 25% to 50%. There is considerable variation in the percentage of opaque minerals present, as well, but the plagioclase composition is very uniform, composition An_{45}.

Handspecimen examination reveals that there are many large, relatively uncrushed grains of plagioclase in an otherwise granulated matrix. Garnet reaction rims around magnetite and pyroxene in the samples are readily visible on fresh surfaces. The uncrushed rock is generally gray even when weathered, whereas the crushed material weathers to a buff color.

Thin section studies revealed many of the common features of anorthositic rocks such as the presence of two pyroxenes and in some case amphibole. The perthitic nature of much of the plagioclase is readily apparent. Often the lower index mineral is distributed as small irregular blebs showing no particular orientation with respect to the plagioclase, but some grains have perthitic growths in the 010 twin planes. The composition of the inclusions is uncertain. Perhaps the problem is best presented in the following excerpt:

> In the thin sections certain small grains and inclusions were determined as doubtful orthoclase or microcline. It is quite possible that these are anorthoclase... (Roessler, 1921, p. 45-46)

Roessler hypothesizes that the reaction of pyroxene and plagioclase could produce an excess of sodium which could form anorthoclase inclusions according to the reaction:

$$MgO \cdot FeO \cdot (SiO_2)_2 + CaO \cdot Al_2O_3 \cdot (SiO_2)_2 + NaAlSi_3O_8 =$$

$$CaO \cdot MgO \cdot FeO \cdot Al_2O_3 \cdot (SiO_2)_3 + SiO_2 + NaAlSi_3O_8$$

Hypersthene + Plagioclase = Garnet + Quartz + Albite

The presence of free quartz in association with pyroxene has been frequently noted in the samples, and hypersthene is a common pyroxene along with ferro-augites. This reaction not only would account for the perthitic plagioclase, but also produces the garnet reaction rims and the free quartz.

There are numerous other features which might be noted, but the following three are perhaps most interesting and useful to this discussion:

1) The plagioclase may be zoned although the change

in extinction is gradual rather than abrupt. The interiors of such grains often contain minute grains which are absent in the outer zones. Examination under high power showed that most of these inclusions are probably clino-pyroxenes as indicated by octagonal cross-sections.

2) The alteration of the hypersthene produces grains of magnetite which often rim grains and fill fractures in the grains. There is also considerable limonitic staining of fractures in feldspars associated with such weathering grains of hypersthene.

3) Pleochroic hornblende (possibly uralite) replaces augite in some instances. The hornblende is generally totally unaltered.

Discussion of the genesis of these rocks is of little value to this work, but a description of the effects of granulation on anorthositic rocks would be pertinent since it is the feeling of the author that such crushed anorthosite is easily altered to a scapolite assemblage under proper conditions.

The area has numerous outcrops of granulated anorthosite, notably on the west flanks of Porter and Cascade Mtns. The granulites may be fairly hard or rotten to depth, but this is apparently a function of the amount of weathering to which the exposure has been subjected as well as the degree of cementation which has taken place following granulation. No thin section of this rock type was made so the following description of an unweathered hand specimen must suffice.

Even freshly broken surfaces have brownish weathering, especially around the dark minerals. The rock is very thoroughly granulated. Very few large grains of plagioclase have remained and those that have are heavily fractured. Aside from these remnants, no crystals of greater than a millimeter are present in most samples. Garnet reaction rims are still present, but are altered and stained. In general, the rock appears quite susceptible to alteration by fluids with access through the numerous fractures. In this regard it seems the most likely candidate for replacement and development of the scapolite-pyroxene-garnet assemblage locally found in the anorthosite.

Basaltic dike rocks (Appendix-sample CL22) These dike rocks are typical of the trap dikes found in the Adirondacks. There are three major dikes in the area trending roughly northwest to southeast at a high angle to the prevailing fault system and the major jointing in the area. The dikes range up to five feet in width and several hundred yards in length. They are apparently the latest of the rock types intruded and create no contact effects in the rock types they invade.

In hand specimen the dike rock is very fine grained, black, with some small (1mm) phenocrysts visible. It weathers to a rust color or to a black smooth surface, apparently dependent upon the amount of mechanical erosion involved versus simple oxidation. No information on mineralogy can be obtained from hand specimen examination.

Petrographic analysis revealed a diabasic texture of plagioclase laths with a highly altered groundmass composed of augite and an opaque mineral, presumably magnetite. The plagioclase is twinned in both Carlsbad and albite modes, but is generally of such size as to prohibit any accurate determination of composition. The augite and opaque matrix is highly altered in comparison to the fresh plagioclase. The only accurate determinations which could be made optically were on the phenocrysts which proved to be augite in the section examined. These phenocrysts composed some 7% of the sample.

There was no further analysis, as the rock is of only minor importance to this report.

Syenites and limestones As syenites are not exposed in the thesis area, the reader is referred to the Appendices, Samples 57A and 57B, for information on samples.

from the north side of the lakes.

No thin sections were made of the limestone which outcrops near the thesis area. It suffices to present the rock as a possible source of CO_2, but otherwise its mineralogy and distribution are immaterial.

Granite pegmatite (Sample CL23P) While there are many pegmatites in the northern part of the quadrangle, this discussion will be limited to the pegmatite which outcrops on the south side of the lower Cascade Lake as it is most pertinent to the discussion of the Scapolite-pyroxlene-garnet assemblage.

The pegmatite is easily found by tracing large blocks of float. It is well exposed and attains a width of some 15 feet. It can be distinguished from the normal anorthositic country rock at a considerable distance since it supports varieties of lichens which do not grow on anorthosite. Weathered samples show two feldspars one weathering white, the other pinkish, as well as gray quartz. The major minerals, easily recognized in hand specimen, are plagioclase, perthite, quartz and magnetite. Grain size is somewhat variable but is generally greater than ½ inch with an apparent maximum of two inches.

Petrographic analysis provided much interesting detail on the rock type. The plagioclase is an unzoned Oligoclase of composition, An_{78} often myrmekitically associated with quartz. It composes about one-third of the bulk of the sample with quartz and perthite also about one-third each. The perthite is beautifully developed and some of the inclusions show distinct albite twinning. There is very little orthoclase which is not perthitic in at least part of the grain; all feldspar is somewhat sericitized. The quartz in the sample is strained in all instances except where intergrown graphically with plagioclase or perthite. All grains are generally anhedral.

The minor constituents include magnetite, pyroxene, and their alteration products. The section examined contained 10% magnetite and 1.3% pyroxene (all pyroxene was adjacent to the magnetite) and could represent reaction of the pegmatite melt with magnetite. It would appear that this percentage of magnetite is a local variation as most of the body did not show appreciable dark minerals at the time of field study.

The high calcium content of this body in relation to granite pegmatite would seem to favor a genetic relationship to the anorthosite. The presence of magnetite also seems to be a favorable criterion. The straining of the quartz grains could be indicative of crystallization accompanied by high pressures, i.e., dynamic metamorphism. There was apparently a large amount of volatile material associated with the intrusion of the body as shown by the contact effects on the gabbroic anorthosite, i.e. scapolitization, as to be discussed further in the next section.

<u>Scapolitized gabbroic anorthosite</u> (CL23) This sample was collected about five feet from the contact with the granite pegmatite. The hand specimen shows a somewhat lighter color than other gabbroic anorthosite already described, but is in other regards quite normal as far as hand specimen identification is concerned.

Thin section analysis revealed the nature of the alteration. The Scapolite is present along grain boundaries and fractures in the plagioclase grains. Replacement is of a patchy nature and many small irregular grains of magnetite occur with the scapolite (no magnetite appears in the plagioclase). The dark minerals are highly altered pyroxene and hornblende which is quite fresh. Quartz associatesonly with the pyroxene, apparently as a reaction mineral.

Minor features include a few high index grains which may be zircons, twinning and pleochroism of hornblende and sericitization of some of the plagioclase.

The scapolitization is apparently a result of introduction of volatiles along fractures and easily replaced grain boundaries. There is perhaps an inference to be drawn that some filter pressing of the pegmatite took place causing volatile constituents to migrate into the anorthosite along even the smallest avenue of escape. There is little doubt that the scapolite is a result of the pegmatite emplacement for scapolitized anorthosite is not found except in this association or in the type of ore deposit at Sanford Lake where scapolitization is associated with the late stage formation of titaniferous magnetite (Stephenson, 1947). (See figures 3 and 4)

Scapolite-pyroxene-garnet gneiss This is the major rock type under investigation, and though it is of limited areal extent, it shows many interesting variations. There are several features which set this rock apart from all other rock types encountered.

1) Unusual mineralogy

2) Density is a very high 3.26. This is intermediate between gabbro and eclogite in density and is indicative of high pressure formation and dense mineral phases.

3) The foliation is conformable to the foliation and major jointing of the anorthosite, indicating structural control.

4) The grain size is extremely variable, ranging from less than one millimeter to a conformable pegmatitic phase with individual grains reaching one centimeter.

In hand specimen it is markedly banded due to segregations of the three constituents. Even weathered surfaces fail to lose the distinct banding. Fine-grained samples appear nearly black and the bands are less distinct. The pegmatitic bands contain a higher percentage of scapolite

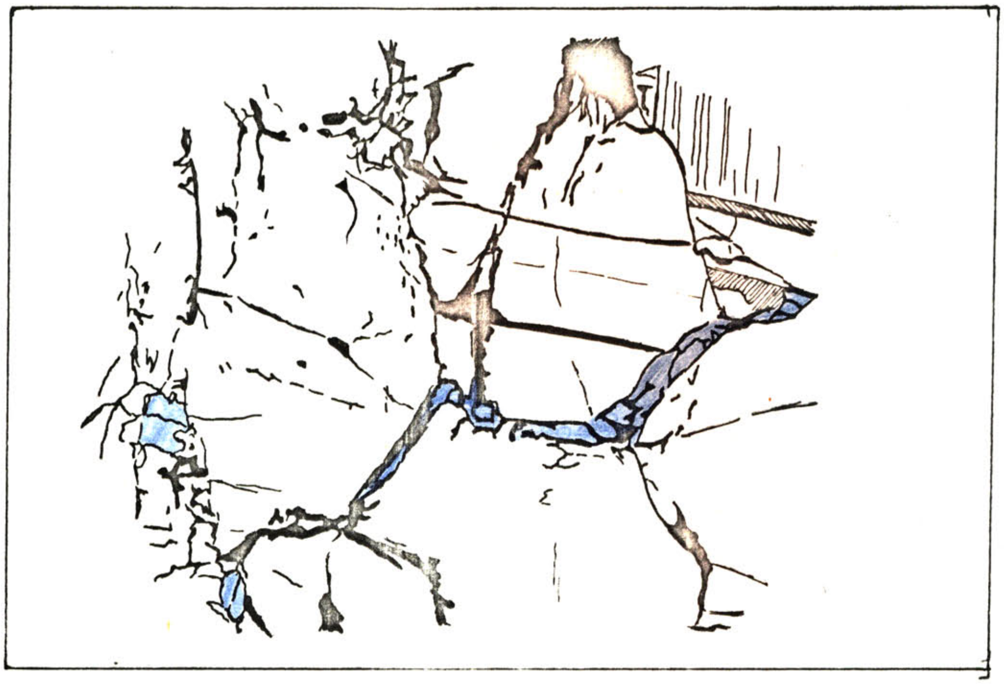


Figure 3: Scapolite replacing plagioclase along grain boundaries and fractures. Sample No. CL23 Scapolite shown in blue, plagioclase in white.

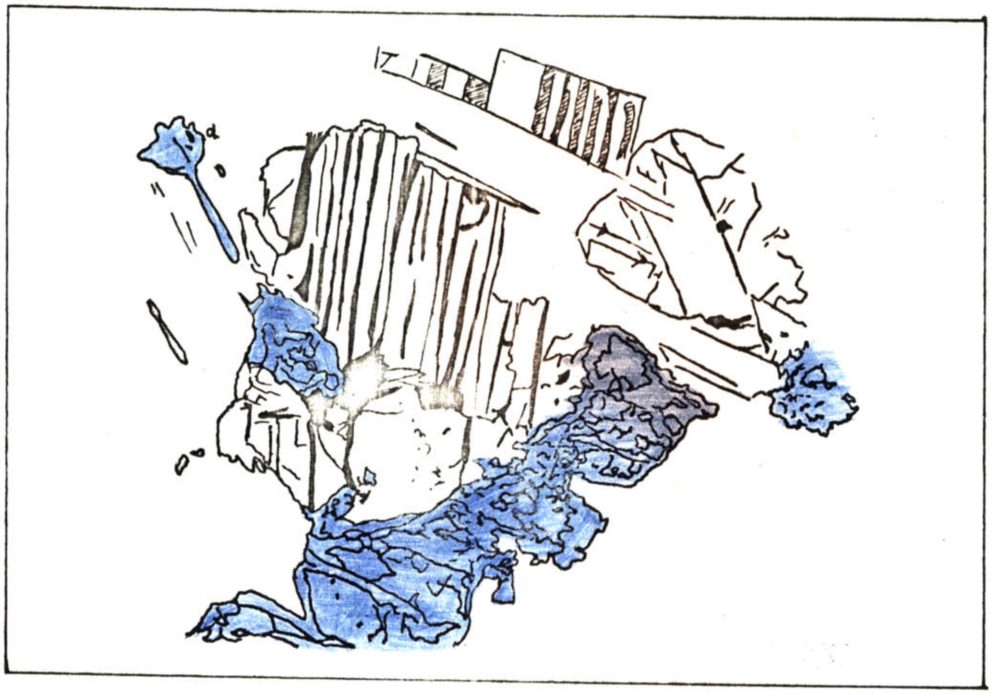


Figure 4: Scapolite replacement of plagioclase in anorthosite. Near contact with pegmatite. Scapolite in blue. Sample CL23.

than their finer grained counterparts, and are consequently light colored.

Local variations in mineralogic make-up are common, but only two of these variants deserve further consideration. One is a nearly garnetless phase which contains large (5mm) irregular masses of pale green scapolite in a matrix composed of pyroxene and white scapolite, (CL25-B) and the other is a granulite composed of pyroxene, scapolite, and magnetite with no garnet whatsoever. These two variants are very local in extent but are nonetheless of considerable interest.

Samples of the "normal" gneiss and the scapolite-magnetite-pyroxene assemblage were crushed and the minerals separated magnetically. The resulting concentrates were subjected to oil immersion analysis with the optical microscope. Since they were too opaque to obtain accurate determinations of sign or birifringence, the pyroxenes could not be identified. The garnet proved to be of index 1.7794 $\pm$ .005 which places it in the almandite series according to Larsen and Berman (1945). It is likely intermediate between the compositions given for the following indices:

1.766 $3(Mn,Fe,Ca)O(Al,Fe)_2O_3 \cdot 3SiO_2$

1.789 $3(Fe,Ca,Mg)O(Al_2O_3) \cdot 3SiO_2$

These analyses also indicate a probable trace of manganese.

The scapolite yields most readily to optical methods. The difference between the two scapolites is minor, the "normal" assemblage contains scapolite close to Wernerite of composition $Ma_{48}Me_{52}$, and the magnetite assemblage indicates $Ma_{50}Me_{50}$. The birefringence of the scapolites is higher than would be expected and according to Larsen and Berman, an increase in CO_2 content could be the cause of this increase. The higher carbonate content of the scapolite is likely a function of the limestone outcrops present in the area. The pegmatite has already been mentioned as a source for chloride ion.

Petrographic work on these samples proved to be exceptionally interesting. (see Figures 5 and 6). The first thing which became evident was the close association of the garnet and pyroxene. In some instances the garnet appears to form reaction rims between the pyroxene and scapolite.

The variation of the three constituents from sample to sample is apparently limited in some manner. If the three major minerals are plotted after adjustment to 100%, the plot of figure 7 is obtained. There appears to be a definite system to the variation as defined by the line in red on the graph. The inferences of this relationship will be discussed later.

Several accessory minerals are present, notably sphene which may comprise as much as 12.4% of the sample. Apatite is also present, often in large grains of anhedral nature.

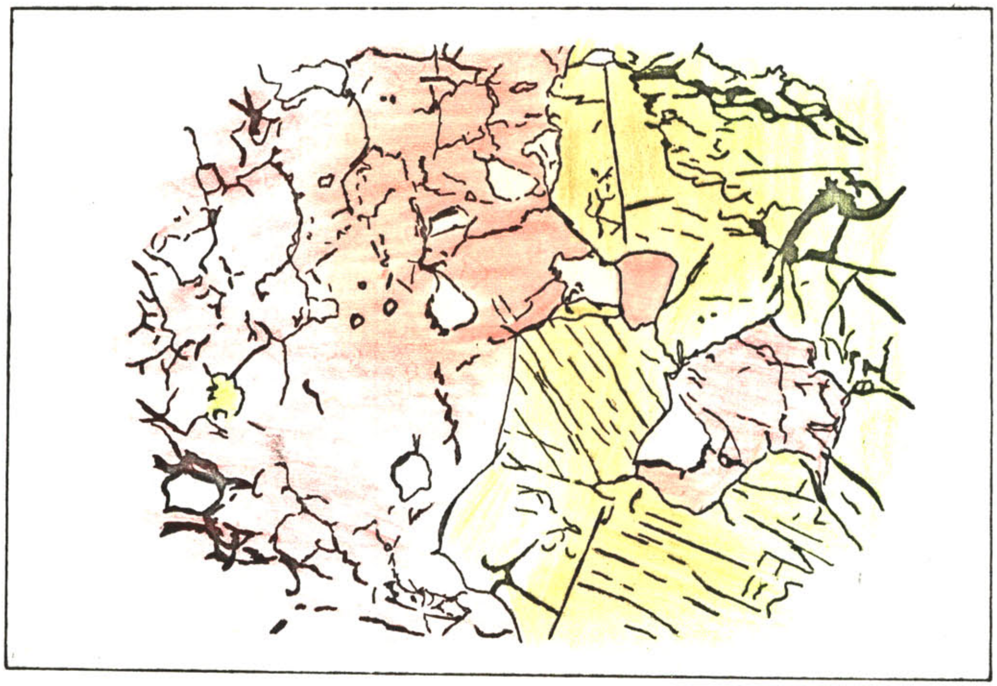
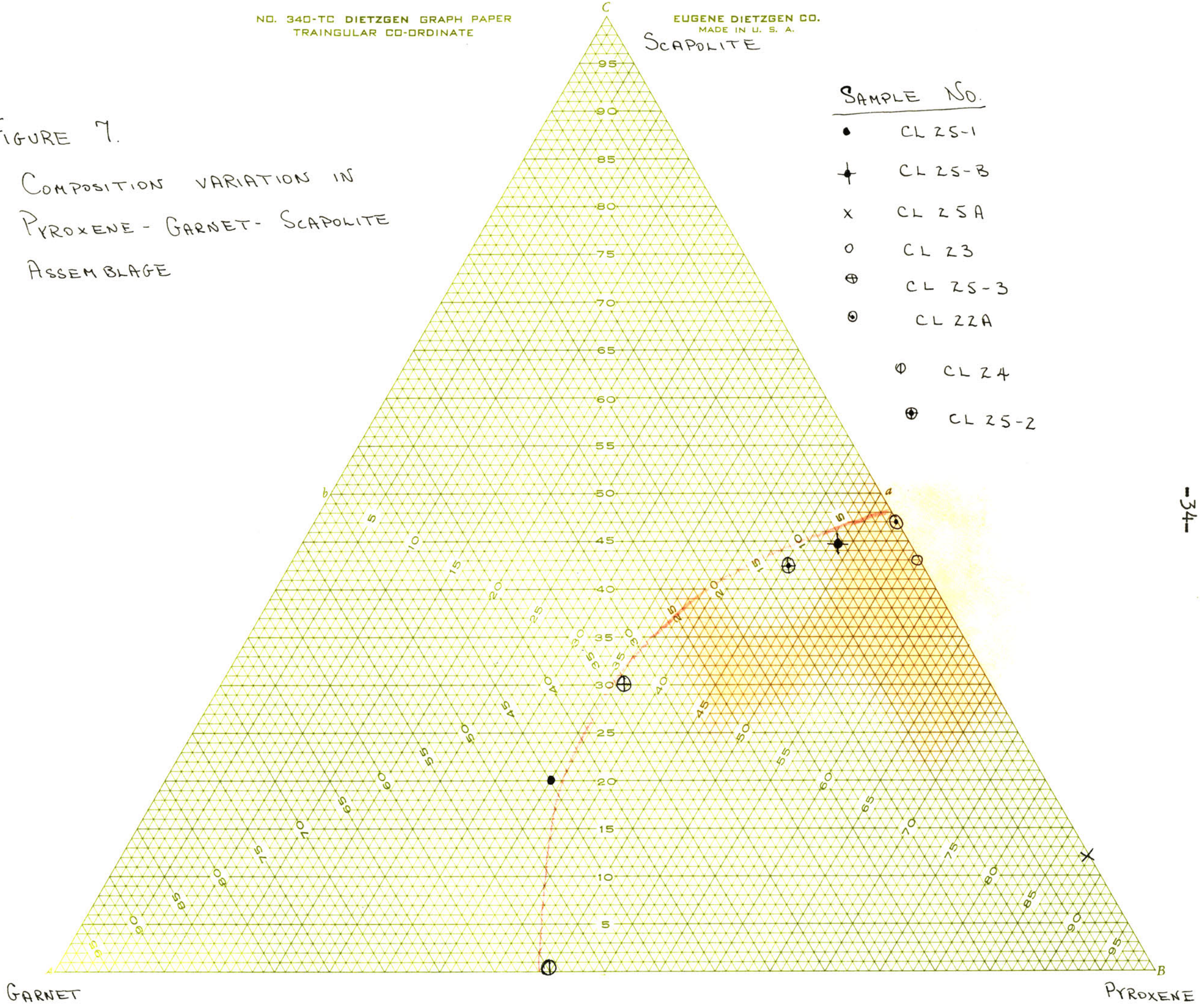


Figure 5: Garnet-pyroxene-scapolite granulite in a garnet rich region. Sample number CL25. Garnet in orange, pyroxene in green, scapolite in white.

Figure 6: Garnet-pyroxene rich portion of granulite showing development of interstitial quartz and the small grains of quartz commonly developed in the garnet. Pyroxene in green, quartz in yellow, garnet in orange.

Figure 7.

Composition variation in Pyroxene - Garnet - Scapolite Assemblage



highlighted by alteration.

The presence of garnet and diopside is indicative of high temperature and high pressure conditions. It is almost certain that this phase would represent the upper granulite facies. The formation of scapolite must be considered as well, however, so that a general discussion of theoretical data and some of the processes of metamorphism would seem necessary before any finalized theory for the formation of the assemblage is propounded.

Assemblages of scapolite-pyroxene-garnet are not uncommon in the literature, and the phenomenon of scapolitization is familiar to most geologists. The following list is meant as a guide to some of the more important area where regionally distributed scapolite rocks have been found.

1) Buddington described widespread scapolitization of the Grenville sediments in the northwest Adirondacks as a result of emplacement of syenite. (Turner, 1948, p. 101)

2) Sundius described regional scapolitization and a pyroxene-garnet-scapolite gneiss in Norway in 1915. (Turner, 1948, p.101)

3) Weiss described a local metagabbro which had been altered to a scapolite metagabbro composed of diopside and scapolite. (Weiss, 1958)

4) Edwards and Baker described samples of a series of scapolite granulites of regional distribution in Queensland, Australia. (Edwards and Baker, 1953)

5) von Knorring and Kennedy described a pyroxene-hornblende-garnet-scapolite occurence of possibly regional extent in Ghana. (von Knorring and Kennedy, 1958, pp. 842-862)

Before discussing any field data, it seems worth while to spend some time reviewing the information on scapolite formation which has been gathered experimentally.

Very little information of practical value is available in the literature on scapolite. Stability, melting point, temperature of formation, and temperature of reactions with other minerals have been only sparsely determined for some parts of the series. Chemical and optical work have yielded the information that as the percentage of calcium in a scapolite rises, the carbonate content rises at the expense of the chloride. Some experiments in synthesis have been conducted and been successful in forming single end members, but these experiments have not resolved basic problems.

Deer, Howe and Zussman (1964, p. 328) make the following summary of synthesis experiments:

> "Eitel (1925) synthesized meionite at CO_2 pressures of 112 bars during his investigation of the system Na_2CO_3-$CaCO_3$-$NaAlSi_3O_8$-$CaAl_2Si_2O_8$. Fyfe et. al. (1958) failed to synthesize scapolite from anorthite-calcite-$CaCl_2$ mixtures at temperatures between 400-700°C at H_2O pressures of 500 bars. The dry synthesis of marialite from seeded mixtures of $Na_2O \cdot 6SiO_2$, Al_2O_3 and NaCl at one atmosphere pressure and temperatures between 700 and 850°C in runs of one to two weeks has been reported by Eugster and Prostka (1960)."

They also note that Marialite melts incongruently at 860°C to form albite and NaCl rich liquid. The eutectic lies very close to the NaCl side. In general, however, the scapolite series is so complicated by volatiles that little about its crystallization is understood. Although Barth mainstains that scapolite can be synthesized from the components at 800°C, Fyfe, Turner and Verhoogen maintain that the temperature must be below 700°C or the chloride will be hydrolized and no scapolite can crystallize. (Barth, 1963, p. 255) and (Fyfe, Turner, and Verhoogen, 1958, p. 161)

Due to the paucity of information from laboratory research, it is necessary to return to the literature for information gained empirically. One of the best sources is Harker's Metamorphism. Several of his comments are worthy of quotation.

> "Metamorphic minerals containing boron, fluorine or chlorine are found in general only near igneous intrusions belonging to the epoch of the metamorphism.... We may infer with confidence that the more active solvents and mineralizers in metamorphism, carbon dioxide excepted, are of direct magmatic origin." (1939, p.18)

Thus the implication that the scapolite of the Cascade area gained its volatiles in association with a pegmatite is not at all unreasonable and may indicate that the two features are of similar age.

Another quote from Harker:

> "The pneumatolytic action of chlorides is shown principally in the production of scapolites in limestone... but the conversion of plagioclase to scapolite many often be observed in practice." (1939, pp. 124-25)

The replacement of plagioclase by scapolite is common in the Cascade Lakes near the pegmatite and the molecular ratios of albite to anorthite and marialite to meionite are approximately the same. Unfortuneately, there seems to be no correlation between the composition of the scapolite and plagioclase in the general geologic setting (Turner, 1948, p. 21: Deer, et. al., 1964, p. 330).

Scapolite is practically unknown as a detrital mineral, and with the exception of a few pegmatites it is not a primary constituent of igneous rocks. A paragenesis has been given by Shaw (Deer, et. al., 1964, p. 330)

a) Metamorphic rocks of regional distribution, especially marbles, calcareous gneisses, granulites, and greenschists and to a lesser extent, pelitic and psammitic rocks.

b) Skarns at the contacts of calcareous sediments and adjacent plutonic intrusions.

c) Pneumatolytically or hydrothermally altered basic igneous rock.

d) Veins in regionally metamorphosed rock.

e) Blocks ejected from volcanoes, and contact volcanism.

f) Metamorphosed salt deposits.

Considering the possibilities presented it would seem necessary to eliminate choices involving vulcanism or regional considerations for this occurence. This would leave c) and d) as reasonable possibilities, but structural features of the gneiss rule out origin as a vein without calling on subsequent metamorphism.

Figure 8 shows the metamorphic facies chart given by von Knorring and Kennedy. They places their Ghanaian scapolite gneisses just above the border of the granulite and eclogite facies, and it seems to be common practice to assign rocks of this mineralogy to a similar area. Since the samples from the Cascade Lakes contain sphene, an effort was made to limit the field that the gneiss would fall into by limiting of a component. However, this line of attack proved unfavor-

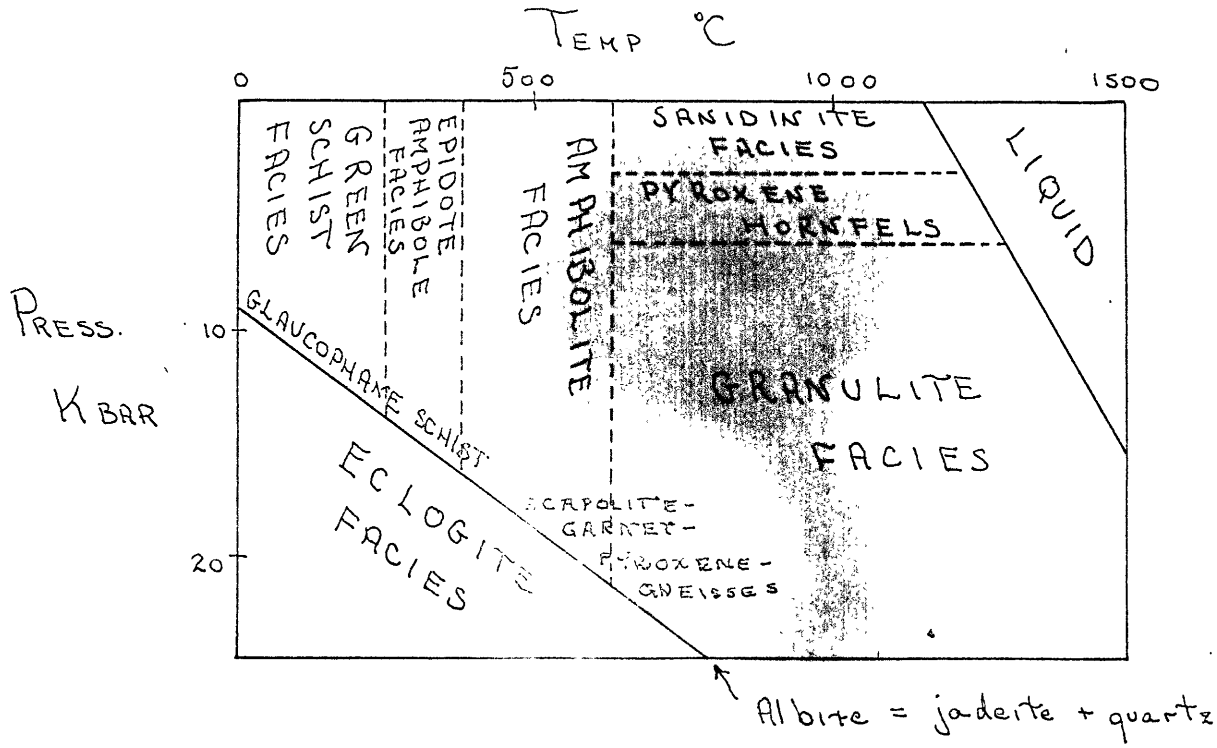


FIGURE 7: METAMORPHIC FACIES (After Knorring & Kennedy)

able, since sphene is stable from lowest temperature to melting under most situations. While it is rare in the granulite facies, sphene is stable in that field if there is abundant lime such as in a scapolite- diopside- garnet assemblage. (Ramberg, 1952, pp.72-75)

As a result the writer had no choice but to use the general region of the upper granulite facies and amphibolite facies as a definition of grade.

The scapolitization of the wall rock around the pegmatite is indicative that the source of volatiles for this entire process was the pegmatitic melt. Certainly from Harker it is possible to draw such an inference. The temperature must have been high in the entire system, for there are no chill zones on the pegmatite. Thus any volatiles escaping might not be forced to react until they found the favorable conditions of a crushed zone. It is the author's hypothesis that these eminations did find such a crushed zone which was then altered to the present assemblage through a series of intermediate steps of composition similar to sample C125A. That anorthosite could be altered to such a rock is substantiated by the work of Weiss on a metagabbro which becomes scapolitized.

Reference must be made at this juncture to figure 7, a discussion of which has been left until this point. As is readily observed, the line begins at a point where pyroxene and scapolite are about equal in volume. This line then gradually falls off until garnet is equal to pyroxene and scapolite is nonexistent. The shape of the curve is apparently a reflection of the fact that the garnet is a product of reaction between scapolite and pyroxene as seen in some reaction rims in thin sections. Up until the samples are composed of equal portions of garnet, pyroxene and scapolite there is apparently equilibrium; but when the composition goes too rich in garnet, the balance is apparently destroyed and garnet and pyroxene rapidly become the dominant minerals.

In conclusion, I would like to make three pertainent points on the geology of the scapolite-pyroxene-garnet gneiss and its origin.

1) The rock is representative of the upper amphibolite or upper granulite facies, but may be limited to a temperature below 700°C.

2) The rock represents the result of action of volatiles, namely carbon dioxide and chloride, on granulated anorthosite.

3) The granitic pegmatite is responsible for the volatiles with the exception of CO_2, but it is possible that the siliceous solutions from the pegmatite caused the silicification of the local limestones, thus releasing the CO_2.

Appendix 1

Sample Number CL7	Gabbroic anorthosite
Mineral	
Hypersthene	32.6 %
Hornblende	10.4 %
Opaques	7.4 %
Plagioclase- An_{45}	37.5 %
Perthitic plagioclase	2.9 %
Quartz	0.7 %
Apatite	4.8 %
Limonitic alteration	1.4 %
Sericite	2.0 %

1) Hypersthene pleochroic in green and pink- alters to an unidentified mineral in some grains

2) Considerable specks of opaque minerals disseminated along planes in the plagioclase. These are probably tiny prisms of pyroxene.

3) Inclusions of low index feldspar are nearly parallel to the albite twin planes of the plagioclase.

4) Alteration of hypersthene produces borders of tiny magnetite grains.

5) Feldspars are occasionally zoned with the included crystals of pyroxene confined to the interior portion of the grain.

Appendix 2

Sample Number CL22 **Basalt**

Mineral

Augite	7.0 %
Opaques	9.0 %
Plagioclase (composition indet.)	38.0 %
Alteration products- groundmass	46.0 %

1) Augite phenocrysts compose the seven percent of the augite listed above, although the matrix appears to be altered augite as well.

2) Texturally diabasic, with long laths of plagioclase interlocking: the groundmass fills the interstices.

3) Carlsbad and albite twinning in plagioclase, but grains make composition hard to determine.

Appendix 3

Sample Number CL22A — **Scapolite gneiss** (pegmatitic)

Mineral	
Pyroxene (diopside)	30.4 %
Scapolite	27.6 %
Plagioclase	10.4 %
Quartz	1.3 %
Sphene	12.4 %
Apatite	1.0 %
Unidentified	7.4 %
Sericite	8.4 %

1) The grain size of this specimen reaches one centimeter, by far the coarsest sample discovered.

2) The percentage of sphene is a factor of four higher than in most samples.

3) There is plagioclase in the sample; this was found in only one other sample.

4) Alteration products and unidentified portions are considerably greater than in the other samples.

5) There is a complete lack of garnet.

Appendix 4

Sample Number CL23 — **Scapolitized** gabbroic anorthosite

Mineral	
Augite	6.2 %
Hornblende	6.2 %
Plagioclase- An_{48}	74.3 %
Quartz	1.0 %
Scapolite	9.5 %
Apatite	0.2 %
Magnetite	1.5 %
Sericite	1.1 %

1) Contains small grains of very high index, clear, anhedral.

2) Scapolitization almost exclusively confined to grain boundaries or fractures.

3) Augite extensively altered.

4) All magnetite in sample is contained in the scapolite.

5) Quartz appears as a reaction mineral in association with pyroxene almost exclusively

6) Excellent pleochroism in green and brown-green in the hornblende. Occasional twin planes visible.

Appendix 5

Sample Number CL23P — Granitic Pegmatite

Mineral	
Perthite	31.5 %
Plagioclase- Ab_{68}	26.2 %
Quartz	28.6 %
Opaques	10.0 %
Pyroxene	1.3 %
Unidentified	1.7 %
Sericite	1.9 %

1) Inclusions in the perthite have a higher index than the potassium feldspar and show twinning.

2) Excellent myrmekitic intergrowths of quartz with perthite.

3) Graphic intergrowth of quartz and plagioclase.

4) Quartz shows straining in all instances with one exception, in the graphic intergrowth it appears relatively strain free.

5) Opaque minerals are associated with the pyroxene and are considerably altered to limonitic oxides.

6) Numerous grains of a clear, high relief mineral. Interference colors reach second order yellow, and the mineral is apparently biaxial.

Appendix 6

Sample Number CL24 **Gabbroic anorthosite**

Mineral	
Augite + hornblende	5.1 %
Garnet	7.9 %
Opaques	4.5 %
Plagioclase- An_{46}	65.3 %
Perthitic plagioclase	11.8 %
Sericite	5.4 %

1) The augite appears pale green in section while the hornblende is pleochroic in green and green-brown. The hornblende probably comprises some 75% of the above total.

2) The amount of plagioclase containing exsolution blebs and lamellae of low index feldspar is considerable in the sample, while quartz is almost nonexistent.

Appendix 7

Sample Number CL25A **Intermediate gneiss**

Mineral	
Pyroxene	49.1 %
Plagioclase (indeterminate)	15.7 %
Orthoclase	7.4 %
Scapolite	6.4 %
Sphene	5.4 %
Apatite	0.2 %
Quartz	8.4 %
Sericite	7.6 %

1) Granular texture with most mineral grains about equal in size.

2) Scapolite occurs in distinct grains apparently in some sort of equilibrium with the assemblage since there is no evidence of its replacing any of the other minerals.

3) Sphene content is rather high.

Appendix 8

Sample Number CL25B — Scapolite-pyroxene-sphene gneiss

Mineral	
Pyroxene (diopside)	42.5 %
Garnet	1.8 %
Scapolite	38.8 %
Sphene	2.2 %
Alteration	14.7 %

1) There are two distinct alteration products present, one apparently sericite, the other a fibrous alteration of the scapolite.

2) Quartz is absent except for an occasional fracture filling in pyroxene.

3) Sphene has a tendency to be crystalloblastic in this specimen whereas it had been found to be generally anhedral in other samples.

Appendix 9

Sample Number CL25-1 — Scapolite-pyroxene-garnet gneiss

Mineral	
Garnet	41.1 %
Pyroxene	33.8 %
Scapolite	16.5 %
Sphene	2.4 %
Apatite	0.4 %
Quartz	3.4 %
Alteration products	1.8 %

1) There is alteration of scapolite along cleavages and contacts with other minerals.

2) Scapolite grains, while not so numerous as others, are generally larger.

3) Pyroxene is very fresh with quartz often separating it form other minerals. Garnet is often found rimming pyroxene.

4) Apatite occurs occasionally as small hexagonal prisms.

5) Sphene is in small rounded grains, and is nearly the same color as the garnet, being distinguishable only by relief or use of the crossed nichols.

Appendix 10

Sample Number CL25-2 Scapolite-garnet- pyroxene gneiss

Mineral	
Scapolite	41.5 %
Pyroxene (diopside)	38.2 %
Garnet	8.9 %
Sphene	3.3 %
Apatite	1.4 %
Unidentified	1.4 %
Sericite	5.4 %

1) Some of the garnet shows a trace of hematite or some similar red-brown mineral.

Appendix 11

Sample Number CL25-3 Scapolite-pyroxene-garnet gneiss

Mineral	
Garnet	32.2 %
Pyroxene	36.6 %
Scapolite	25.0 %
Sphene	2.4 %
Quartz	2.7 %
Alteration	1.1 %

1) Considerable quartz in reaction rims with pyroxene and garnet.

2) Pyroxene shows excellent cleavage and is very fresh

3) Scapolite is often altered to fibrous mineral of high relief and patchy distribution.

4) Pyroxene often includes small grains of a high relief mineral, probably sphene.

5) Garnet grains often contain anhedral grains of what seems to be quartz.

6) Garnet is strained. It exhibits some undulatory extinction.

Appendix 12

<u>Sample Number 57A</u> Syenitic gneiss

Mineral

Plagioclase	66.2 %
Perthitic plagioclase	1.8 %
Pyroxene	12.2 %
Garnet	11.8 %
Opaques	2.0 %
Apatite	2.0 %
Quartz	2.9 %
Sericite	1.1 %

1) Apatite grains are abnormally large and anhedral.

2) Alteration of the pyroxene takes the form of a green, clear mineral.

3) Plagioclase shows two types of twinning, one is very broad albite twinning apparently representing uncrushed grains, the second, better defined and narrower apparently representing recrystallized material.

4) Shows evidence of extreme pressure with some grains actually penetrating others.

5) Some grains look very much like microcline, but may actually be severely strained quartz.

6) Plagioclase shows excellent albite and pericline twinning.

Appendix 13

Sample Number 57B | Syenite gneiss

Mineral

Plagioclase	73.4 %
Garnet	10.3 %
Pyroxene	9.0 %
Magnetite	2.9 %
Quartz	1.6 %
Apatite	1.9 %
Alteration	1.0 %

1) Strained quartz is sometimes in myrmekitic intergrowth with feldspar.

2) Numerous large apatie grains.

3) Considerable exsolution of low index mineral in plagioclase.

4) Alteration limited to pyroxene except for minor sericitization of plagioclase.

5) Some alteration of magnetite to limonite.

6) Magnetite and quartz tend to associate in this sample.

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