The Properties of Sodalite and its Petrogenesis at the Princess Quarry, Bancroft, Ontario.

The Properties of Sodalite and its Petrogenesis at the Princess Quarry, Bancroft, Ontario

By

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Proposed line of Research.

a) To study and establish variations in the chemical and physical properties of sodalite; in particular, to obtain chemical analyses of samples collected in the field and using the same material, to determine the refractive index, specific gravity and cell dimensions of each sample analysed; with this data to establish whether the variations in each parameter is significantly different from experimental error, and if so to compute a correlation matrix and regression equations to relate the physical and chemical properties determining the variation observed.

b) To describe in detail the sodalite deposit at Bancroft, Ontario and to attempt to establish a reasonable hypothesis concerning its origin.

Abstract.

The chemical and physical properties of nine samples of sodalite have been determined along with the physical properties of an additional thirteen samples. Taken together with selected data from the literature these data indicate that: (1) the cell dimension of sodalite is constant for samples from one deposit within the limits ascribed to experimental error (± 0.0015 A°) and the variation of a_o for samples from other deposits is quite limited (i.e. ±0.005 A°); (2) the specific gravity and refractive index exhibit small but measureable variations which cannot however be related to compositional variation; (3) the variation in chemical composition for sodalite indicated by analyses from the literature appears to be in error; much of the variation is attributed to zeolite impurities which were not removed from the samples before analysis; (4) probably all sodalites are represented to within 5 per cent by $6NaAlSiO_4 \cdot 2NaCl$ with less than 0.30 weight per cent H_2O.

A petrographic study of the sodalite deposit at the Princess Quarry, Bancroft, Ontario, indicates that this mineral has formed from the reaction of chlorine-rich solutions with nepheline. The solutions appear to be derived from granite and syenite bodies which are regionally abundant in the vicinity of the Bancroft band of nepheline syenite gneiss. Many facts suggest that the present veins in the quarry have formed by the replacement of a pre-existing nepheline pegmatite.

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GENERAL INTRODUCTION.

A brief glance at the current geological literature reveals an active interest by field and experimental petrologists in nepheline syenites and their volcanic equivalents. Experimental investigators have studied in some detail the accessory minerals commonly associated with these rocks. Nosean and hauyne occur exclusively as minor constituents in undersaturated alkaline volcanic assemblages. Sodalite has been found along with nosean and hauyne as phenocrysts in volcanic rocks, but it is most common in pegmatite assemblages. Cancrinite, like sodalite, is most commonly found in hydrothermal environments. In a few instances, both sodalite and cancrinite have been reported as primary phases in undersaturated alkaline plutonic rocks.

Sodalite, nosean and hauyne are isostructural (Barth, 1932B) and very similar chemically. Anderson (1963) demonstrated that the hydroxyl varieties of nosean and hauyne synthesized under experimental conditions invert to cancrinite structures at temperatures and pressures imagined to prevail in hydrothermal environments. This appears to be the reason why nosean and hauyne are not found in plutonic rocks. Sodalite undergoes no such inversion to an hexagonal structure.

The present investigation began as a petrologic study of the occurrence of sodalite at the Princess Quarry, Bancroft, Ontario. The research was expanded to include an investigation of the chemical and physical properties of sodalite. Samples were collected from the quarry at Bancroft to study variations in their properties within one mineral deposit. In addition, samples were obtained from other localities in North America, and also from regions in Europe, Asia and South America. Analyses from the literature have also been reviewed.

PART ONE

A Mineralogical Study of Sodalite.

A Mineralogical Study of Natural Sodalite.

I. Introduction. A review of the knowledge of sodalite from the literature.

In table 1-1 the main physical, optical and structural properties of sodalite, nosean, and hauyne are summarised. In table 1-2 chemical analyses and physical properties determined on samples of sodalite from a large number of localities are presented. The individual properties of sodalite are discussed below.

A. Structure.

Sodalite is a cubic mineral with $a_o = 8.9$ A°, space group P$\bar{4}$3m (Barth, 1932B; Pauling, 1930A), and one formula unit per unit cell. Pauling (1930A) determined the structure of sodalite, and Barth (1932B) determined the structure of sodalite, nosean and hauyne. Sodalite consists of SiO_4 and AlO_4 tetrahedra in approximately equal numbers linked together to form the basic alumino-silicate framework. The distribution of the Al and Si atoms at the tetrahedral sites is unknown. Large cavities left vacant within this framework are occupied by Cl and Na atoms. One Cl atom lies at the centre of the cube and one at each corner. They are each tetrahedrally coordinated by four Na atoms; four near the centre Cl and four along the cube diagonals about each corner Cl atom. There are eight Na atoms per unit cell and each atom is in eight fold coordination with oxygen. The entire structure is somewhat collapsed and twisted since the cavities are larger than necessary to contain the Na and Cl ions.

*Table 1-1: The properties of the sodalite group of minerals.

	Sodalite.	Nosean.	Hauyne.
n	1.483-1.487	1.495	1.496-1.505
D	2.27-2.33	2.30-2.40	2.44-2.50
H	$5\frac{1}{2}$-6	$5\frac{1}{2}$	$5\frac{1}{2}$-6
Cleavage	(110) poor	(110) poor	(110)
Twinning	(111)	(111)	(111)
Colour	pale pink, grey, yellow, blue, green, colourless in thin section.	grey, brown, blue, colourless or blue in thin section.	white, grey, green, or blue colourless or pale blue in thin section.
Unit Cell	a_o(A°) 8.91 Z 1	9.05 1	9.13 1
Space Groups	P$\bar{4}$3m.	P$\bar{4}$3m.	P$\bar{4}$3m.

Readily gelatinized by acids.

* Taken from Deer, Howie and Zussman, (1961).

Nosean and hauyne are isostructural with sodalite. In hauyne Ca^{+2} replaces Na^{+} and in both nosean and hauyne $SO_4^{=}$ replaces Cl^{-}. The ionic radius of Ca^{+2} is greater than that of Na^{+} and the size of the $SO_4^{=}$ ion is much greater than Cl^{-} , hence the structures of these two minerals are less collapsed. The unit cell dimensions for both nosean and hauyne are therefore greater than that of sodalite.

Van Peteghem (1961) formed synthetic phases of sodalite, nosean and hauyne of natural compositions at temperatures and pressures from 100°C. to 750° C. and 10,000 to 30,000 p.s.i.

A polymorphic transition, independent of pressure, occurred at approximately 475°C for both nosean and hauyne. A cancrinite structure appeared at temperatures below 475° C. Sodalite exhibited no such polymorphism. Anderson (1962) established that such an inversion of structures occurred in synthetic hydroxyl varieties of nosean and hauyne. The hydroxyl variety of sodalite showed no inversion to an hexagonal structure.

B. Physical and Optical Properties.

Sodalite has a glassy lustre; it exhibits a variety of colours including blue, grey, yellow and green, and that variety of sodalite called hackmanite is often pale pink and strongly flourescent. Sodalite has a poor (110) cleavage. Its hardness is approximately $5\frac{1}{2}$-6.

Deer, Howie and Zussman (1961) quote the cell dimension of sodalite to be 8.91A°. The physical data associated with the chemical analyses in table 1-2 give no values for a_0. Van Peteghem and Burley (1962) determined the cell dimension for synthetic and natural sodalite. They are given in table 1-3 along with some values found in the literature. The cell dimension is observed to vary between 8.81 A° and 9.933 A°, but most values fall within the range 8.86 A° to 8.89 A°. The accuracy and precision of the data as indicated in Table 1-3 is insufficient however to establish the exact limits in the variation of a_0. For the synthetic hydroxyl sodalites synthesized by Van Peteghem (1961) no significant variation in the cell parameter was observed as a function of temperature

Table 1-2: Chemical analyses of sodalite and hackmanite from the literature.

	1.	2.	3.	4.	5.	6.	7.	8.	9
SiO_2	37.33	29.66	41.56	36.63	36.72	36.70	37.96	36.36	38.05
Al_2O_3	31.87	30.09	29.48	31.08	31.17	31.14	30.96	32.09	31.30
Fe_2O_3		0.31		1.06	0.70	0.81	0.85	0.09	tr.
Fe O			0.49						
MgO			0.15						
CaO		0.18	0.49				0.46		tr.
Na_2O	24.56	22.60	19.21	24.54	24.53	24.51	22.93	24.73	24.77
K_2O	0.10	1.14	0.91	1.01	1.13	1.16	0.74	0.12	
H_2O^-	1.07	0.17	0.45	0.31	0.23	0.19	1.10	0.12	0.82
H_2O^+		0.79	3.73					0.86	
MnO								0.06	
Cl	6.83	6.12	4.79	7.20	7.22	7.21	5.34	6.79	7.18
SO_3								tr.	tr.
$CaCO_3$								0.50	
Sum	101.76	101.06	101.26	101.83	101.70	101.72	100.34	101.70	
O≡Cl	1.54	1.39	1.08	1.03	1.63	1.63	1.21	1.53	1.62
Total	100.22	99.67	100.18	100.20	100.07	100.09	99.13	100.17	100.51
S.G.			2.265		2.295			2.278	2.27
N					1.484			1.483	

Table 1-2 Continued.

	10.	11.	12.	13.	14.	15.	16.	17.
SiO_2	38.52	36.69	36.99	36.70	37.60	51.58		
Al_2O_3	27.48	31.40	31.77	32.01	31.62	11.15		
Fe_2O_3		0.85	0.17	0.07	0.55	tr.		
MgO						0.20		
CaO		0.19			0.28		0.25	
Na_2O	28.50	25.96	25.84	24.79	24.02	25.52	26.30	22.4
K_2O		0.23	0.16	0.17	0.46	0.12	0.18	0.4
H_2O^-	1.70	0.04		0.00		0.03		1.10
H_2O^+		0.30		0.36	0.28			
Cl	3.00	5.64	6.44	7.00	5.56	7.29	7.30	5.27
S	2.10	0.34	0.39	tr.	1.10	0.33		0.55
BeO						5.40		
Sum	100.00	101.71	101.81	101.39	101.62			
O≡Cl		1.39	1.64	1.58	1.80			
Total.	100.00	100.32	100.17	99.81	99.82			
S.G.	2.378	2.285	2.33	2.286				
N		1.487		1.487				

1) Blue sodalite, Litchfield, M . (U.S.G.S.Bull.220) Anal. F.W. Clarke.

2) Blue sodalite, Ice River, British Columbia, (U.S.G.S.Bull.220) Anal. G. Steiger.

3) Sodalite from sodalite syenite, Square Butte, Highwood Mountains, Montana, (U.S.G.S.Bull.220) Anal. W.H. Melville.

4) Sodalite from Cerro Sapo, Bolivia, (Brendler, 1934)

5) Sodalite from Cerro Sapo, Bolivia, (Brendler, 1934)

6) Sodalite from Cerro Sapo, Bolivia, (Brendler, 1934)

7) Sodalite from Tichuanaco, Bolivia, (Brendler, 1934)

8) Blue sodalite, Magnet Cove, Arkansas (Miser and Glass 1941).

9) Blue sodalite, associated with colourless hackmanite, nepheline syenite, Kishengarh, Rajaputana, India (Vredenburg, 1904) Anal. E. Vredenburg.

10) Green sodalite, Greenland (Miser and Glass, 1941)

11) Light grey sodalite, pegmatite cutting sodalite nepheline syenite, Khibina tundra, Kola peninsula (Fersman and Bonshtedt, 1937) Anal. M. Vladiminova.

12) Hackmanite, sodalite aegirine rock, Kola peninsula (Borgstrom 1901) Anal. L.M. Borgstrom.

13) White hackmanite, tinguaite, Magnet Cove, Arkansas (Miser and Glass, 1941) Anal. J.J. Fahey.

14) Hackmanite, Luyavrurt, Kola peninsula (Vorobieva, 1946). Anal. V.A. Moleva.

15) Beryllium sodalite from southwest Greenland (Sørensen, 1962) Anal. McMouritzen.

16) Green sodalite developed poikilitically with microcline and aegirine (Sørensen 1962) Anal. McMouritzen.

17) Yellow sodalite in analcime - natrolite veins (Sørensen, 1962) Anal. McMouritzen.

Table 1-3 : Unit cell dimension for synthetic and natural sodalite.

Sample or locality	Synthetic or natural	Author	a_o(A°)
SS-2	Synthetic	This study	8.89± 0.01
SS-6	"	"	8.89± 0.02
SS-8	"	"	8.89± 0.02
SS-9	"	"	8.88± 0.04
SS-11	"	"	8.89± 0.02
SS-12	"	"	8.89± 0.02
SS-14	"	"	8.89± 0.06
SS-18	"	"	8.88± 0.03
Bancroft	Natural	This study	8.87± 0.01
Bancroft	"	Barth (1932)	8.89
Bancroft	"	Pauling (1930)	8.87
Unstated	"	Barth (1932)	8.85
Mt. Somme, Italy	"	Jaeger (1926)	8.91
Livaara, Finland	"	Lehijarvi (1960)	8.89
Mt. Vesuvius, Italy	Natural	Kolaczkowska (1935)	9.933

of synthesis over a temperature interval from 300°C. to 650°C. It appears that in the synthetic systems at least the cell dimension may be quite constant.

Deer, Howie and Zussman (1961) quote the variation of the specific gravity of sodalite to be 2.27 to 2.33. The data given in table 1-2 suggests that this is appoximately the correct range for this parameter. Also a comparison of the range of the refractive index in table 1-1 with those quoted for samples in table 1-2 indicates satisfactory agreement.

C. Chemical Properties.

Both Dana and Winchell (1956) have constructed a sodalite group of minerals. It includes

Sodalite : $6NaAlSiO_4 . 2 NaCl$
Nosean : $6NaAlSiO_4 \cdot Na_2SO_4$
Hauyne : $6NaAlSiO_4 . 2Ca SO_4$

This grouping is based upon the similarity in chemical and physical properties between these minerals. Van Peteghem (1961) established that complete solid solution exists between nosean and hauyne using natural compositions, but that only a very limited amount of solid solution exists between nosean and sodalite, and hauyne and sodalite. He also concluded that for synthetically produced natural sodalite, composition is strikingly constant.

An examination of the chemical analyses of natural sodalites does reveal some variation in the major elements which form this mineral. Table 1-2 presents the analyses of sodalite and hackmanite collected from the literature. In all but a few instances, three oxides (SiO_2, Al_2O_3, and Na_2O) and one anion (Cl) form better than 97 percent of the constituents reported in each analysis. In proportion to the amount present, chlorine exhibits the widest variation of the four ionic species (i.e. from 4.79 to 7.22 weight percent). Small amounts of Fe^{+3} appear to substitute for Al^{+3} as does K^{+} for Na^{+}. In that variety of sodalite called hackmanite $S^{=}$ may replace Cl^{-} up to 1.10 weight percent. When Cl^{-} is quite low, water in the form of the OH^{-} ion possibly fills the unoccupied sites. It is the suspicion of the author however that much of the variation observed in chlorine is not due to a substitutional phenomena. Sodalite commonly alters to a sodium rich zeolite such as natrolite. Impure sodalite samples would yield on analysis significant amounts of water and lower than expected values for chlorine. Brendler's (1934) study on Bolivian sodalites (see table 1-2 for analyses) suggests such a possibility.

D. Quality of the Data in the Literature.

The data just reviewed has been presented with the hope that it would be used along with data from samples studied by this investigator to establish variations in the physical, optical and chemical properties of sodalite. A critical analysis of the data is presented in point form below stipulating the limitations inherent in such data.

1) Only rarely are the chemical analyses accompanied by a complete set of physical and optical data. Incomplete sets of data restrict the completeness of this study.

2) Only rarely have the techniques used to determine the physical properties been stated. Various techniques exist to determine these properties and slightly different results can be expected from each. It is especially critical in this study, where variations if present are quite small, to standardize all the data obtained by using the same

technique to determine a specific property. It is realised that this is not possible when using data from the literature, but a knowledge of the manner by which the values were determined may enable the investigator to allow for obvious differences. In general only the chemical data of table 1-2 have been considered comparable to data determined in this study.

3) Nothing is known concerning the composition and amount of impurities present in the material represented by analyses in table 1-2. This, as will be illustrated, is a critical factor when determining the acceptability of an analysis.

E. Conclusions based on the data from the literature.

1) The cell dimension exhibits only a limited amount of variation: it is suspected that this parameter may have a quite constant value.

2) The refractive index and specific gravity possibly show more real variation than a_o (i.e. their variation is not attributable to experimental error).

3) The Cl^- and $S^=$ ions are interchangeable to a limited extent suggesting that a solid solution series exists between sodalite and hackmanite.

4) It is possible that the Cl^- and OH^- anions are interchangeable and reflect another solid solution series between hydroxyl and chloride types of sodalite. Brendler's (1934) work on the Bolivian sodalite however, tends to disprove this theory.

5) Other than the above mentioned substitutions and quite limited substitutions of Na^+ and Al^{+3} by K^+ and Fe^{+3} respectively, the three

oxides, SiO_2 , Al_2O_3 and Na_2O, and one anion Cl , occupy all the available sites in the sodalite structure.

II. Preparation of Samples.

A) Introduction.

Nine samples of sodalite were submitted for chemical analyses, seven from the Princess Quarry, Bancroft and one each from Ice River, British Columbia and Blue Mountain, Ontario. In the Princess Quarry, sodalite samples were taken from six veins in such a manner as to sample from all of the quarry. The samples were obtained using a hammer and chisel, chipping in order to get the purest material possible. In this way sodalite from an area 1-2 feet in length in each vein was obtained.

Thirteen other samples were studied to determine their physical and optical properties only.

B) Preparation of samples for chemical analyses.

Most of the samples contained nepheline, oligoclase, microcline, perthite, lepidomelane, calcite, zeolite and magnetite in addition to sodalite. The purity before separation of the above phases ranged between 50 and 90 percent. The following set of techniques was used to purify the samples.

1) The samples were crushed and sieved to obtain the grain size fraction between 120 and 200 mesh.

2) Fines (less than 200 mesh) were separated by allowing the sample to settle through water in a 500 ml. separatory funnel: a ten second interval was allowed before the coarse fraction was taken off.

3) Magnetite was removed by running a hand magnet over the crushed sample.

4) Using the Frantz isodynamic mineral separator;

i) the instrument was set with a tilt of 7° from the horizontal, plunging 30°-40°, and a current strength of 0.5 amperes; most of the lepidomelane and any remaining magnetite grains (composites etc.) were removed in this manner.

ii) the separator was reset to $1-1\frac{1}{2}^{\circ}$ horizontal tilt and a current strength of 1.5 amperes; any remaining lepidomelane and some iron stained zeolite was removed.

Both steps were repeated until the separation ceased to be efficient.

5) A tetrabromoethane-acetone mixture with a specific gravity just greater than that of sodalite was used to separate the sodalite and zeolite from nepheline, oligoclase and alkali feldspar; a 500 ml. separatory funnel was used; the technique was repeated at least twice.

6) The sodalite fraction was dried and heated in a porcelain crucible to 500-550°C for 45 minutes at atmospheric pressure and then allowed to cool.

7) Sodalite was then separated from zeolite using the heavy liquid mixture mentioned in step 5; small amounts of the sample were placed in 50ml. centrifuge tubes and centrifuged for 30 minutes; the light fraction was poured off and collected for analysis; this technique was repeated until the results showed no improvement in sample purity.

Step 6 is necessary to separate the sodalite from the zeolite impurity which was common to all samples. The separation of the two phases results from a decrease in the specific gravity of sodalite and a slight increase in that property of the zeolite when the mixture is heated.

The effects that the heat treatment had on the optical and physical properties of sodalite are indicated in table 1-4. The specific gravity of sodalite decreased by 0.022 gms/cc.

Table 1-4: The effects of heating on the optical and physical properties of sodalite.

Sample	a_o (A°)	Density	n	colour
EX-I Unheated	8.881±0.0015	2.308±0.002	1.483±0.005	deep blue
EX-I	8.882	2.286	1.483	white

During heating the colour of sodalite turned from blue to white. Other than the specific gravity, no physical property pertinent to this study changed significantly upon heating. X-ray diffraction patterns run on a sample of sodalite before and after heating were identical. A thermogram, which records weight loss versus temperature was run on a small pure sample (3% impurity) of powdered sodalite. It indicated that there was a 7.0 weight percent loss at 98°C but that no further losses occurred up to 750°C. A similar sample was heated in an open porcelain crucible from room temperature to 900°C at one atmosphere pressure. A two percent weight loss was calculated on the basis of weighings before and after heating.

The experiments involving the heating of sodalite which have just been described indicate that heating did not seriously alter the structure of the mineral. In one instance a 7.0 weight percent loss was recorded upon heating. This is attributed to interstitial water. A very finely powered sample in a quite humid atmosphere could easily adsorb this amount of water which it would lose upon heating. In the experiment being referred to it was observed that as the sample cooled to room temperature in a normal atmosphere, it was gaining weight quite rapidly indicating that water was probably being adsorbed from the air. It was the author's opinion at the time of experimentation that no significant amount of chlorine or structural water in sodalite was lost during heating. One sample of sodalite (table 1-12, #620708-6) which had not been heated was submitted for chemical analyses. A comparison of the analyses of the heated samples with this sample reveals no large differences in the major oxides or anions which form the structure of sodalite.

The zeolite however changes markedly during the heating process. It assumes a frosted appearance when heated, and an x-ray pattern of the heated zeolite shows no reflections in contrast to the number of excellent peaks of the unheated sample (see"mineralogy", part II). It is probable that the mineral is completely dehydrated in the temperature interval from 300°C. to 400°C.(see Hey, 1932a,b,1933) and possible that such a loss of water (12.0 - 13.0 wt.%) causes the structure to collapse. This might be indicated by the apparent increase in density which could not result unless some such phenomena occurred. That the density did increase is indicated by the fact that sodalite remained the lighter of the two minerals. If all the water in the zeolite were lost but the volume of the unit cell remained constant then the effect would surely be to make the zeolite as light or lighter than sodalite. The opposite situation is observed however.

Table 1-5: Percentage and type of impurity of samples submitted for chemical analyses.

Sample	% Impurity		Major Impurity
	Before	After.	
1-I	15%	3.3%	Zeolite.
1-III	15%	7.7	"
3-I	15%	3.7	"
3-II	15%	4.7	"
3-IV	40%	7.7	"
3-V	50%	11.8	"
620708-6		5.8	Zeolite, magnetite
IR-1-63	40%	13.2	Zeolite.
BM-1-63	50%	16.7%	"

The results of the separations are recorded in table 1-5. Sample impurity was estimated by point counting using a petrographic microscope. Sample 620708-6 was the only sample not heated. It contained less than 3% zeolite impurity. The table indicates that three samples still contain greater than 10 percent impurity. Composite zeolite-sodalite grains may be plentiful in any sample since the alteration of sodalite to zeolite (described in "Petrology") has proceeded on scales ranging from macroscopic to sub-microscopic. It is therefore difficult to estimate accurately the percent impurity in most samples.

A sample of the zeolite was also submitted for chemical analysis. It was hoped that for those samples in which the zeolite impurity was high, corrections could be made in order to compare them with the other data.

C. Additional samples studied.

In addition to the nine samples of sodalite submitted for chemical analysis, thirteen other specimens were studied for only their optical and physical properties. These samples were obtained from the Royal Ontario Museum, Toronto and are listed in table 1-6. Only the sample from Ice River, British Columbia, yielded sufficient material for chemical analysis.

Table 1-6. Samples of sodalite obtained from R.O.M., Toronto.

Catalogue No.	Locality	Comments on sample
IR-1-63	Ice River, British Columbia	medium blue colour; extensive alteration to zeolite.
M16651	French River, Bigwood Township, Ontario.	deep blue sodalite in nepheline syenite
M15281	Tukushinzan, Korea.	blue sodalite as semi-rounded anhedral crystals in nepheline-orthoclase rock.
M19678	Red Hill, New Hampshire.	white sodalite in grey nepheline syenite.
M16211	Ayopaya, Bolivia	deep blue sodalite associated with small cubes of galena.
M5430	Slidudianka River, Lake Baikal, Siberia	sodalite associated with nepheline.
M5275	Monte Somma, Vesuvius.	green sodalite.
M13887	Kishengaih, Rajaputara, India.	grey coloured mass with green inclusions of sodalite (?)
M21855	Lake Nipissing, Ontario	deep blue lenses of sodalite in pinkish grey nepheline syenite.
M5274	Greenland	blue sodalite associated with grey feldspar.
M23298	Minas Gerais, Brazil.	blue sodalite; slightly altered to zeolite.
M22162	Mias Station South Urals, Siberia.	pale blue sodalite associated with nepheline, feldspar and zeolite.
M19664	Iles de Los, Guinea.	grey sodalite mixed with white feldspar, nepheline and zeolite.
M5272	Litchfield, Maine.	deep blue sodalite with nepheline, pink feldspar and biotite.

III. Determination of the Properties of Sodalite.

A. Refractive Index.

The refractive index of each sample of sodalite was determined at 25°C. by oil immersion. An Abbé refractometer was used to check the index values of all the oils between n = 1.476 to n = 1.490. The calibration of the refractometer was first checked and then each oil was checked in turn. All readings were made using monochromatic light from a sodium vapour lamp. Temperature control was regulated with a constant temperature water bath. The results are quoted to ± 0.0005. They were found to be reproducible within the limits of experimental error.

B. Specific Gravity.

Small pure samples of unheated sodalite were allowed to just barely sink in a heavy liquid mixture of tetrabromoethane and a non-volatile organic liquid, dimethylformamide. A 10ml. pycnometer was filled with this liquid, capped, washed completely with acetone and allowed to dry for two to four minutes. The bottle and contents were then weighed at one minute intervals for the next six to seven minutes. A graph of weight versus time was then drawn and extrapolated to zero time. This value was used as the weight of the bottle plus heavy liquid. The same technique was used to determine the weight of the bottle and distilled water. The values were read to six figures and the final value for the specific gravity was rounded to four. All values are quoted for 23°C. The reproducibility of a value for any one sample is indicated in table 1-7. The values determined using this technique are accurate to ± 0.0015 units.

Table 1-7: Reproducibility of specific gravity determinations.

Sample	Specific Gravity
Ex - I	2.307
Ex - I	2.308
Ex - I	2.306

C. Cell Dimension.

The cell dimension a_o was determined using a Norelco diffractometer unit. The sodalite samples and a silicon standard were mixed in a 3:1 ratio and ground to below 200 mesh in acetone. A small drop of nail polish was added to the acetone, then the mixture was poured on a glass slide and allowed to dry. Samples prepared in this manner gave the best results (i.e. distinct and strong reflections even at high 2θ angles).

Table 1-8 outlines the pertinent features of the reflection used for the determination of the cell dimension. The samples were radiated with FeKα radiation. The index of the reflection used was taken from the work of Borchert and Keidal (1946). A complete set of reflections for natural sodalite is given in table 1-9 after Borchert and Keidal (1946).

Table 1-8: Sodalite reflection studied.

hkl	d_{hkl}	2θ(Cu $K\alpha_1$)	2θ(Fe $K\alpha_1$)
721,633, 522	1.210A°	79.20°	106.35°

For each sample the exact location of the reflection with d = 1.210A° was determined by counting the intensity of the reflections every 0.05° 2θ for 0.20° 2θ on either side of the approximate peak

Table 1-9: Sodalite reflections and their index (after Borchert and Keidal, 1946). Cu Kα radiation.

°θ	hkl	°θ	hkl
7.05	110	39.70	721,633,552
9.95	200	40.60	642
11.15	210	41.55	730
12.25	211	43.20	732,651
15.85	310	44.85	811,741,554
17.55	222	45.85	820,644
19.00	321	47.55	822,660
20.40	400	49.30	662
21.65	411,330	50.05	752
22.80	420	51.10	840
24.10	332	51.85	910,833
25.20	422	52.85	842
26.30	510,431	53.70	921,761,655
28.45	521	55.55	920,851,754
29.40	440	57.45	932,763
30.45	530,433	58.30	844
31.45	600,442	59.35	941,853,770
32.40	611,532	61.30	1011,772
33.35	620	63.40	950,943
34.25	541	64.60	1022,666
35.30	622	65.65	1031,952,765
36.15	631	68.05	871,855,774
37.05	444	69.20	1040,864

Table 1-9 Continued,.

θ	hkl
70.55	1033,961
76.85	1121,1051,963
79.05	880

location. The time to record a unit number of counts was plotted against degrees 2θ thus outlining the exact position of the reflection. Figure 1-1 illustrates a typical diffractogram obtained in this way. The 331 reflection for silicon was used as an internal standard. The curves for sodalite and silicon plotted in the diffractogram were bisected symmetrically. The corrected values in degrees 2θ for the sodalite reflection obtained in this manner were converted to d-spacings using tables produced by Parish and Irwin (1953) and the cell dimension was calculated.

Table 1-10 indicates the reproducibility of a_o using this method. From these results the experimental error can be expected to account for an uncertainty in the cell dimension of approximately ±0.0015A°.

Table 1-10: Reproducibility of the x-ray determination of the cell dimension a_o of sodalite.

Sample	d-spacing	a_o
1-I	1.2093	8.887
1-I	1.2093	8.887
1-I	1.2091	8.885
1-I	1.2091	8.885
1-I	1.2090	8.884
		$\sigma = \pm 0.0015$

D. Chemical Analyses.

The chemical analyses were performed by Mr. J. Muysson, chemical analyst, McMaster University. Rapid silicate methods were used. The oxides and volatiles determined were SiO_2, Al_2O_3, TiO_2, Fe_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O, CO_2, H_2O^+, H_2O^-, Cl, F, and S. Also

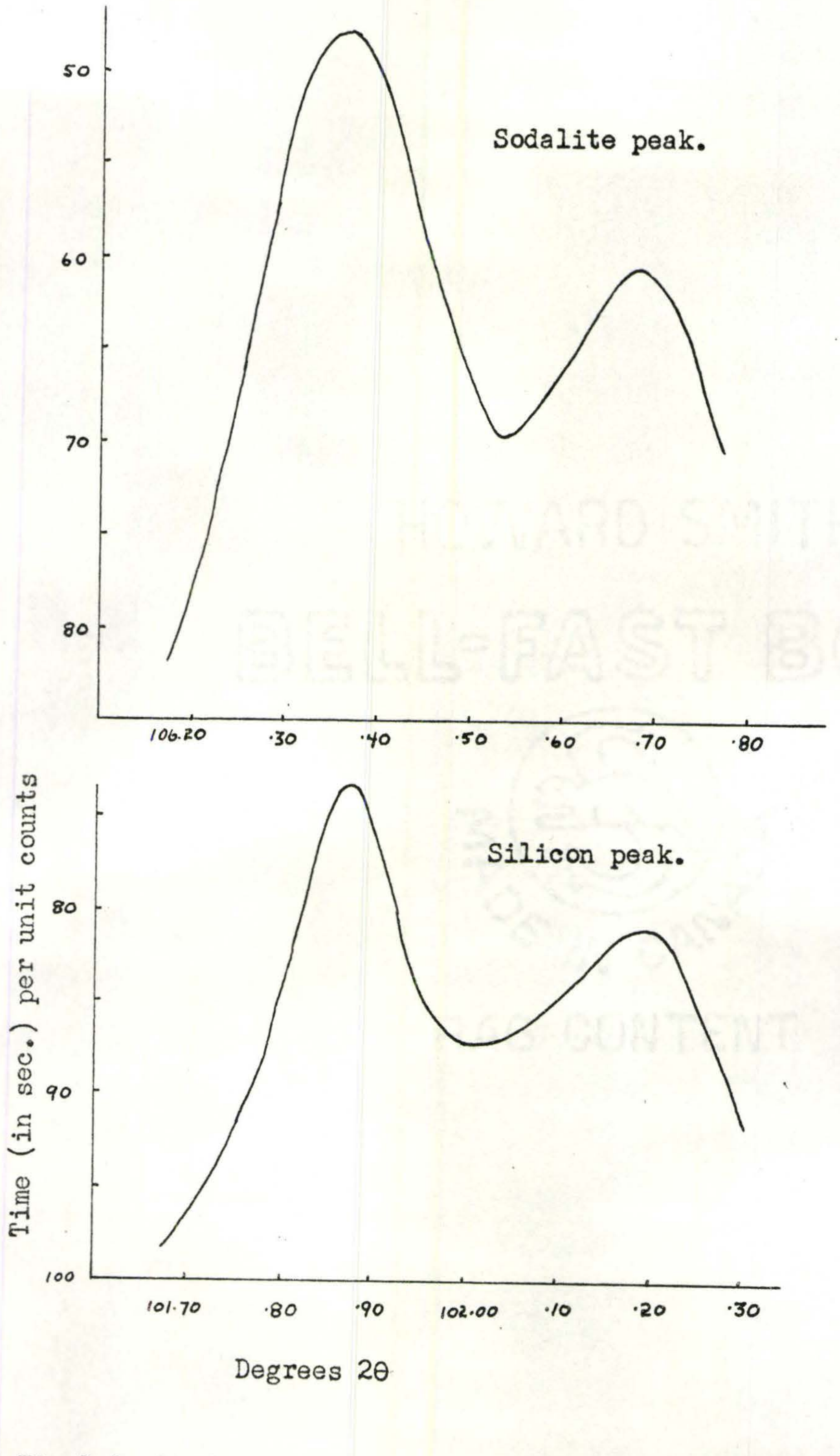


Fig.1-1 Diffractogram for computation of cell dimension of sodalite.

a qualitative investigation for a number of trace elements was made by Mr. P. van deKamp. Two samples of sodalite from the Princess Quarry were analysed in duplicate.

IV. Discussion of Data.

A. Physical and Optical Properties.

Table 1-11 lists the values for each of the physical and optical parameters determined in this study. The following points are noted.

1) The maximum range of the refractive index for sodalite is from 1.482 to 1.487. Within one mineral deposit this parameter varies by ± 0.0015.

2) The cell dimension a_o does not vary outside the limits ascribed to experimental error for samples from within one deposit. Determinations on samples from other occurrences indicate a maximum deviation of ± 0.005 A° from a mean value of 8.885 A° quoted for the samples from the Princess Quarry. Sample M5274 from Greenland is the exception to this rule. Sample M5272 is a volcanic sodalite. Powder photographs of this sample did not show the highest reflections which were common to most of the other samples studied. It is worth noting that most of the samples formed in hydrothermal or plutonic environments. Possibly the absence of these reflections at high 2θ angles indicates a lack of ordering in the structure of the mineral. An alternative explanation is that the grain size of the sample was so small as to produce only very diffuse lines on the photographs.

3) The results of the study on the specific gravity of sodalite indicate that this parameter shows the most variation of all the physical parameters measured. Samples from the Princess Quarry fell within a range of 2.305 ± 0.005. The remaining samples studied give

Table 1-11 Data accumulated on physical parameters of sodalite samples.

Sample	Chem. Analyses.	RI	S.G.	a_o(Å)
P.Q. 1-I	✓	1.482	2.302	8.887 ± 0.0015
P.Q. 1-II		1.482	2.309	
P.Q. 1-III	✓	1.483	2.310	8.884
P.Q. 3-I	✓	1.483	2.301	8.884
P.Q. 3-II	✓	1.485	2.308	8.884
P.Q. 3-IV	✓	1.483	2.302	8.885
P.Q. 3-V	✓	1.483	2.303	8.885
P.Q. 3-VIII		1.483	2.301	8.885
620708-6	✓	1.482	2.304	8.886
BM-1-63	✓	1.483	2.305	8.886
IR-1-63	✓	1.483	2.304	8.884
M16651		1.485	2.289	8.890
M15281		1.484	2.306	8.887
M19678		Material too poor		
M16211		1.484	2.308	8.889
M5430		1.484	2.296	8.883
M5275		1.485	2.365	8.884
M21855		1.482	2.298	8.884
M5274		1.484	2.297	8.859
M23928		1.483	2.305	8.887
M22162		1.485	2.337	+ reflections too weak

Table 1-11 Continued.

Sample	Chem. Analyses.	RI	S.G.	a_o(Å)
M5272		1.486	2.299	8.887
BRE^{V}-N-63		1.483	2.318	8.887

+ Sample too impure to obtain sufficiently strong reflection for determination of cell dimension.

maximum and minimum values of 2.365 and 2.289 respectively, but even these samples tend to cluster about the mean quoted for the samples from the Princess Quarry. The variation however may be significant and is definitely much greater than that ascribed to experimental error.

Since all the values presented in this section have been determined at one time by the same experimental procedures, they give a more reliable estimate of the range than can be obtained from a study of values in the literature. For the purposes of subsequent statistical analysis it is not essential that they be absolutely accurate although reasonable precautions have been taken to assure accurracy as well as precision. The results indicate that the specific gravity is the one physical parameter which possibly exhibits real variation distinct from that produced by experimental error and impurity of material.

B. Results of Major Chemical Analyses.

In table 1-12 the chemical analyses made on nine samples of sodalite and one sample of zeolite are presented. Each sodalite analysis is almost completely described in terms of SiO_2, Al_2O_3, Na_2O and Cl . Trace amounts of Fe_2O_3 are assumed to be substituting for Al_2O_3 and similarily small amounts of K_2O probably replace Na_2O. Calcite is often a common inclusion in sodalite (see petrologic section). The amounts of CaO and CO_2 which are rarely greater than 0.30 weight percent may be accounted for in this manner. In sample 620708-6 significant amounts of TiO_2 , MnO, Fe_2O_3, FeO and S are attributable to a small amount of magnetite and/or a sulphide mineral in the original sample.

In the first four analyses in table 1-12 H_2O^+ is present in only negligible amounts and does not contribute significantly to the total. These samples were heated before analysis and this is probably the reason for the low values for water. Sample 620708-6 however was not heated, yet H_2O^+ is not greater than 0.30 weight percent. In samples 3-V and BM-1-63 H_2O^+ is present in amounts approaching 1.0 percent. Note however that both of these samples contain greater than 10.0 percent zeolite impurity. An analysis of a zeolite from the Princess Quarry indicates that it contains 11.61 percent H_2O^+ . A comparison between the first four analyses of sodalite and the zeolite analysis indicates that the zeolite is slightly richer in SiO_2 , contains approximately the same amount of Al_2O_3, is distinctly richer in CaO, H_2O^+ and H_2O^- , and is

Table 1-12 CHEMICAL ANALYSES - J. Muysson(1964)

	1-I	1-III	3-I	3-II	3-II-1	3-V	620708-6	BM-1-63	IR-1-63	(Z-1-63)
SiO_2	37.25	37.53	37.27	37.46	37.68	38.09	36.68	38.50	37.32	39.28
TiO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.48	0.00	0.00	0.00
Al_2O_3	31.61	31.85	31.83	31.64	32.44	31.66	31.53	31.56	31.74	32.15
Fe_2O_3	0.03	0.02	0.02	0.06	0.02	0.03	0.14	0.00	0.04	0.00
FeO	0.02	0.01	0.02	0.02	0.03	0.02	0.54	0.02	0.04	0.03
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.00
MgO	0.09	0.02	0.00	0.07	0.04	0.04	0.17	0.04	0.07	0.08
CaO	0.15	0.13	0.32	0.13	0.21	0.28	0.26	0.13	0.50	1.79
Na_2O	24.72	24.56	25.02	24.76	23.99	23.79	23.95	23.63	24.26	12.83
K_2O	0.08	0.11	0.03	0.08	0.24	0.09	0.08	0.05	0.06	0.72
P_2O_5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H_2O^+	0.06	0.09	0.13	0.10	0.02	0.41	0.29	0.95	0.08	11.61
H_2O^-	0.06	0.01	0.01	0.02	0.17	0.08	0.10	0.20	0.01	1.31
CO_2	0.24	0.19	0.07	0.13	0.14	0.19	0.31	0.26	0.60	0.00
Ign	-	-	-	- -	-	-	-	-	-	-
F	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Cl	6.91	6.89	7.00	6.81	6.77	6.53	6.84	6.09	6.44	0.19
S	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00
Sum	101.23	101.48	101.72	101.28	101.76	101.21	101.58	101.43	101.16	99.99
Cl≡O less	1.56	1.56	1.58	1.54	1.53	1.47	1.54	1.37	1.45	0.04
Total	99.67	99.92	100.14	99.74	100.33	99.74	100.04	100.06	99.71	99.95
Total Fe	0.05	0.03	0.04	0.08	0.05	0.05	0.74	0.01	0.08	0.02

Table 1-12 Continued.

	1-I	1-III	3-I	3-II	3-II-1	3-V	620708-6	BM-1-63	IR-1-63	(Z-1-63)
%Impurity	3.3	7.7	3.7	4.7	7.7	11.80	5.8%	13.2%	16.7%	

Note: 1) First seven samples (i.e. 1-I to 620708-6) are from Princess Quarry, Bancroft, Ontario.

2) IR-1-63 : Sodalite, Ice River, B.C.

3) BM-1-63 : Sodalite, Blue Mountain, Ontario.

4) Z-1-63 : Zeolite, Princess Quarry, Bancroft, Ontario

much poorer in Na_2O and Cl . A sample of sodalite containing 10 - 15 percent zeolite might be expected to exhibit a somewhat higher than average SiO_2, H_2O^+ and CaO content and lower amounts of Na_2O and Cl . Sample BM-1-63 for example contains 13.2 percent zeolite impurity. In its analysis SiO_2 is observed to be high, Na_2O low, H_2O^+ quite high and Cl very low, relative to any one of the first four analyses in table 1-12. Brendler (1934) in his study of Bolivian sodalites pointed out that the chemical weathering of sodalite caused a leaching out of the alkali metals and chlorine. In table 1-2 analyses 4,5 and 6 were made on samples of sodalite from the same deposit in Bolivia. Analysis 7 was made on a slightly weathered sodalite from Bolivia. The weathered sample contains less Na_2O and Cl and more SiO_2 and water than the fresh samples.

On the basis of the analyses made for this study the author will define what he considers to be an acceptable analysis of sodalite (i.e. one which contains a minimum of impurities and has not been weathered appreciably.) Such an analysis consists almost entirely of SiO_2 ,Al_2O_3, Na_2O and Cl . In the case of hackmanite S may substitute for Cl . The extent of this substitution is unknown. For the remaining oxides and anions TiO_2, MnO and F are present in amounts less than 0.05% or absent; Fe_2O_3, FeO, MgO less than 0.10%; CaO and CO_2 only rarely greater than 0.30%; and K_2O generally less than 0.20% although in rare cases it may be as large as 1.20 weight percent (e.g. Bolivian sodalite; table 1-2 analyses 4,5,6). The acceptability of values for the major oxides is determined on the basis of: (1) their weight percent, and (2) the molecular ratio of $(Na_2O + K_2O)$: $(Al_2O_3 + Fe_2O_3)$:$(SiO_2 + TiO_2)$:$(Cl + S)$ which is predicted to be 1.33: 1.0: 2.0:0.33 by the structural formula.

Table 1-13: Partial analyses of sodalite and associated molecular ratios.

	1.		2.		3.		4.	
	wt.%	Ratio	wt.%	Ratio	wt.%	Ratio	wt.%	Ratio
SiO_2	36.72	1.97	37.25	2.0	37.46	2.01	38.09	2.04
$Na_2O + K_2O$	25.66	1.319	24.80	1.29	24.84	1.29	23.88	1.24
$Al_2O_3 + Fe_2O_3$	31.87	1.0	31.61	1.0	31.64	1.0	31.69	1.0
Cl + S	7.22	0.329	6.91	0.313	6.81	0.309	6.53	0.296

(1) Sodalite from Bolivia (anal. #5. table 1-2)

(2) Sodalite from Princess Quarry, sample 1-I, table 1-12.

(3) Sodalite from Princess Quarry, sample 3-II, table 1-12.

(4) Sodalite from Princess Quarry, sample 3-V, table 1-12.

Table 1-13 gives four sodalite analyses and the corresponding molecular ratios. Column 1 gives a set of ratios which are almost identical to those predicted by the structural formula. The analyses which represent columns 2 and 3 are not in exact agreement with the theoretical ratios. These samples are known to contain 3.0 - 7.0% zeolite impurity. The fourth column represents a sample with greater than 10% zeolite impurity. Its molecular ratios for $Na_2O + K_2O$ and Cl + S are definitely different from those of the theoretical formula and the other samples in the table.

On the basis of this data the author would reject as unacceptable analyses of sodalite with molecular proportions of the major oxides and anions indicated in table 1-13 different from the theoretical ratio by more than that indicated by sample 3-II in table 1-13. In terms of a chemical analysis this corresponds to a minimum of approximately 6.80% Cl , and 24.50% $Na_2O + K_2O$; approximately 31.60% $Al_2O_3 + Fe_2O_3$, and a maximum of 37.45% $SiO_2 + TiO_2$. As a rule, the weight percent chlorine is the best indicator of a poor analysis.

In table 1-14 a comparison is made between two analyses drawn from the data in table 1-12. Column (1) represents the averages calculated from acceptable analyses (i.e. sample 1-I, 1-III, 3-I, 3-II, 3-IV, and 620708-6) in table 1-12. The observed maximum variation for these units is also given. Column (2) is the analysis of sample BM-1-63 in table 1-12 which contains approximately 13.2% zeolite impurity. Column (3) is the analysis of a zeolite from the Princess Quarry. The writer assumes that the composition of the zeolite from the Princess Quarry given in column 3 is representative of all zeolites which have formed from the alteration of sodalite. The discussion to follow supports this assumption for those oxides and anions considered.

Table 1-14: Comparison of average sodalite analysis with impure analysis and zeolite analysis.

Oxide or Anion.	(1)	(2)	(3)
$SiO_2 + TiO_2$	37.39 ± 0.29	38.50	39.28

Table 1-14 Continued:

Oxide or Anion.	(1)	(2)	(3)
$Al_2O_3 + Fe_2O_3$	31.86 ± 0.60	31.56	32.15
$Na_2O + K_2O$	24.60 ± 0.57	23.68	13.55
Cl	6.87 ± 0.13	6.09	0.19

It is obvious from a comparison of columns (1) and (2) that the impure sample is slightly high in SiO_2, possibly low in $Fe_2O_3 + Al_2O_3$, and definitely low in $Na_2O + K_2O$ and Cl. Since column (3) is considered to be an analysis of the impurity in sample BM-1-63, it is reasonable that chlorine shows the most change since it is almost absent in the zeolite. $Na_2O + K_2O$ shows the next largest difference followed by $SiO_2 + TiO_2$. $Al_2O_3 + Fe_2O_3$ falls within the range acceptable for natural pure sodalite. From this data the author has concluded that the apparent variation in the oxides and anions of sodalite in table 1-12 is not real. It has arisen from the presence of a sodium rich zeolite admixed with sodalite in varying proportions.

In table 1-12 chlorine exhibits quite a wide variation and the associated data on H_2O^+ in a few analyses suggested a substitutional phenomenon between the two anions. The facts subsequently presented however illustrate that if such a substitution does exist it is much more limited than is implied by the chemical analyses of table 1-12. The observed variation in chlorine for the acceptable analyses is ±0.13 weight percent. Since all the sodalite samples were heated before analysis with the exception of sample 620708-6 water may have been driven out of the structure. Only 0.28 weight percent was reported for sample 620708-6. This may represent the approximate amount which could be expected in a sample of sodalite from the Princess Quarry. It is worth noting that if this amount of water were added to the weight percent Cl for each acceptable analysis in table 1-12, the molecular ratios calculated in table 1-13 would come very close to the predicted theoretical values.

In summary: it is the author's opinion that most of the variation observed for SiO_2, Al_2O_3, Na_2O and Cl in the nine sodalite analyses in table 1-12 is attributable to experimental error and variations in the amount of admixed sodium-bearing zeolite, with most emphasis on the latter factor.

It is worthwhile to expand this discussion to include the analyses presented in table 1-2. The analyses represent both sodalite and hackmanite. SiO_2, $(Al_2O_3 + Fe_2O_3)$, $(Na_2O + K_2O)$ and (Cl + S) all show a maximum variation ranging from ± 1.0 to ± 2.0 weight percent. On the basis of the preceeding discussion of analyses made in this study, analyses were taken from table 1-2 which were considered representative of natural sodalite and hackmanite (i.e. relatively free of impurities). These analyses are presented in table 1-15. In table 1-16 average values for the main oxides and anions are presented for acceptable analyses of sodalite from the Bancroft and Bolivian occurrences. The maximum observed variation for each constituent is also given. Also averages

Table 1-15: Sodalite (and hackmanite) analyses from the literature.
(acceptable analyses)

	1.	2.	3.	4.	5.	6.	7.	8.
SiO_2	37.33	36.68	36.36	38.05	36.70	36.99	37.60	
Al_2O_3	31.87	31.99	32.09	31.30	32.01	31.77	31.63	
Fe_2O_3			0.09	tr.	0.07	0.17	0.55	
FeO								
MgO								
CaO				tr.			0.28	
Na_2O	24.56	25.63	24.73	24.77	24.79	25.84	24.02	
K_2O	0.10	0.25	0.12		0.17	0.16	0.46	
H_2O^-	1.07		0.12		0.00			
H_2O^+			0.86		0.36		0.28	
TiO_2								
MnO			0.06					
P_2O_5								
CO_2								
Cl	6.83	7.21	6.79	7.18	7.00	6.44	5.56	
F								
S								
SO_3			tr.	tr.	tr.	0.39	1.10	
$CaCO_3$			0.50					
Sum	101.76	101.75	101.70		101.39	101.81	101.62	
$O \equiv Cl$	1.54	1.63	1.53	1.62	1.58	1.64	1.80	
Total	100.22	100.12	100.17	100.51	99.81	100.17	99.82	

1) Blue sodalite, Litchfield, Me. (U.S.G.S. Bull 220) Anal. F.W. Clarke.

2) Average of three sodalite analyses, Cerro Sapo, Bolivia (Brendler, 1934).

3) Blue sodalite, Magnet Cove, Arkansas (Miser and Glass, 1941)

4) Blue sodalite, Rajputana, India (Miser and Glass, 1941)

5) Hackmanite, tinguaite, Magnet Cove, Arkansas (Miser and Glass, 1941) Anal. J.J. Faley.

6) Hackmanite; sodalite aegirine rock, Kola peninsula (Borgstrom, 1901). Anal. H. Borgstrom. (Deer, Howie and Zussman, 1961).

7) Hackmanite, Luyavrurt, Kola peninsula (Vorobieva, 1946) Anal. V.A. Moleva. (Deer, Howie and Zussman, 1961).

Table 1-16: Comparison of averages of analyses on all sodalite analyses presented in table 1-2, 1-12, 1-14.

	$SiO_2 + TiO_2$	$Al_2O_3 + Fe_2O_3$	$Na_2O + K_2O$	Cl + S
$\bar{X}$ Bancroft	37.39	31.86	24.60	6.87
	±0.29	±0.60	±0.57	±0.13
$\bar{X}$ Bolivia	36.68	31.99	25.63	7.21
	±0.05	±0.15	±0.08	±0.01
$\bar{x}_1$	37.09	31.85	24.91	6.98
V_1	±0.96	±0.55	±1.09	±0.32
$\bar{x}_2$	37.84	31.37	24.32	6.32
V_2	±4.72	±1.89	±4.20	±1.57

$\bar{X}$ Bancroft: Average of six acceptable analyses (table 1-12)

$\bar{X}$ Bolivia: Average of three analyses (table 1-2)

$\bar{x}_1$: Means based on all acceptable analyses plus averages from Bancroft and Bolivian samples.

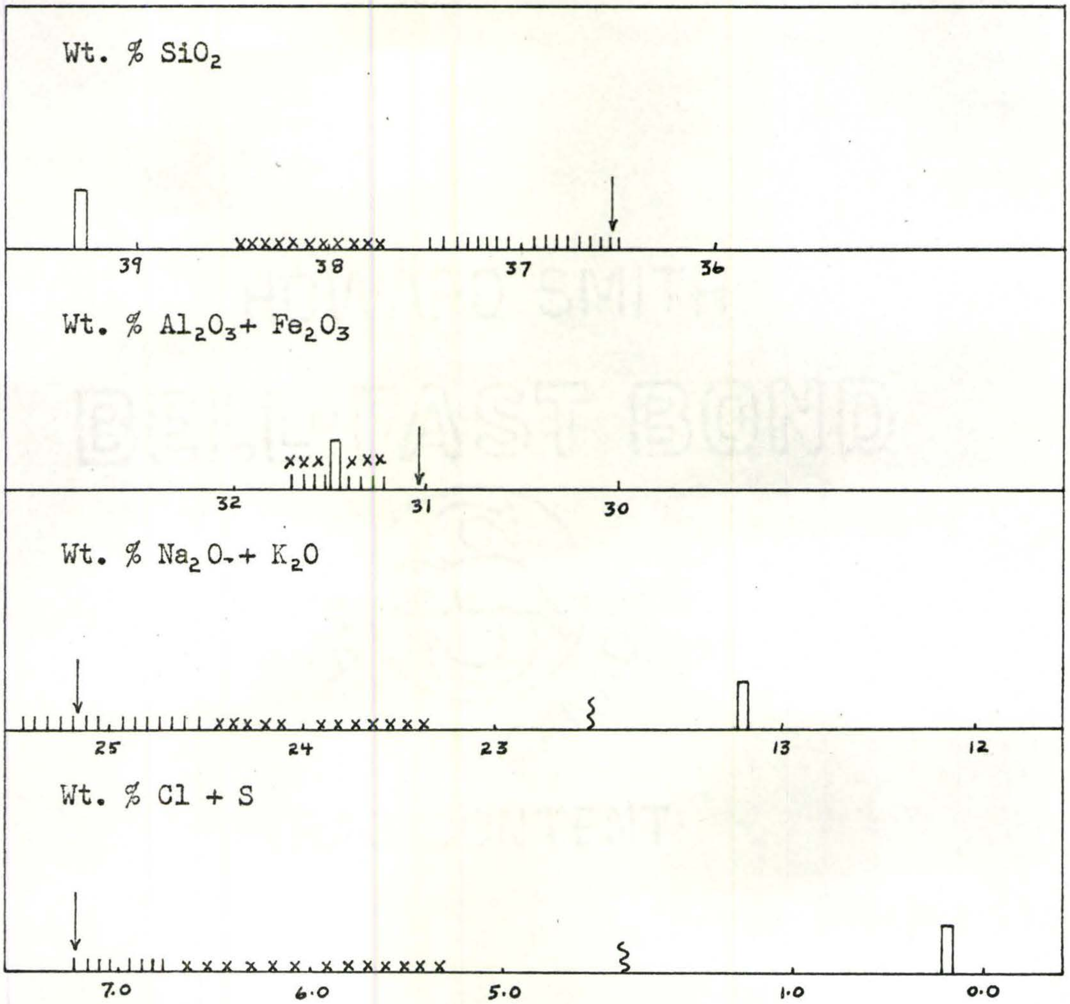
$\bar{x}_2$: Means based on all analyses plus averages from Bancroft and Bolivian samples.

V : Maximum observed variation for each group of oxides and anions.

were calculated for two groups based upon: (1) all acceptable analyses from the literature in addition to those acceptable analyses made in this study (tables 1-12 and 1-15); and (2) all the analyses taken from the literature (table 1-2) plus all the analyses made in this study (table 1-12). For each group of oxides and anions the maximum observed variation is indicated for both (1) and (2). These values are not particularly useful due to the positively skewed nature of the frequency distribution being studied. The group (2) averages are seriously biased by analyses which are not considered acceptable by the standards proposed earlier in this section. A comparison of the two sets of averages indicates that SiO_2 + TiO_2 in group (1) is lower than that in group (2), and that Al_2O_3 + Fe_2O_3 , Na_2O + K_2O and Cl + S. are all higher in group (1). In figure 1-2 the differences between a pure sodalite analysis, an impure sodalite analysis and a zeolite analysis for the oxides and anions considered above are illustrated diagrammatically. The results of this study lead to conclusions which are identical to those arrived at from a smaller but more detailed study on samples given in table 1-12.

This study tends to indicate that at least some of the analyses in the literature are not representative of pure sodalite. The variation indicated by analyses 3,7,10 and possibly 11, in table 1-2 is not due so much to variation in composition of the sodalite as it is to the varying amounts of impurity. Water in the form of the hydroxyl ion

Fig.1-2 Oxide and anion content of pure and impure sodalite and zeolite A.



- ||| Acceptable analyses of sodalite.
- × Unacceptable analyses of sodalite.
- ▯ Zeolite analyses.
- ↓ Ideal sodalite analyses (Stoichiometric proportions).

appears to substitute for chlorine up to approximately 0.30%. Additional water recorded in some analyses is probably due to the presence of hydrated impurities. SiO_2, Al_2O_3 and Na_2O content also reflect the effect of impurities but the differences for each of these oxides is much smaller and is liable to be largely masked by errors involved in the methods used to determine the amounts of each oxide present, as well as by natural variation. The problem of poor analyses of sodalite has largely arisen out of the difficulty of separating the pure mineral from the fine grained zeolite alteration product due to their similar physical properties.

C. Trace Elements.

Samples 1-I and 3-I from the Princess Quarry were analysed in duplicate for fourteen trace elements. The examination was only qualitative. Zr, V, Ni, Co, Sc Mn, Ba, Mo and Sn were not found in these samples. Cr, Ti and Sr, were found in trace amounts to concentrations between 10 - 100 ppm. Ga and Cu occurred in amounts between 10 - 100 ppm but the results for Cu are possibly spurious due to contamination. Medved (1954) reports traces of Be, Ba and Sr; 0.01% Li and Ga; 0.0015% MnO; and 0.005% Pb in a sample of hackmanite. None of these elements were found in sodalite.

D. Statistics.

The chemical, physical and optical data that have been presented in the previous sections were studied for evidence of correlations between any two properties. As a general rule if correlations are not evident from a study of the data using graphical techniques then statistical methods will seldom reveal any significant relationships. In most studies the correlations are fairly obvious by inspection and statistical methods are used to quantify the relationships. The author has attempted to establish correlations using the data presented in tables 1-2, 1-12 and 1-15

The data was treated in two ways. The chemical analyses of samples 1-I, 1-III, 3-I, 3-II, 3-IV and 620708-6 in table 1-12 and those samples 1,4,5,6,8,9 and 13 in table 1-2 were studied for evidence of correlations between the main chemical parameters of sodalite. Note that for analyses of hackmanite Cl and S are combined. The inverse relationship between these two anions is obvious from the analyses in the literature but is not studied in this paper. Graphical methods failed to reveal a relationship between any two parameters or any two ratios. Each analysis was then divided into five units: SiO_2 + TiO_2, Al_2O_3 + Fe_2O_3,Na_2O , K_2O, and Cl + . A program for the Bendix G-15 digital computer prepared by Dr. G.V. Middleton was used to compute a correlation matrix. The resulting matrix is presented in table 1-17-A. Each number represents a correlation coifficient (r) which can range from +1.0 to -1.0. A high absolute value of r may indicate a significant correlation between the two parameters involved. Low absolute values indicate no correlation exists. At the 95% and 99% confidence level the only significant correlation is between K_2O and Cl. This relationship is possibly overemphasized due to the data used to calculate the matrix. Three samples from Bolivia all contain high Cl and K_2O while the majority of the remaining analyses used were much lower in K_2O and Cl. Many more analyses would be necessary to establish whether this correlation indicates a real trend or whether it is significant only due to insufficient data.

The chemical analyses from table 1-12 used in calculating the above matrix were then combined with the physical and optical data determined for each of these samples. An attempt to correlate, by graphical or statistical methods, the physical and optical data with the chemical properties was unsuccessful. Table 1-17-B illustrates the correlation matrix which was calculated using these data. The percent

Table 1-17-A: Correlation matrix on chemical data.

	$SiO_2 + TiO_2$	$Al_2O_3 + Fe_2O_3$	Na_2O	K_2O	Cl
$SiO_2 + TiO_2$	1.0	-0.466	-0.099	-.555	-.147
$Al_2O_3 + Fe_2O_3$		1.0	-.309	.286	-.330
Na_2O			1.0	-.152	0.285
K_2O				1.0	0.635
Cl					1.0

at 95% confidence level: significant if $r > 0.476$*

at 99% confidence level: significant if $r > 0.634$*

at 99.95% confidence level: significant if $r > 0.801$*

Table 1-17-B: Correlation matrix on chemical, physical and optical data.

	$SiO_2 + TiO_2$	$Al_2O_3 + Fe_2O_3$	Na_2O	K_2O	Cl	SG	RI	%Imp.
$SiO_2 + TiO_2$	1.0	.421	.044	.544	-.264	-.018	.008	.119
$Al_2O_3 + Fe_2O_3$		1.0	-.539	.925	-.566	-.308	.016	.595
Na_2O			1.0	-.676	.726	.052	.356	-.668
K_2O				1.0	-.747	-.046	.000	.742
Cl					1.0	-.256	-.290	-.586
S G						1.0	.497	.434
RI							1.0	.020
%Imp.								1.0

at 95% confidence level: significant if $r > 0.729$*

at 99% confidence level: significant if $r > 0.882$*

at 99.95% confidence level: significant if $r > 0.974$*

* Confidence level taken from table A-30-a; Dixon and Massey (1957)

impurity of each sample was also included. At the 99% confidence level the only significant correlation is between K_2O and Al_2O_3+ Fe_2O_3. It is regarded as a spurious correlation possibly due to the closed array nature of the chemical data (Chayes, 1962). The cell dimension a_o for the analyses used is regarded as approximately constant and therefore was not included in the analysis. The density and refractive index show no significant correlations with any of the chemical parameters.

V. Conclusions.

The following points have been concluded from the data presented in the previous sections.

1) The cell dimension a_o for samples of sodalite from the Princess Quarry does not vary more widely than the experimental error. The variation is considered sufficiently small to indicate that the cell dimension for samples from this deposit are constant. For samples from other occurrences there is a wider but still quite narrow variation. Its significance is not evident.

2) A measureable variation in the specific gravity occurs, but its significance is not clear. The author still regards the wide variation with suspicion since the alteration to a zeolite can proceed on a very fine scale without being clearly visible, yet cause an apparent variation in the density of the mineral.

3) The refractive index varies measurably but the variation is not correlated with any chemical variation.

4) A significant number of analyses in the literature are not representative of pure natural sodalite. The variation in the important chemical oxides and anions is narrower for samples from one deposit than for samples from a number of wide-spread occurrences. When reduced to molecular ratios the oxides and anions for the acceptable analyses of table 1-12 and all of the analyses in table 1-15 exhibit ratios to each other which agree quite closely with those predicted by the structural formula. It

should be kept in mind that high Na_2O and high Cl are difficult to determine using rapid silicate or classical silicate methods of analysis. This factor, in part, may explain some of the remaining variations in the analyses.

5) This study has been restricted by the lack of samples from regions other than in Canada in sufficient quantities for chemical analysis. A possibility still remains that the narrow range in variation for all the properties determined, and the lack of correlation between any of them, is due to the lack of sufficient data.

<u>VI</u>. Recommendations for further study.

Hackmanite is a variety of sodalite with the sulphide ion substituting for chlorine. It has been mentioned only sparingly in this study, and analyses of this mineral have been treated as analyses of sodalite by combining the S and Cl . This study has established that the OH^- ion does not substitute for Cl^- in sodalite to any large extent. It definitely appears however that the $S^=$ and Cl^- ions are interchangeable to a much greater degree. A study of the extent of solid solution between a hypothetical sulphide sodalite (hackmanite) and natural sodalite may reveal the only solid solution series to which sodalite belongs.

Part II.

The Genesis of Sodalite at the Princess Quarry, Bancroft, Ontario.

I. Introduction: Previous studies of sodalite occurrences.

Sodalite is not a common silicate mineral, and for this reason it is probably instructive to review the types of environments in which it is found as reported in the literature. The occurrence at Bancroft, Ontario is omitted from the present discussion.

In table 2-1 twenty-one occurrences of sodalite are listed. They are classified according to their environment of formation. Sodalite is found to occur in volcanic, plutonic and hydrothermal rocks. The term hydrothermal is used to designate an environment in which minerals are formed by replacement and precipitation processes due to reactions between hot aqueous fluids and pre-existing mineral phases. To separate hydrothermal minerals from those which form as primary phases, the term magmatic is used. It signifies crystallization from a silicate melt containing a variable amount of volatile substance. Of the three physical states of matter which constitute the magmatic environment (i.e. solid, liquid and gas), sodalite probably forms from replacement reactions between the solid and gas phases. Strictly speaking therefore, there is probably little difference between the processes of formation of sodalite in magmatic and hydrothermal environments.

The problem which has arisen from attempting to separate magmatic and hydrothermal sodalites is illustrated in the study by Allan (1902) of the Ice River complex in south west British Columbia. Sodalite syenite (ditroite) occurs as the last member of a differentiated alkaline

Table 2-1: Sodalite Occurrences.

LOCALITY.	MINERAL ASSOCIATION.	ENVIRONMENT.	REFERENCE.
Bancroft, Ontario	As veins in joint planes in nepheline syenite associated with nepheline, microcline, perthite, oligoclase lepidomelane, calcite, magnetite and zeolite.	Hydrothermal	this work.
Blue Mountain, Ontario.	As veins in joint planes in nepheline syenite associated with cancrinite, neph. oligoclase	Hydrothermal	studied by writer.
Ice River, British Columbia	As anhedral crystals in nepheline syenite and in veins with cancrinite and pyrite.	Hydrothermal Magmatic	Allan (1902)
Fukushinzan, Korea.	In veins in nepheline syenite associated with cancrinite, melanite, fluorite.	Hydrothermal	Haraguchi (1928)
Mogok District, Burma	In pegmatite veins in nepheline syenite associated with nepheline and calcite.	Hydrothermal	Lacroix (1931)
French Guinea	In pegmatite in nepheline syenite as large crystals associated with plates of microcline.	Hydrothermal	Lacroix (1931)
Kola Peninsula	Sodalite in pegmatites associated with sodalite syenite and nepheline syenite.	Hydrothermal	Gerasimovsky (1937)
Cerro Sapo, Bolivia	Sodalite dyke associated with nepheline syenite.	Hydrothermal	Brendler (1932)

Table 2-1 Continued.

LOCALITY	MINERAL ASSOCIATION	ENVIRONMENT	REFERENCE.
Red Hill, New Hampshire.	Grey sodalite in grey nepheline syenite.	Magmatic	Quinn (1935)
Pilansberg, Transval.	Poikilitic sodalite syenite	Magmatic	Partridge (1938)
Beemersville, New Jersey	Fluorescent sodalite in nepheline syenite.	Magmatic	Wilkerson (1946)
Ditro Complex East Carpathians.	Blue sodalite in nepheline syenite	Magmatic	Streckeisen (1960)
Solwezi, N. Rhodesia.	Sodalite nepheline syenite: albite replacing microcline; sodalite replacing nepheline, microcline and albite.	Magmatic (?) Hydrothermal (?)	Adams and Osborne (1932)
Messum, Igneous complex S.W. Africa.	Sodalite in dyke rock in sodalite tinguaite	Magmatic (?) Hydrothermal (?)	Mathias (1956)
Rocky Boy stock, Bearpaw mts. Montana	Sodalite with sanidine and nepheline syenite	Magmatic	Pecora (1942)
Trapian Law phonolite Scotland.	Sodalite in dyke rock in sodalite tinguaite	Volcanic	MacGregor (1922)
Ahaggar, central Sahara, Portuguese, E. Africa.	Sodalite in phonolites	Volcanic	Teale and Smith (1923)

Table 2-1 Continued.

LOCALITY	MINERAL ASSOCIATION	ENVIRONMENT	REFERENCE.
Naples, Italy	Sodalite trachyte	Volcanic	Deer, Howie and Zussman (1963)
Laacher See	Sodalite in trachytes and sanidinites	Volcanic	Deer, Howie and Zussman (1963)
Rhineland	Sodalite in drusy cavities of ejected volcanic blocks.	Volcanic	Kalb (1939)
Monte Somme, Vesuvius	Sodalite in volcanic bombs	Volcanic	Deer, Howie and Zussman (1963)

intrusive series. It contains perthite, orthoclase, nepheline, hornblende and sodalite. Sodalite occurs in part as independent anhedral crystals, and as irregular veins interstitial to the other minerals. The veins extend into metasediments and there consist of sodalite, cancrinite and pyrite. Allan states that the crystals of sodalite represent primary crystallization under late stage magmatic conditions, whereas the veins formed in a hydrothermal environment. Bonney (1902) argues that all the sodalite formed under hydrothermal conditions. In table 2-1 where both magmatic and hydrothermal are listed as the environment of formation, an occurrence such as the Ice River complex is implied.

In volcanic rocks, sodalite may occur as small phenocrysts associated with leucite, nosean and hauyne. In such cases sodalite occassionally forms as small modified cubic crystals. Positive identification of these phases is often difficult due to the small size of the crystals and similar optical properties of these isometric minerals.

The pertinent facts concerning the occurrences of sodalite are briefly summarized below.

1) Sodalite is restricted to per-alkaline undersaturated rocks in particular nepheline syenites and associated pegmatites.

2) Minerals commonly associated with sodalite are nepheline, oligoclase or albite, microcline, orthoclase, sanidine, perthite, lepidomelane, iron rich pyroxene or hornblende, cancrinite, calcite, magnetite, natrolite and

other zeolites.

3) Sodalite may form in:

   a) pegmatites of the type nepheline-microcline-lepidomelane-calcite-sodalite.

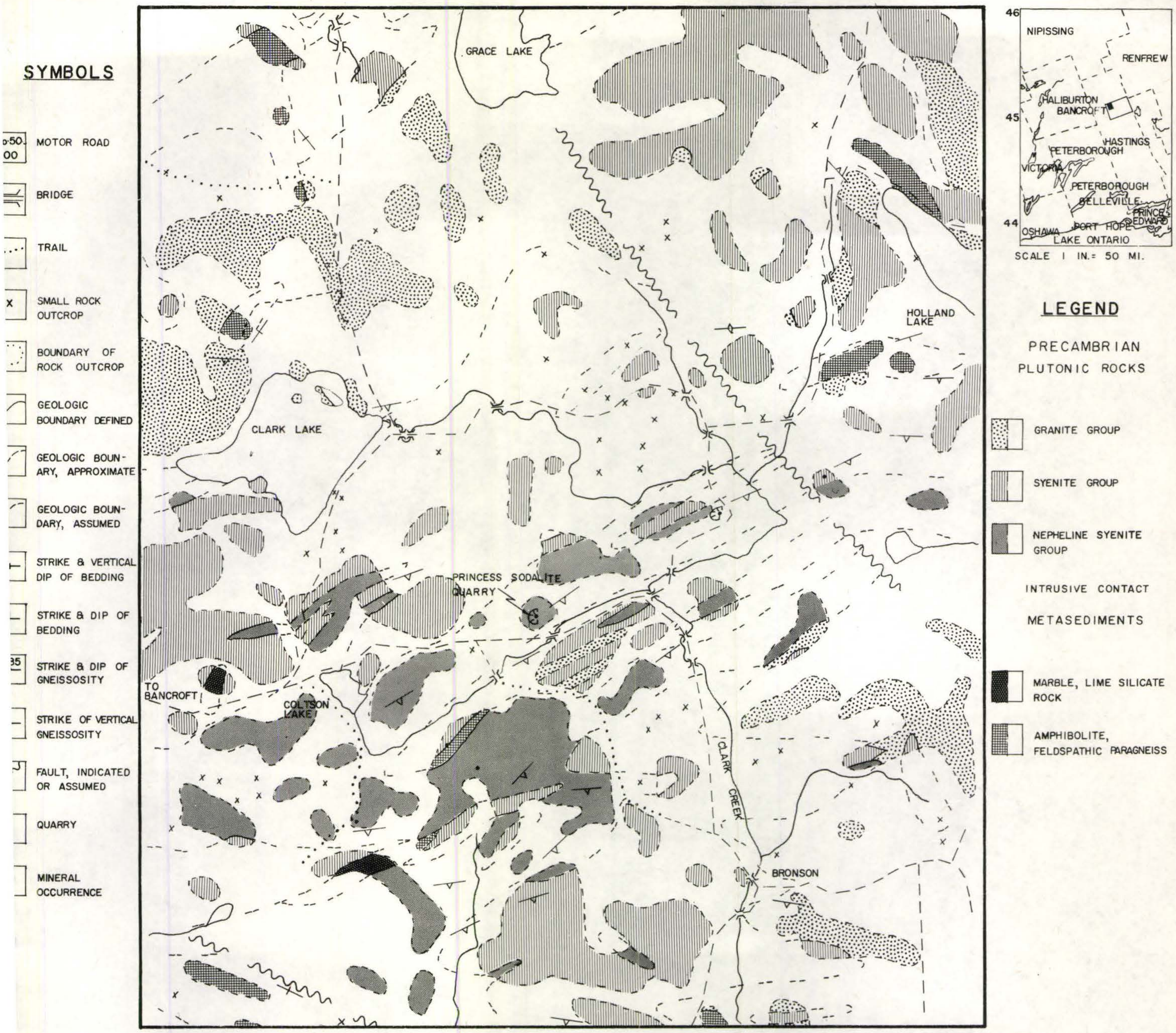
   b) in nepheline syenite host rock replacing nepheline and possibly sodic plagioclase feldspar due to chlorine metasomatism from veins of the type in a.

   c) in per-alkaline plutonic rocks as a primary accessory phase of the last rock type of a differentiated series.

   d) in volcanic rocks such as trachytes and phonolites as a primary phase associated with other feldspathoids.

II. Regional Geology.

The area most pertinent to this thesis is that portion of the Hastings Highlands gneiss complex extending a few miles east and west of Bancroft, Ontario. Map 1-A outlines in detail the geology of this region in the immediate vicinity of the Princess Quarry. Numerous detailed accounts of the geology of this region have been published. Among the most significant papers are those by Adams and Barlow (1910), Gummer and Burr, (1946), Moyd (1949), Barrager (1952), Hewitt and James (1955), Tilley (1957), Hewitt (1960), Tilley and Gittins (1961) and Gittins (1961).



GEOLOGICAL MAP OF

PART OF THE NEPHELINE SYENITE AREA EAST OF BANCROFT

(COPIED FROM MAP PREPARED BY HEWITT D.F. AND JAMES W.; MAP No. 1955-8)

SCALE IN MILES

MAP No. 1-A

The southern portion of the Grenville Province which crops out in southeastern Ontario consists of a series of metamorphosed and metasomatised volcanic and sedimentary rocks intruded by numerous plutonic bodies. The region is subdivided into the Hastings Basin, a series of altered volcanic and sedimentary rocks and the Hastings Highlands, a region of predominantly plutonic intrusive rock complexes. The two regions are separated by the McArthur Mills fault which runs in a sporadic manner from the Albion lake area in Faraday township, east through Dungannon and most of Mayo township where it vanishes near the town of McArthur Mills.

The table of formations (table 2-2) outlines the major lithologic units and their equivalents in the Highlands and Basin. Lumbers (1964) has pointed out that the term basin should not carry any connotation of a structural basin. Here it is simply used to distinguish a region of distinct lithologic character.

The Hastings Highland gneiss complex is a terrane of high-grade metamorphic gneisses characterized by rocks of the amphibolite and lower granulite facies. Metavolcanic rocks now represented by amphibolite, hornblende schist, and pillow lavas (Rowland volcanics), and metasediments comprise the oldest rock units in the gneiss complex.

The metasediments are represented by (1) a paragneiss - amphibolite group of rocks which include amphibolite, garnet amphibolite, garnet-sillimanite paragneiss, quartzite and quartzo-feldspathic paragneiss and schist; and (2) a marble group consisting of interbedded marble and paragneiss, silicated marble, skarn and lime silicate rock.

TABLE OF FORMATIONS. [1]
DUNGANNON AND MAYO TOWNSHIPS.

Table 2-2

		HASTINGS HIGHLANDS		HASTINGS BASIN.	
Pleistocene		Boulder clay, Sand Gravel. UNCONFORMITY		Boulder Clay, Sand, Gravel. UNCONFORMITY	
Precambrian		--------------------		McArthur Mills Granite —— Intrusive Contact ——	
	Plutonic Rocks	Hybrid Gneiss Great Bend Granite Bronson Granite Faraday Granite —— Intrusive Contact		Not Represented	
		Nepheline syenite gneiss —— Intrusive Contact		Not represented	
		Boulter Granite —— Intrusive Contact		Weslemkoon Granite Bessemer Granite —— Intrusive Contact ——	
		Mallard Lake and Raglan Hills Meta - Gabbro		Umfraville Gabbro Gabbro and Amphibolite	
		Intrusive Contact			
	Grenville meta-sediments and meta-volcanics	Marble GP : marble and paragneiss or amphibolite interbedded: Silicated marble	Mayo GP.	North - Central Dungannon Township	
				Hermon FM	Pelitic schist and paragneiss, meta greywacke, meta-arkose
		Paragneiss and Amphibolite. GP. Amphibolite garnet amphibolite, quartzo-feldspathic gneiss		Dungannon FM	Marble, Detlor feather amphibolite and marble.
		Metavolcanic Rocks Amphibolite, hornblende schist, pillow lava.			

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[1] After Hewitt and James, 1955: Geology of Dungannon and Mayo Townships, O.D.M. Report Vol. LXIV, part 8.

The remaining history of this region was dominated by igneous intrusive and metasomatic processes. The oldest intrusives are the Mallard Lake and Raglan Hills metagabbro found in northern Dungannon and Raglan townships respectively. The first intrusion of granitic composition was the Boulter granite. Following the intrusion of these igneous bodies a second phase of activity involved the emplacement of nepheline syenites, syenites and potash granites. Both magmatic and lit-par-lit injection and replacement appear to have played significant roles during this latter period of activity. The nepheline bearing rocks appear to have formed by replacement very early in the plutonic cycle. They are intruded and replaced by syenites which are in turn cut and replaced by younger pink granite and pegmatites.

Metasomatism and large scale assimilation have altered and reduced in volume the original sediments considerably, and have produced an abundance of hybrid rocks. For the most part the intrusives exhibit concordant relationships. Since the grade of metamorphism is quite high remanent sedimentary structures are seldom observed. Later periods of folding have produced a foliated to gneissic texture in most of the rock units described.

III. Petrology of the Nepheline Syenite Gneiss in the Bancroft Region.

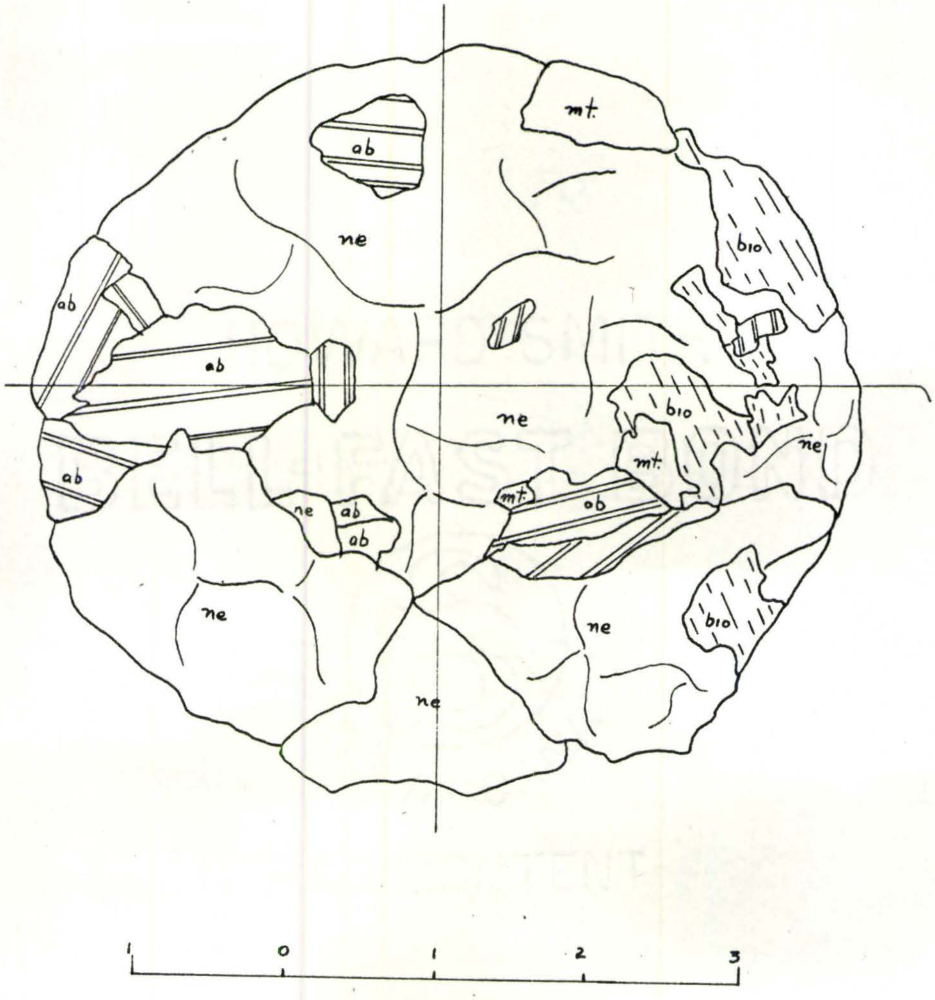
A. Structure and Petrography.

For the purposes of this study the most important rock unit is the Bancroft band of nepheline syenite gneiss. It occurs as lenses rarely greater than one to two miles in length and less than a mile in width. Commonly a zone of syenite gneiss separates the undersaturated rocks from granites. Pink - to - buff coloured syenite gneiss is often mixed with nepheline gneiss whence comes the term "mixed gneisses". Contacts between nepheline syenite and amphibolite and marble are not common and are often faulted. Skarns occur along the rare nepheline gneiss - marble contacts.

The major mineral phases of the nepheline gneiss are nepheline, oligoclase , biotite and magnetite and occassional small amounts of green hornblende. Calcite commonly occurs interstitially and sodalite, cancrinite, hydronepheline and zeolites are abundant as joint fillings. Corundum-nepheline gneiss is found on the Lily Robertson property one-half mile southwest of the Princess Quarry. On a scale of a few feet the texture of the rock varies from gneissic to hypidiomorphic granular and poikilitic. The gneiss exhibits varying degrees of banding due to the segregation of the mafic minerals. Anhedral nepheline crystals are often elongated parallel to the foliation as are the laths of twinned oligoclase. All variations exist between this and a granitic texture. Also large anhedral nepheline crystals in a few places partially engulf the smaller plagioclase and biotite producing a semi-poikilitic texture (see figure 2-2).

In contrast to the nepheline gneisses of the York River band this type of gneiss is commonly interbanded with syenite gneiss.

Fig. 2-1 Nepheline syenite illustrating textural relationship of nepheline (ne), albite (ab), biotite (bio), and magnetite (mt).



Scale in mm.

On map 1-A the lensing pattern of these units is apparent on a regional scale. Locally a similar distribution of rock types is observed but it is less obvious. Gummer and Burr (1946) have described nepheline - poor gneiss interbanded with nepheline rich gneiss. The nepheline deficient gneiss contains hornblende, albite, calcite and microcline. They also report potash feldspar in minor quantities as the latest formed mineral in nepheline gneiss. It is noticeably more abundant in certain bands than in others where it is frequently associated with the more intense alteration of nepheline, and has been observed more abundant adjacent to pink syenite dykes.

In the vicinity of the Princess Quarry an untwinned potash feldspar identified as orthoclase was found in the nepheline gneiss. It forms anhedral and subhedral crystals very similar in appearance to those of nepheline and occurs concentrated in narrow bands in the nepheline gneiss. Oligoclase is noticeably less abundant in such bands. The orthoclase is easily distinguished from microcline and microcline perthite, which are the predominant feldspar phases in the veins and wall rock of the Princess Quarry.

B. Petrogenesis.

Adams and Barlow (1910) proposed a magmatic origin for the nepheline gneisses. Thirty years later a metasomatic process called nephelinization was used to explain their numerous characteristics. Gummer and Burr (1946) and Moyd (1949) were the two main proponents of this theory. Hewitt and James' (1955) report on the Bancroft and York

River nepheline rocks, and Tilley's (1957) study of the York River band support the earlier work of Gummer and Burr, and Moyd.

The most recent studies on the nepheline rocks have been made in Glamorgan township (west of Bancroft) by Gittins and Tilley (1961) and Gittins (1961). Gittins concluded that both igneous and nephelinized gneisses exist in this township. The problem with the nepheline rocks has become one of distinguishing metaigneous from nephelinized gneisses. According to Gittins a nepheline syenite magma has crystallized to produce a variety of igneous alkaline rocks by differentiation, and fluids from the parent magma have caused nephelinization of the surrounding country rock. The variety in composition of the nephelinized rock has resulted from the original variation in the pre-existing sediments or metasediments and the variation in the nephelinizing fluids by differentiation of the parent magma.

Gittin's (1961) theory depends upon the existance of a nepheline syenite magma. Moyd (1949) and other earlier investigators proposed that the nephelinizing solutions were derived from a granitic source. This theory probably arose from observations of the intimate mixture of nepheline and granitic rocks in the Bancroft region. Which of the two theories is correct remains undecided.

IV. Geology of the Princess Quarry.

A. Location.

The Princess Quarry is located immediately north of the east road (highway 500) on lot 25, concession XIV, Dungannon township, Hastings County, Ontario. The town of Bancroft is situated approximately three miles west of the quarry at the intersection of highways 500 and 28.

B. Description and Structure.

The workings in the quarry have formed two major pits totalling 500 feet in length and 50-100 feet in width. The pits plunge into the south side and top of a hill approximately 50 feet high underlain by nepheline syenite. Veins 1-2 feet wide containing nepheline, microcline, perthite, sodalite, lepidomelane, magnetite, calcite and apatite run continuously for the entire length of the quarry. It has not been established whether the veins extend further in the north-south direction than has been indicated by quarrying operations. Map 1-B illustrates the features of the quarry in detail, as of July, 1963.

The wall rock and country rock immediately surrounding the quarry vary from non-foliated massive syenite to distinctly banded syenite gneiss. The foliation trends consistently N 15° E dipping to the east at 70°-90°. This trend agrees with the regional foliation of the area. A well developed joint pattern is present in the gneiss in the vicinity of the quarry. The two most prominent joint sets have trends of N 15° E dipping 70°-90° east and rarely steeply west, and N 85° E dipping 75°-90° to the north or south. A third less distinct joint set strikes N 15° E dipping at a very shallow angle to the east. Figure 2-2 illustrates the major trends of 70 joints measured in and about the quarry.

A shear zone striking N 15-20° E and dipping 45°-50° east runs the entire length of the quarry. The major shear is marked by a strongly mylonitized zone of dark micaceous material. Slickensides are common along

Fig. 2-2 Poles of 70 joints, Princess Quarry, Bancroft, Ontario. Contours, 6.5%, 5.5%, 4.5%, 3.5%, 2.5%, 1.5%, 0.5%, per 1% area.

the sheared surfaces but an indication of the direction of movement was not obtainable due to the broken nature of the material in the pits from quarrying operations. Evidence of shearing is most prominent in the upper pit but it also appears on the west side of the lower pit indicating that the mylonitization extends at least 20-30 feet in depth. Thinner, less significant subparallel shear zones or fractures are common in the wall rock for 20 to 30 feet on either side of the main zone of breakage.

The veins in the quarry in most cases trend parallel to the joint pattern in the country rock. Comparison of the main trends of the joints indicated in figure 2-2, and that of the veins in map 1-B illustrates the control that the joint pattern exhibits upon vein occurrence in the quarry. The shear zones were all formed after emplacement of the veins and cut them in places.

C. Mineralogy of vein minerals.

The present discussion is intended to summarise the characterizing features of each mineral which occurs in the veins of the Princess Quarry.

1) Nepheline: stubby prismatic subhedral to euhedral crystals with pinacoidal terminations; 1.0 - 5.0 cms. in length, dull grey weathered surface; no evident cleavages; assumes an anhedral form in mylonitized zones of veins.

2) Alkali feldspar: subhedral to anhedral pseudomonoclinic crystals; generally 1-5 cms. in length but rarely as large crystals up to 20cms. long; light pink to grey colour; in mylonitic zones of the veins the

crystals are anhedral.

The optical properties reveal that both microcline and microcline perthite are present in the veins. Microcline has 2v = 85° (—); excellent albite and pericline twinning. Some of the microcline is perthitic containing rods and irregular patches of twinned or untwinned albite. A partial analysis of one euhedral perthite crystal gave 9.30% K_2O and 5.1% Na_2O. The crystals contained approximately 80% microcline and 20% albite.

3) Lepidomelane: $(K_{2.05}, Na_{0.02}, Ca_{0.07})(Fe^{+2}_{2.37}, Fe^{+3}_{0.58}, Mg_{2.19}, Ti_{0.38}, Mn_{0.08})(Al_{2.40}, Si_{5.56})(OH_{1.97}, F_{0.42}, C_{0.02}, Cl_{0.01}, S_{0.01})O_{21.57}$; formula calculated from analysis 1, table 2-4; occurs as pseudo-hexagonal plates up to 15cms. in length rarely extending more than 2-3cms. in the direction of c' axis; dark brown to black in hand specimen; medium brown to dark reddish brown pleochroism, and often almost opaque; the mineral forms as intergrowths of crystals in irregularly shaped pods 2-5 feet in diameter; the crystals are often bent and broken in mylonitized zones.

4) Apatite: euhedral prismatic crystals 2-3cms. in length terminated by a well developed basal pinacoid; good basal parting; apple green; No = 1.626; identified as fluorapatite.

5) Magnetite: $(0.42\ Fe_2O_3, 0.02\ TiO_2)(0.42\ FeO, 0.01\ MnO,)$; fractions of oxides were calculated from analysis 2, table 2-4; subhedral intergrown octahedra 2-3cms across restricted to small segregations less than a

foot in diameter.

6) Calcite (0.97 CaO, 0.01 MnO, 0.01 FeO).(CO_2); subhedral crystals 1-2cms. in length and width; weathered surface is tan to reddish brown; tends to fill the central position of the veins lining and/or cutting earlier formed minerals; also occurs as an abundant inclusion in sodalite. For chemical analysis see table 2-4, col. #3.

7) Sodalite: $6Na\ AlSiO_4 \cdot 2NaCl$: for discussion of properties see section I of thesis; occurs as fine grained aggregates of anhedral crystals and as subhedral and rarely euhedral pseudomorphs after nepheline.

8) Zeolite A: $(Na_{5.27}, K_{0.23}Ca_{0.82}Mg_{0.05})\ (Al_{16.04}, Si_{16.65})\ O_{80} \cdot 16.54\ H_2O$: occurs most commonly as massive white to light pink anhedral crystalline aggregates; rarely fibrous prismatic and short tabular prismatic crystals are observed in small vugs within anhedral masses of the same mineral; G = 2.306; Ny = 1.507, Nx=1.504; biaxial negative and positive, 2v = 85°; elongation positive; 1st order yellow birefringence; microscopically it forms radiating fibrous aggregates; one good cleavage parallel to the elongation; parallel extinction.

The results of x-ray diffraction analysis are given in table 2-3. In table 2-4 col. #4 an analysis of this mineral is given. The mineral is similar to natrolite in composition but its x-ray pattern does not agree with any of the commoner zeolites. This mineral also has a composition similar to material loosely called hydronepheline by some investigators (Barlow, 1902). In table 2-4 col. #5 and #6, two analyses

Table 2-3: X-ray data for Zeolite A.

2θ (uncorrected) Cu Kα, radiation	d_{hkl} (corrected using Si standard)	Relative Intensity.
12.98	6.811	ms
13.35	6.623	mw
14.37	6.151	m
14.82	5.969	mw
18.47	4.792	vs
19.92	4.441	mw
20.74	4.267	w
21.30	4.157	w
24.41	3.636	w
27.17	3.268	w
27.38	3.242	w
30.23	2.946	w
30.55	2.913	w
30.69	2.902	w
31.12	2.862	vw
33.80	2.644	vw
35.72	2.506	vw
40.02	2.247	vw
41.40	2.227	vw

of hydronepheline are given but no optical or physical data were reported. The author has chosen to call the white alteration mineral in the Princess Quarry Zeolite A, and not identify it with any of the phases mentioned in the literature to avoid undue confusion.

9) Cancrinite: anhedral and subhedral prismatic crystals less than 0.1mm. in length; only rarely found in vein zone.

10) Pyrite, Pyrrhotite: occur together as anhedral aggregates in the vein zone. The atomic percent iron in pyrrhotite was estimated using the x-ray method of Arnold (1962). A sample was ground to below 200 mesh, heated to approximately 360°C in an evacuated tube for 10-15 minutes, and allowed to cool. The heating process converted the symmetry from monoclinic to hexagonal. Hexagonal pyrrhotite has a strong 102 spacing at 43.50°-44.00° 2θ. The sample used gave d_{102}= 2.0579 A°(i.e. 43.99° 2θ using CuKα radiation). The value corresponds to 46.70 atomic percent iron.

Neither pyrite nor pyrrhotite are abundant in the veins.

Table 2-4: Chemical Analyses.

	1.	2.	3.	4.	5.	6.	7.
SiO_2	35.59	0.43	0.18	39.28	38.99	42.80	33.21
TiO_2	3.30	1.34					2.21
Al_2O_3	13.19	0.00		32.15	33.62	28.50	17.49
Fe_2O_3	5.00	67.14				0.34	3.17
MnO	0.66	0.37	0.91				0.51
FeO	18.35	30.35	0.99	0.04			23.10
MgO	9.51		0.10	0.08			7.45
CaO	0.38	0.09	54.53	1.79	0.07	1.90	0.06
Na_2O	0.03		0.04	12.83	13.07	14.33	0.54
K_2O	9.25			0.72	1.12	0.30	8.96
P_2O_5	0.03	0.11					
H_2O^+	1.91	0.16	0.04	11.61	12.98	10.81	3.67
H_2O^-	0.42	0.08		1.31			
CO_2	0.07		43.37				
F	1.72		0.02				
Cl	0.10		0.06	0.19			
S	0.07						
Sum	99.58	100.07	100.24	99.99	99.85	98.98	100.37
F,Cl ≡ O	0.74	0.00	0.02	0.04			
Total	98.84	100.07	100.22	99.95			
Total Fe as Fe_2O_3	25.39	100.87	1.08	0.02			

Table 2-4 Continued.

1) Lepidomelane: Princess Sodalite Quarry, Bancroft Ontario.

2) Magnetite: Princess Sodalite Quarry, Bancroft Ontario.

3) Calcite: Princess Sodalite Quarry, Bancroft Ontario.

4) Zeolite A: Princess Sodalite Quarry, Bancroft Ontario.

5) Hydronephelite: Litchfield Maine. Dana's Mineralogy, 1898, 2nd edition, John Wiley and Sons Inc., New York, P.609

6) Hydronephelite, Ice River, British Columbia, Ann. Rep. Geol. Surv. Canada. Vol. XII, P. 13R.

7) Biotite from nepheline - feldspar - biotite pegmatites. Mackay property, lot 14, Conc. VI, Monmouth Twp. (Gittins, 1961, p.306).

D. Petrography.

(1) Veins.

The minerals which form the veins in the quarry have been listed in the previous sections. Shearing and subsequent mylonitization of some of the veins have produced textures which will be discussed separately from the details of the unsheared zones.

a) Unsheared Veins.

The main textural features and mineral associations in the unsheared veins are listed below. Continual reference to plates 1-17 which are photographs of representative textural features will undoubtedly aid the reader in understanding the forthcoming descriptive data.

a) Plate #2 shows subhedral to euhedral nepheline crystals growing perpendicular to the sides of the joint planes into open spaces between joint faces. Blue sodalite is commonly found pseudomorphically replacing the nepheline crystals. Nepheline may also be found as small anhedral and rarely euhedral crystals 0.1 to 2.0mm. in diameter enclosed in massive sodalite (plates 3,4,5). The nepheline crystals often show narrow granular transition zones into sodalite. The surfaces of nepheline crystals are not uncommonly patchy with hydronepheline and/or zeolite A.

b) Microcline and rarely microcline perthite occur as anhedral crystals up to 15cm. long and 7cm. wide (plate 6). Rarely there is a suggestion that they have grown out from joint planes in a manner similar to nepheline. Both feldspar phases also occur as small anhedral crystals with embayed borders imbedded in sodalite (plates 4,7). In contrast to nepheline the potash feldspar rarely shows strongly altered interfaces with sodalite.

c) Within the veins lepidomelane occurs as pseudohexagonal books randomly distributed as patches in the veins. It may also occur as basal plates 0.5 - 1.5mm. in length enclosed in sodalite. In such an environment it is invariably associated with anhedral magnetite, smaller in size than itself, which grows within and along the borders of the mica. This association is most conspicuous in the veins and wall rock but is also present in unaltered nepheline syenite.

d) A green fluorapatite is sparsely developed in the veins. It forms short euhedral prismatic crystals 2-3cm. long with pyramidal and pinacoidal terminations. It is found associated only with calcite and sodalite.

e) In many portions of the vein sodalite is the most abundant mineral. Reference to its relation with nepheline has already been described. Where it is most abundant it may often contain "eyes" and aggregates of nepheline, microcline, lepidomelane and small microscopic inclusions of calcite (plates 5,7). On both the macroscopic and microscopic scales, sodalite is usually severely cracked and a white alteration mineral, zeolite A, commonly forms along such cracks. Plate #8 illustrates a vein of sodalite altered to zeolite A, plate #9 illustrates the distribution of zeolite A in relatively fresh sodalite. The light-brown inclusions in this photograph are calcite. The narrow white lines and disseminated spots in the black background of sodalite in plate #4 illustrate the appearances of zeolite A on a microscopic scale.

f) Calcite occurs in coarsely crystalline masses in the central portion of the veins lining the earlier formed silicates such as nepheline and microcline. The large vug opened in the lower centre part of plate #10 was largely filled with calcite. The roof and sides of the vug contain euhedral nepheline crystals and massive zeolite A speckled with light blue patches of sodalite. Calcite is also a common microscopic inclusion in sodalite as massive irregular patches rarely as large as 0.5mm in diameter. It may also be found filling cracks in sodalite.

g) Magnetite occurs in the veins as aggregates of euhedral intergrown octahedra. It appears to form in patches much like lepidomelane. Magnetite also occurs as euhedral inclusions in sodalite and less commonly as fillings in the cracks in this mineral. Its mode of occurrence is texturally like that of calcite.

h) In the veins zeolite A replaces sodalite on a microscopic and macroscopic scale. Plates # 4,8 and 9 illustrate the range in size of alteration. In rare cases the zeolite develops narrow long prismatic and short tabular crystals up to 1cm. in length. Euhedral and subhedral crystals are formed within the fine-grained massive zeolite and appear to have formed in solution cavities. Plate #11 best illustrates the appearance of the zeolite on a microscopic scale; such radiating aggregates are common.

i) Pyrite and Pyrrhotite are the only sulphide minerals which have been found in the quarry. They are both rare. In thin section they were observed filling cracks in nepheline which had been rimmed by sodalite. They exhibit no crystal form but do exist in close proximity to each other.

The data presented in the previous section on mineralogy established that pyrrhotite contained 46.70 atomic percent Fe. Using the geothermometer developed by Arnold (1962) this corresponds to a temperature of formation (i.e. last equilibrium temperature) of approximately 475°C. This figure however, can not be regarded as acceptable in the light of further studies. Kullerud et. al. (1963) studied four monoclinic pyrrhotites from four different deposits. All of these samples were associated with pyrite. The d_{102} values for the four sulphides varied from 2.056A to 2.059A. This restricted range corresponds to a variation of 46.45 - 46.70 atomic percent iron. These results suggested to Kullerud that monoclinic pyrrhotites in equilibrium with pyrite have a nearly constant composition unlike hexagonal types in which the atomic percent iron is a function of temperature. Since the determination made in this study lies within the range quoted by Kullerud for monoclinic pyrrhotites, the author would suggest that the temperature value is not particularly useful.

(b) Mylonitic and Cataclastic textures.

Superimposed upon the textures and mineral assemblages described above are mylonitic and cataclastic textures, developed in the veins. Oligoclase, which is most common in the nepheline gneiss and wall rock, and perthite which is most common in the wall rock, are locally abundant in the sheared veins. This suggests that shearing has caused the incorporation of much of the wall and country rock into the vein zone. Plate #17 illustrates a sheared vein zone with blue sodalite and dark micaceous sheared wall rock lying side by side. On a microscopic scale the sheared veins often contain alternating bands and lenses of: (1) sodalite full of angular to subhedral crystals of nepheline, microcline, perthite and oligoclase; (2) opaque fine grained zones with rare well developed bent and strained crystals of lepidomelane: and (3) mylonitized nepheline syenite with large subangular to rounded crystals of oligoclase, nepheline, microcline and perthite. In places the vein rock appears to be a breccia of pegmatite fragments while elsewhere it is a fine mylonite streaked with sodalite veins. Plates 3,5 and 17 illustrate some of the textures described above. Away from the sheared zones, the presence of mylonitic and cataclastic textures decrease sharply.

Flowage structures are very obvious in the sheared sodalite. Fine inclusions of feldspar, nepheline, calcite and zeolite A define this structure (see plates 3 and 5). In the sheared zones the crystal size of sodalite is not visible due to the isotropic nature of this mineral;

rarely anhedral augen of this mineral are observed and appear to be relict porphyroclasts of unsheared vein sodalite. These crystals are distinguished from much finer grained sodalite by (1) the total lack of small birefringent inclusions common to most of the vein sodalite, or (2) the noticeable bulging or bending effect they produce on narrow mylonitic bands much like that displayed by garnet in a metamorphic rock.

The textures described above have been produced by shearing subsequent to crystallization of the pegmatite and alteration to sodalite. Small shear zones offset sodalite veins as well as small zeolite veins which formed from the alteration of sodalite. Sodalitized nepheline syenite is observed against sodalite - free nepheline rock with a straight and abrupt boundary between the two. The breccia described above is also a conspicuous feature demonstrating shearing subsequent to sodalite formation. Sodalite in unsheared zones often shows cleavage surfaces up to 1.0cms. in length and width. Their absence in sheared sodalite probably indicates that the sheared material is very fine grained although the crystal size cannot be determined microscopically due to its isotropic nature. To verify this, two samples of sodalite were taken, one from a mylonitized zone and the other from a zone exhibiting no effects of shearing. Thin slivers from each sample were x-rayed using a medium size powder camera. The sample from the shear zone gave a diffraction pattern consisting of smooth continuous Debeye - Scherer rings indicating that the material was a microcrystalline randomly oriented aggregate. The other sample gave a spotty photograph suggesting coarser grain size than the sheared specimen. This is confirmed by noting the size of the cleavage faces on the unsheared material. This study suggests that shearing occurred after the formation of the sodalite in the quarry.

(2) The Wall Rock Zone.

The wall rock is a zone 1-3 feet in width comprised of an assemblage of minerals displaying distinctive textural features not found in either the veins or the county rock. In this zone potash feldspar, sodalite and zeolite A form three mineralogical fronts. The potash feldspar front delineates the outer limit of the wall rock zone. Plate #8 and #10 illustrate the sodalite and zeolite fronts respectively. Figure 2-3 illustrates all three fronts but it is somewhat schematic in that not all three fronts have been recognized together at a single location in the wall rock. The term front is used as a genetic term to describe the outer boundaries of the zones surrounding the veins. A front is defined as "any surface in the crust of the earth forming the boundary (sharp to diffuse) between any two arbitrary mineral assemblages." In addition to the above mentioned characterizing minerals, oligoclase, biotite, magnetite, calcite and cancrinite occur in the wall rock zone.

The potash feldspar front delineates the maximum penetration of the wall rock zone into the unaltered nepheline syenite country rock. This front is diffuse (e.g. rarely recognizeable in rock outcrops), and is defined by the appearance of more than 2.5 percent potash feldspar.

Fig. 2-3 Schematic diagram of minerals in veins and commonest assemblages in wall rock. Note the extent of the potash feldspar, sodalite and zeolite fronts.

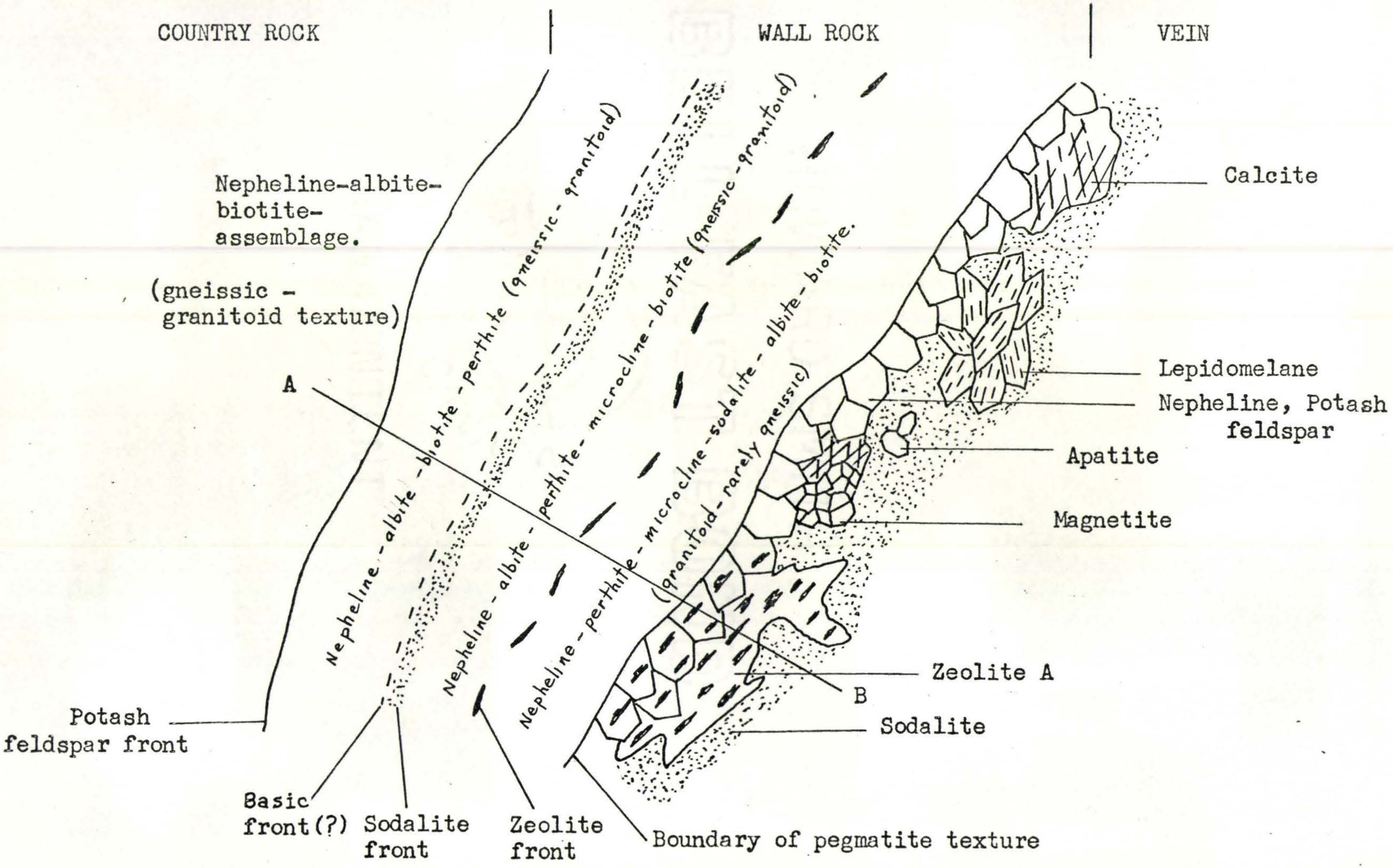
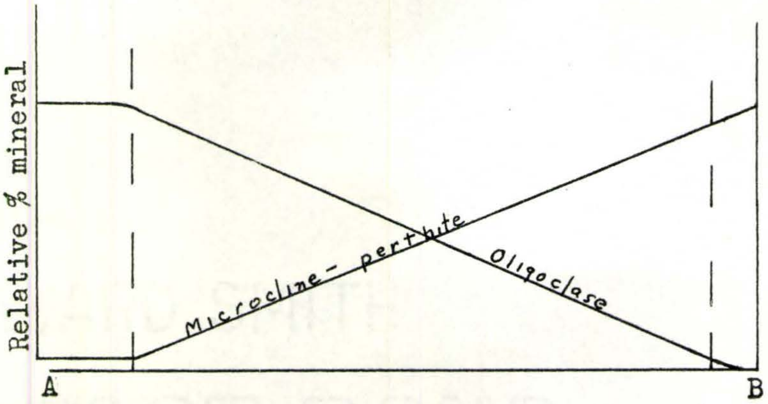
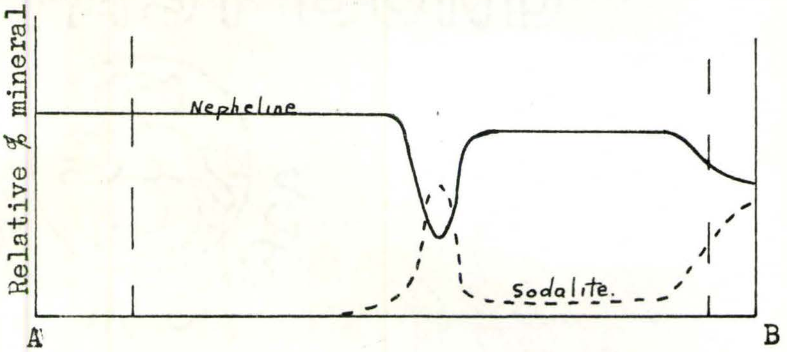


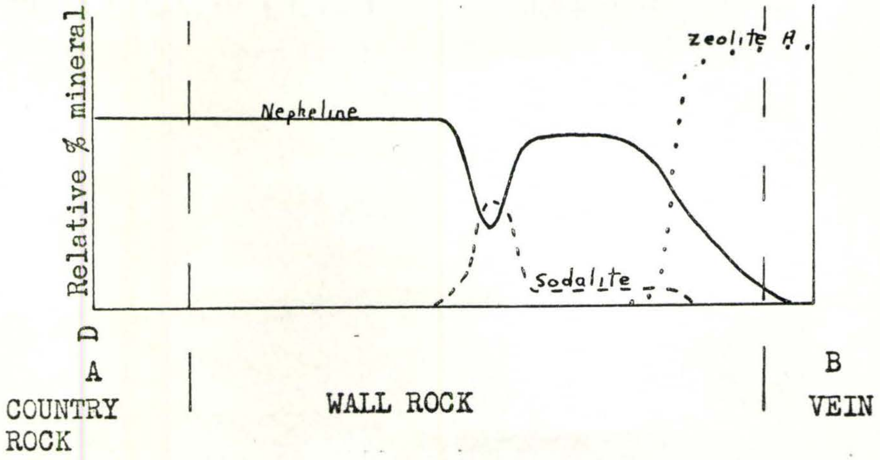
Fig. 2-4 Relative distribution of characterizing minerals in wall rock zone, Princess Quarry.



(a) Distribution of feldspar in wall rock zone.



(b) Distribution of nepheline and sodalite in wall rock zone.



(c) Distribution of Zeolite A in wall rock zone.

Unaltered nepheline syenite from outside this front contains 1-2 percent microcline.

Figure 2-4, part (a) indicates the distribution of the alkali and plagioclase feldspars in the wall rock. Note the reciprocal relationships between the abundance of microcline and microcline perthite, and oligoclase.

The sodalite front varies in character from place to place within the quarry. In one instance it is very sharp and distinct but more commonly it is quite diffuse and difficult to observe, not unlike the feldspar front. Such a sharp front is rarely present so far from the vein zone. More commonly the sodalite front is quite diffuse and not more than a few inches from the vein. In figure 2-4, part (b) the distribution of sodalite in the wall rock is shown for both types of fronts. Note the reciprocal relationship between sodalite and nepheline. In one instance a narrow band of biotite rich rock was noticed on the country rock side of the sodalite front less than an inch from the band of sodalite (see figure 2-3). This may represent a basic front which formed concurrently with the sodalization process.

The zeolite front occurs closer to the vein than the other two fronts. In plate #10 it appears as a sharp white line. On the vein side of this front nepheline and sodalite are replaced by radiating clusters of Zeolite A. Also the feldspars are strongly sericitized and are locally represented by kaolinized masses with remanent cleavages of the pre-existing feldspars.

In figure 2-4, part(c) the distribution of zeolite A is illustrated diagrammatically. Its abundance is inversely proportional to the feldspathoidal content of the rock. Like the sodalite front, the zeolite front may extend some distance into the wall rock or only a few inches. However, alteration of the rock between the vein and the front is always severe attacking as it does both nepheline and feldspar unlike the process of sodalitization which alters nepheline alone.

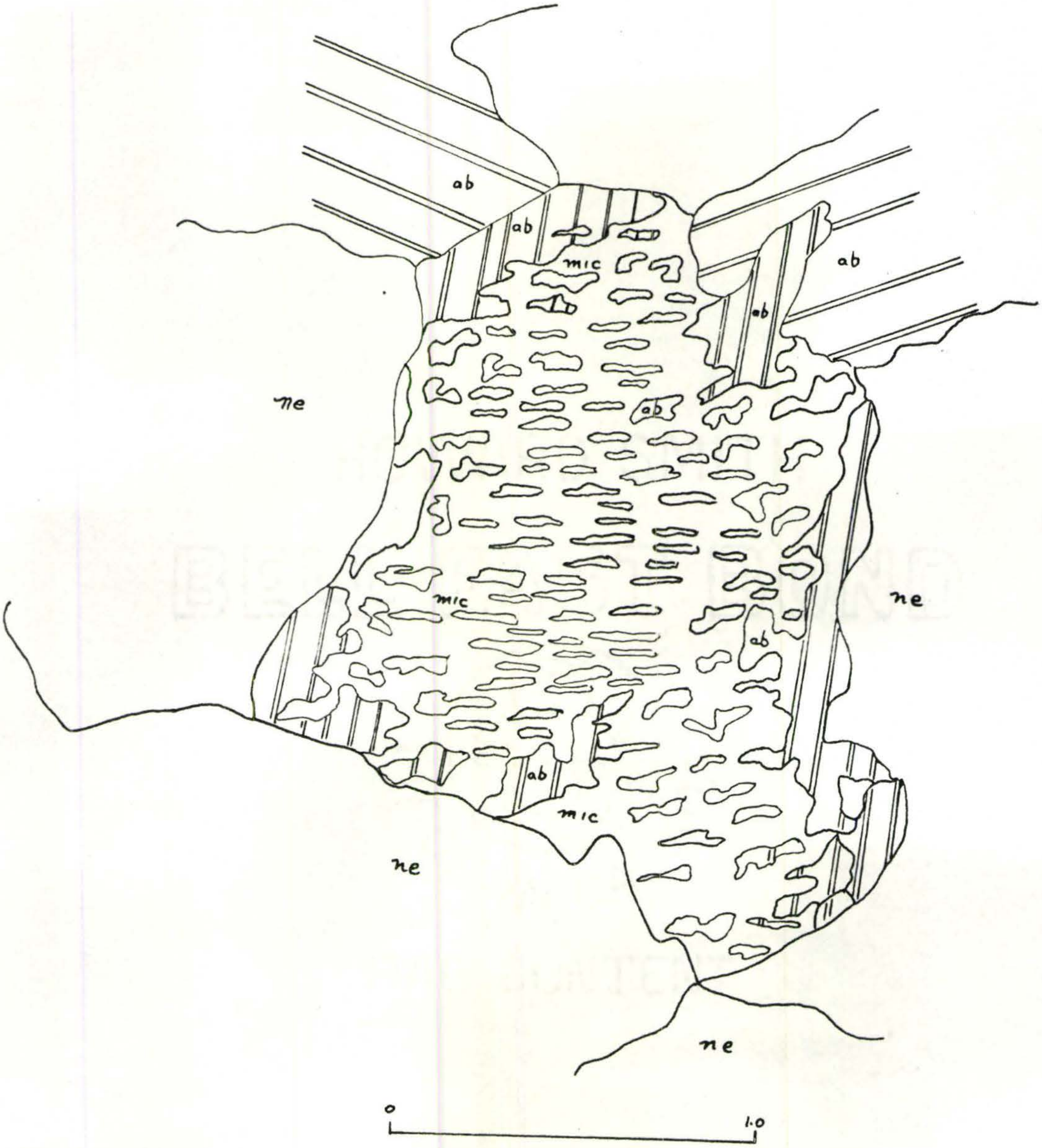
All three fronts have never been identified in one small section of the wall rock, consequently figure 2-3 is only a diagrammatic representation of the distribution of the fronts. Also distinct sharp fronts are only rarely observed for sodalite and zeolite A, and never for the potassium feldspars. In general the fronts are diffuse surfaces arbitrarily chosen by the investigator.

Microcline perthite and cancrinite are the only new minerals not described in the vein or country rock. Using the nomenclature of Alling (1934), two types of perthites occur in the wall rock: a) rod perthite in which rod shaped lamallae of albite, usually oriented approximately parallel to the 001 cleavage, are embedded in a tartan twinned microcline ground mass (see plates 12,13), and (b) patch perthite in which the albite phase is commonly twinned,blocky or irregular in shape, with jagged borders imbedded in a microcline ground mass (see plates 14). Commonly the perthite may have a complete or partial rim of albite which is invariably in optical continuity with the albite lamellae (plate #12). It is not always clear however whether the rims are associated genetically with the albite lamellae. Judging from the similarity in refractive indices, where this could be measured, the composition of the two phases are approximately identical. It was often noticed that one portion of a perthite crystal might be predominantly microcline while another part was comprised of albite lamellae. Plate #12 illustrates quite an even distribution of the lamellae but plate #13 shows a perthite with the albite lamellae concentrated towards one part of the crystal. Albite twinning in the sodic lamallae of the perthite was most common in the patch perthites (plate #14). The exsolved phase is oriented in a constant crystallographic direction as indicated by the parallelism of the twins from lamella to lamella. Rarely the albite rims are also twinned according to the albite law and in such instances the twin planes parallel those of the twinned lamellae. Figure 2-5 illustrates twinned sodic rims and their relationship to the exsolved sodic lamellae in the central portion of the perthite.

The volume percent of albite in the perthite crystals varies significantly between thin sections. Comparison of the perthite crystals in plates #12 and #13 indicates this feature. This property is discussed in detail in a subsequent section.

The wall rock probably represents a transition zone between the veins and nepheline gneiss in terms of the amounts of chemical oxides and minerals present. Since it is the zone which is most unlikely to attain

-5 Perthite with twinned sodic rims in microcline groundmass (mic) and adjacent albite (ab) and nepheline (ne): note continuity of albite twin orientation.



Scale in mm.

complete chemical equilibrum, it probably best exhibits textures which indicate the major reactions which have taken place between the thermal fluids which have formed the vein and the unaltered country rock. The following paragraphs describe the textures common to only the wall rock zone.

The initial alteration of the country rock (just within the potash feldspar front) is observed 3 to 5 feet from the veins where microcline and microcline perthite are found in amounts greater than 1-2 volume percent, as small anhedral crystals. Small interstitial zones of microcline, perthite, oligoclase, biotite, calcite and rarely cancrinite are found between anhedral and subhedral crystals of nepheline and oligoclase (see plates #12 and #13). Sodalite is rarely present in this zone and cancrinite may be common, always associated with nepheline and calcite. The modal analysis of such a rock would be similar to samples 2-1 or 2-2, table 2-5.

Closer to the veins, within the sodalite front shown in plate 8, rare large crystals of microcline perthite up to 1.0mm. in diameter are found. Microcline and microcline perthite are more abundant than in the previous sample described and oligoclase is noticeably less abundant. In the recrystallized zone there is occassionally a suggestion that microcline and/or perthite has replaced oligoclase (plate #15). Biotite is present as subhedral laths 0.5 to 1.0mm. in length and is invariably associated with smaller anhedral magnetite. Nepheline remains present in roughly the same amount as in the unaltered nepheline gneiss.

Table 2-5: Modal analyses of samples of wall rock and country rock.

	1-1	1-2	1-3	1-4	1-5	1-6	1-7	1-8	2-1	2-2	3-1	3-2	3-4
Nepheline	62.9	59.3	68.9	62.9	64.8	59.8	73.8	65.2	58.1	57.3	50.0	63.2	66.5
Plagioclase	7.9	17.2	3.1	11.9	5.4	11.1	15.2	7.1	25.6	23.4	32.2	24.3	16.3
Perthite	19.3	16.5	17.4	15.7	24.0	16.6	7.5	21.5	5.6	4.7	0.4	7.7	7.6
Biotite	4.2	3.3	5.7	3.8	2.4	2.6	1.3	0.2	8.4	2.3	4.5	0.6	2.5
*Accessory	5.8	3.7	4.8	5.5	3.3	10.0	2.1	6.1	2.2	12.3	12.9	4.2	7.1

*Include magnetite, calcite and microcline: except in slide 3-1 which represents an unaltered sample of wall rock; total accessory when greater than 4.0% probably includes significant amounts of microcline since studies were made to establish distribution of perthite rather than total potash feldspar.

Sodalite may or may not be a common interstitial phase. It may be very abundant especially at the sodalite front (plate #8). Where sodalite is not present cancrinite may form prismatic crystals approximately 0.1mm. in length, occassionally in fan-like clusters associated with nepheline and calcite. In one instance calcite was observed to occur along the boundary between nepheline and oligoclase. The boundary with nepheline was smooth whereas that with oligoclase was quite jagged much like pressure solution boundaries in limestones. The modal analyses of samples 1-2 and 1-4 in table 2-5 are typical of the wall rock in this zone.

Adjacent to the vein, the feldspar in the wall rock is largely microcline perthite and microcline. Less than 5.0 percent oligoclase is present. The abundance of sodalite and nepheline are inversely related. Farther from the vein sodalite appears as an interstitial mineral much like quartz in a granite or as small veins and rims about nepheline. Here, however it "floats" the other mineral phases of the rock (see plate #16). The texture of biotite and magnetite remain unchanged. In a few instances the mica exhibits darker than usual shades of brown pleochroism transitional in appearance to the deep reddish brown to opaque pleochroism typical of lepidomelane in the veins. Calcite remains as an important interstitial mineral (2.0 to 5.0%) and as in the vein, is a major inclusion in sodalite. In this zone the feldspathoids and much of the feldspar may be severly altered to zeolites and sericite. Sample 1-1 and 1-3, table 2-5, indicate the approximate modal composition of rocks in this zone except for those samples rich in sodalite.

The effects of shearing noted in the quarry are also evident in the wall rock. Grain boundaries become poorly defined and granular. In extreme cases mylonitized rock surrounds remanent crystals which are commonly bent and strained. Most of the primary textures are destroyed due to mylonitization and recrystallization.

Table 2-5 contains modal analyses of samples taken from the wall rock zone. The samples were chosen randomly from all parts of the quarry. Sample 3-1 represents the country rock. The samples were studied specifically to investigate the relative proportions of oligoclase, microcline perthite and nepheline. In most of the sections sodalite is not present or only in very small amounts. Points worth noting are: (1) nepheline is the most prominent mineral in all the sections studied; (2) the total feldspar content both in the wall rock and unaltered nepheline gneiss is approximately 30 volume percent; (3) there is a reciprocal relation between perthite plus microcline and oligoclase (4) a fairly complete gradation exists between nepheline gneiss in which oligoclase is the major and often only feldspar, to the altered wall rock which in the extreme case contains less than 5 volume percent oligoclase and 20-25 percent microcline and perthite.

E. Resumé of petrographic study.

Table 2-6 and 2-7 summarize the main differences between the veins, wall rock and country rock in the Princess Quarry. Only a visual

Table 2-6: Estimates of modal compostions of vein, wall rock, and country rock.

	VEIN.	WALL ROCK.		COUNTRY ROCK.	
Minerals.	1.	2.	3.	4.	5.
Oligoclase	1%	7.9%	15.2%	50.2%	32.2
Nepheline	35%	62.9%	73.8%	39.1	50.0
Alkali Feldspar	25%	19.3%	7.5%	2.7	0.4
Lepidomelane - Biotite.	5%	4.2%	1.3%	6.1	4.5
Magnetite	2%	1.2%	21.5%	1.5	3.4%
Apatite					
Sodalite	25%				
Cancrinite	trace	1.0%			
Pyrite - Pyrrhotite					
ZeoliteA	3%	—			
Calcite	5%	1-2%	1.5%	0.4	7-8%

1) Visual estimate of amounts of each mineral present in veins; Princess Quarry.

2) Modal analysis of sample of wall rock close to vein; Princess Quarry.

3) Modal analysis of sample of wall rock some distance from vein; Princess Quarry.

4) Modal analysis of nepheline gneiss, Esson Creek Sill, (Hewitt, 1960 p.40)

5) Modal analysis of nepheline gneiss, Princess Quarry.

Table 2-7: Mineral assemblages in veins, wall rock, and nepheline syenite, Princess Quarry; also minerals in sodalite-free nepheline pegmatites.

Mineral	1. Vein	2. Zone A	3. Zone B	4. Neph. Gneiss	5. Sodalite-free neph. pegmatite
Oligoclase		X	X	X	X
Nepheline	X	X	X	X	X
*Alkali Feldspar	X	X	X - *	*	
Lepidomelane - Biotite.	X	X	X	X	X
Magnetite	X	X	X	X	X
Apatite	X				X
Sodalite	X	X			*
Cancrinite	*	*			*
Calcite	X	X	X	X - *	X - *
Pyrite-Pyrrhotite	*	*			
Zeolite A	X	X			

X Significant abundance.

* Minor amounts or occasionally present.

1) Veins in Princess Quarry.

2) Zone adjacent to veins in country rock.

3) Zones 1-3 feet from veins in country rock.

4) Unaltered nepheline syenite gneiss, Princess Quarry.

5) Nepheline pegmatite such as those at York River.

* Includes microcline and microcline perthite.

estimate has been made to determine the amounts of the minerals present in the veins. Table 2-7 contains a list of the minerals found in nepheline pegmatites. It is worthwhile to compare this assemblage of minerals with those found in the Princess Quarry.

V. Petrology of the Nepheline Pegmatites.

The writer believes that the first stage in the development of the veins in the Princess Quarry was the formation of a mineral assemblage similar to those found in sodalite - free nepheline pegmatites in the Bancroft region. Therefore, before proceeding with a discussion of the petrogenesis of the veins in the Princess Quarry, it is instructive to briefly describe nepheline pegmatites and review the theories concerning their origin. Evidence leading to the belief in a pegmatitic origin of the Princess Quarry deposit will be discussed subsequently.

A. Distribution and Structure.

The nepheline pegmatites occur as elliptical pods 1-3 feet in diameter and as dyke-like bodies or sills often 50-100 feet wide and several hundred feet in length both conformable and unconformable to the gneissic foliation of the country rock. Rarely they are found intrusive into neighbouring marble units, but they are most often completely contained in nepheline syenite gneiss. This writer has classified them into four groups listed below in order of decreasing frequency of occurrence.

1. Elliptically shaped pods 1-3 feet in diameter; rarely show remanent textures of nepheline syenite host rock and vug-like structures are not uncommon suggesting that they formed by recrystallization of nepheline syenite host rock; called xenoblastic patch pegmatites by Hewitt and James (1955).

2) Concordant sills in nepheline gneiss; gradational borders; conformable to gneissic foliation of country rock; they are often more than 100 feet wide and several hundred feet in length.

3) Dyke-like bodies cutting the nepheline gneiss transverse to its foliation; may exhibit metasomatic borders; similar to concordant type in size and shape.

4) Pegmatites in rock other than nepheline syenite, commonly marble, structurally similar to type (3).

B. Mineralogy.

The principal minerals in these pegmatites are, in order of decreasing abundance, nepheline, albite or sodic oligoclase, lepidomelane and magnetite plus accessory calcite, apatite, zircon, sodalite, hackmanite, cancrinite, gieseckite, hydronepheline and zeolites.

Nepheline and albite generally form more than 85 modal percent of each nepheline pegmatite. In the large pegmatites the crystal outline of either of these two minerals are rarely obvious. The crystals in such pegmatites average about 1 foot across but are not uncommonly 1-5 feet in length.

Nepheline from the Davis Quarry has been studied using the x-ray diffraction method of Smith and Sahama (1954). The results are presented in table 2-8-A and indicate that 24.09% of the total alkali sites are occupied by potassium. In table 2-8-B, similar data is presented for nepheline from the Princess Quarry. It indicates that 23.45% of the alkali sites are occupied by potassium. Note the similarity in composition of the two nephelines.

The composition of plagioclase feldspar from nepheline pegmatites ranges from albite to oligoclase (Gittins(1961); see also table 2-9).

In the nepheline pegmatites biotite occurs as segregated masses of subhedral to euhedral pseudohexagonal plates up to 10cm. in length but rarely more than a few cms. thick in the direction of the C' axis. A chemical analysis of biotite from a nepheline pegmatite on the Mackay property, Monmouth township is presented in table 2-4, col.#7. It closely resembles an analysis of lepidomelane from the Princess Quarry (table 2-4, col.1).

Calcite and magnetite are commonly present in nepheline pegmatites making up 5 to 10 per cent each of the rock. Both usually exhibit subhedral to euhedral crystal form. Apatite and zircon occur as accessory minerals and generally form euhedral crystals. The remaining accessory minerals rarely exhibit any distinctive crystalline morphology.

Table 2-8-A: X-ray data for analysis of nepheline, Davis Quarry.

	Run#1(°2θ)	Run#2(°2θ)	Average	%Ks.
Nepheline reflection 21.0	27.198	27.218	27.208	24.57
Nepheline reflection 20.2	29.628	29.638	29.633	23.60
			Average =	24.09

Table 2-8-B: X-ray data for analysis of nepheline, Princess Quarry.

	Run#1(°2θ)	Run#2(°2θ)	Average	%Ks.
Nepheline reflection 21.0	27.208	27.213	27.211	24.04
Nepheline reflection 20.2	29.638	29.638	29.638	22.86
			Average =	23.45

Table 2-9*: Partial Analyses of plagioclase feldspars from nepheline pegmatites.

	1.	2.	3.
Na_2O	11.20	10.95	10.36
K_2O	0.13	1.18	0.73
Or	0.8	7.0	4.3
Ab	94.8	92.5	84.4
An	4.4	0.5	11.3

* Analyst: J. Gittins.

1) Feldspar from nepheline pegmatite. Lot 31, Con.IV, Glamorgan Twp.

2) Feldspar from Goulding-Keene Quarry, York River.

3) Feldspar from nepheline pegmatite in Glamorgan Twp., locality unknown.

C. Textures.

A visual estimate of the modal composition of a nepheline pegmatite is 40-55 % nepheline, 30-40% albite, 5-10% lepidomelane plus magnetite, and a maximum of 5% accessory mineral.

The large sill-like bodies of nepheline pegmatite consist of subhedral to euhedral nepheline and albite with patches of biotite 1-3 feet in diameter scattered throughout the deposit. Calcite occurs as small blebs 1-3cms. in diameter in nepheline and albite. Magnetite forms small masses of poorly formed intergrown octahedra in nepheline and albite. Of the accessory minerals only zircon and apatite occur consistently as euhedral crystals. Sodalite, hackmanite, cancrinite, hydronepheline, gieseckite and zeolites are confined to narrow zones adjacent to cracks and fissures in nepheline and albite.

The small patch pegmatites in the nepheline gneiss consist of nepheline, albite, biotite and less commonly magnetite and calcite. Texturally they are identical to the larger pegmatites. Rarely remanent textures of nepheline gneiss are present in these smaller pegmatites suggesting that they were formed by replacement of the country rock.

The two types of pegmatites mentioned above are generally concordant to the gneissic foliation of the nepheline syenite. Contacts with the country rock are abrupt. Chilled border zones have never been observed. For those large pegmatites which exhibit an intrusive relationship to the nepheline gneiss, narrow contact metasomatic borders may be present (Satterly, 1943) as at the Gill and Fraser quarries, Glamorgan township.

Gummer and Burr (1946) have reported occurrences in the nepheline gneiss of vugs lined with coarse euhedral magnetite and nepheline crystals. They interpret this to indicate a paragenetic relationship between "regenerated" nepheline and late magnetite. Also calcite cavity-fillings or replacements, and the existance of several pegmatites with extremely coarse grained calcite matrices suggested to them that there was a period of formation of large amounts of calcite late in the history of formation of the pegmatites. It is noteworthy that magnetite, calcite, and nepheline in the Princess Quarry have modes of occurrence very similar to those just described in sodalite-free nepheline pegmatites.

The large nepheline pegmatites and the majority of the small xenoblastic patch pegmatites do not exhibit zonal structures. In the previous paragraph calcite has been described as sometimes occurring as a cavity filling or replacement mineral in the core of a pegmatite zone into which euhedral nepheline and magnetite have grown. In such pegmatites zonation may be said to exist. In general however, the nepheline pegmatites do not exhibit distinctive zonal features.

With reference to the genesis of the sodalite deposit at the Princess Quarry, the following features should be noted. These are largely based on observations by the author of many of the nepheline quarries in the Bancroft-York River area.

1) Nepheline, albite, lepidomelane (biotite), calcite, magnetite and apatite have the same textural and structural distribution in many nepheline pegmatites as in the veins of the Princess Quarry.

2) Microcline or any related type of potassium feldspar is never present in nepheline pegmatites.

3) Sodalite, and cancrinite are found only in very small quantities, usually less than 1 per cent, in nepheline pegmatites.

4) Within any one area containing nepheline pegmatites in nepheline gneiss more sodalite and cancrinite is found along joint planes in the nepheline gneiss than is found in the nepheline pegmatites.

5) The distribution of the pegmatite minerals in the Princess Quarry is controlled by the fracture pattern of the nepheline gneiss. No evidence of such control is observed for the same minerals in the sodalite-free nepheline pegmatites.

D. Origin of Nepheline Pegmatites.

Adams and Barlow (1910) considered the nepheline pegmatites to be coarse grained phases of the igneous nepheline syenite gneiss. They likened the patch pegmatites to similar pegmatites in granite gneiss. Gummer and Burr (1946) considered the pegmatites to be formed by replacement of nepheline gneiss. Those which truncate the foliation of the nepheline gneiss were thought by them to be formed from liquids produced by the nephelinization process. Like Gummer and Burr, Moyd (1949) associated pegmatization with nephelinization. For those pegmatites which fill joints in the nepheline gneiss (e.g. at the Princess Quarry), he stated that emanations from syenitic material may have acted as fluxing agents causing partial solution and recrystallization of the wall rock.

Hewitt (1956) called the nepheline patch pegmatites "xenoblastic" and attributed them to recrystallization and replacement of nepheline and albite of the gneiss. Gittins (1961) stated that those pegmatites found in rock (e.g. marble) some distance from nepheline gneiss formed from a residual magmatic liquid. He emphasised that the nephelinization process is a continuous passage outwards of fluids from a magmatic source which was constantly changing composition through differentiation. The nepheline gneisses taken as a whole show a wide range in composition, and it is not abnormal according to Gittins (p.307) to find "metasomatic zones" between the gneiss and some pegmatites as Satterly (1943) reported.

In conclusion, probably the nepheline pegmatites have a complex history of formation involving both magmatic and metasomatic processes. Those nepheline pegmatites reported by Gittins in Glamorgan township which exhibit metasomatic borders with the nepheline gneiss host rock possibly are magmatic in origin. This conclusion is based on Satterly's observations and work by Gittins (1961) and Gittins and Tilley (1961) on metaigneous nepheline syenite gneiss in the immediate area. The remaining types of nepheline pegmatites are for the most part found in nepheline gneiss. In places they exhibit cross-cutting relationships with the gneissosity of the nepheline gneiss, but they have never been observed cutting granite or syenite. Their lack of any gneissic structures indicates that no stress field was present during their formation. Also chilled contacts or aplitic phases, common to magmatic pegmatites are not observed. Ramberg (1952, p.246) stated that often, pegmatites in metamorphic-metasomatic complexes appear to have formed as a result of the metamorphism and/or metasomatism instead of the metamorphism being the result of igneous intrusion. Pegmatization in such a case is regarded as a phase of a regional metasomatic process such as granitization or nephelinization. The pegmatites produced from such processes exhibit many of the characteristics described above for the nepheline pegmatites. Also it is noteworthy that very few of the nepheline pegmatites exhibit any degree of zonation. Jahns (1955 p.1043) has stated that modern structural studies of pegmatite bodies commonly have led to emphasis of the role played by magmatic processes if the pegmatite was zoned. Structural studies then, would also probably favour a metasomatic origin for the nepheline pegmatites. It is the writer's opinion that the majority of the nepheline pegmatites in the Bancroft area were formed by the same metamorphic and metasomatic process which formed much of the nepheline syenite gneiss. In this sense he agrees with many of the earlier investigations.

VI Petrogenesis of the Veins and Wall Rock, Princess Quarry.

A: Stage I : Formation of Primary Mineral Assemblage.

In the veins of the Princess Quarry nepheline, lepidomelane, magnetite, apatite and calcite are prominent mineral phases. In terms of chemical composition, crystalline form, and mode of occurrences, they are quite similar to the same minerals in the sodalite-free nepheline pegmatites. In the Princess Quarry these minerals occur in structurally controlled veins (e.g. tension fractures) in the nepheline gneiss. No equivalent structurally controlled nepheline pegmatites have been observed by the writer in the Bancroft area.

In the previous section it was concluded that the sodalite-free nepheline pegmatites developed during a metamorphic episode, probably associated with the nephelinization process which formed the nepheline gneisses. The uniformity in composition of these pegmatites supports the theory that they formed at one time. In the Princess Quarry unlike any nepheline pegmatite, nepheline grows out from the nepheline gneiss wall rock as euhedral crystals into open tension fractures. This fact suggests that the nepheline-rich mineral assemblage in the veins of the quarry formed later than the nepheline gneiss and was not associated with the nephelinization process which formed the sodalite-free nepheline pegmatites. Nepheline, lepidomelane, apatite, calcite and magnetite in the veins appear to have formed during a later metamorphic episode, but earlier than the formation of microcline, sodalite, pyrite, pyrrhotite and zeolite A. It is assumed by the writer that albite or oligoclase also formed at this time as a major phase of the pegmatite assemblage. Moyd (1949) suggested that fluids from adjacent syenitic and granitic material possibly acted as fluxing agents causing partial solution and recrystallization of the nepheline syenite wall rock. This theory, in the writer's opinion, best explains the origin of the above-mentioned mineral assemblage in the Princess Quarry.

This stage in the development of the presently existing veins was marked by the recrystallization of nepheline gneiss. The Na_2O/K_2O ratio of the system forming this mineral assemblage must have been greater than unity and undersaturated with respect to silica. Minerals such as lepidomelane and fluorapatite attest to the existence of significant amounts of fluorine in the system as well. Possibly a high concentration of an aqueous fluid phase along the fracture zones in the nepheline gneiss depressed the melting point of the host rock sufficiently for recrystallization to occur. The grade of metamorphism in this region lies in the amphibolite and granulite facies (Hewitt and James, 1955,p.6) indicating that the temperatures were sufficiently high to promote such a process. The vug-like structures in parts of the veins could most easily be explained by recrystallization.

For reasons which will be made evident in a subsequent section, it remains unclear whether magnetite or calcite formed at this time. Certainly potash feldspar, sodalite, pyrite, pyrrhotite and zeolite A formed later than nepheline, lepidomelane and apatite from reactions involving fluids enriched in potassium and chlorine.

B. Stage II : Hydrothermal Alteration.

1) Formation of Microcline, Microcline Perthite and Sodalite

a) Potash Feldspars.

Both rod and patch perthites have been described from the veins and wall rock. The rod perthites possibly formed by exsolution of an originally homogeneous alkali feldspar. Alling (1938) interpreted rod perthites to have formed in this manner. A review of the literature on feldspars indicates that much uncertainty exists concerning the origin of patch perthites. The alternative ways in which perthites may form are; (a) unmixing of an originally homogeneous phase; (b) simultaneous magmatic crystallization which would probably form homogeneous microperthites; (c) replacement of sodium feldspar by potassium or vice versa. Tuttle (1952a) studied the textures of perthites and correlated degree of exsolution with decreasing temperature of formation and increasing time subsequent to the crystallization of a homogeneous feldspar. In the laboratory when rod perthites have been homogenized and subsequently cooled, the rod-like perthitic intergrowths have been observed to reform in most cases. An exsolution origin for rod perthites is generally accepted, but it remains unclear whether patch perthites form from the same process and whether a replacement process for rod perthites is possible.

Robertson (1959) described the development of perthites from plagioclase by late deuteric potassium metasomatism. The transformation began with the development of sodic rims about a more calcic core of plagioclase. The rims were subsequently replaced by orthoclase. Some of the albite was taken into solid solution in orthoclase while some remained as relicts which were later reorganized into stringers and blebs. His descriptions suggest that both types of perthite could be formed by replacement processes. The patch perthites represent an intermediate stage in the replacement mechanism which ultimately will form uniformly oriented rod-like blebs of albite in a matrix of orthoclase.

In the Princess Quarry examination of thin sections of samples from various parts of the wall rock zone showed that there was a variation in the proportion of albite and microcline in the rod perthites. Twelve thin sections were chosen to study this variation. The samples from which the sections were cut were initially chosen to study the character of the wall rock surrounding the veins. It was not established nor suspected at the time of sampling that an alteration zone existed. As a result the samples were quite randomly chosen. Two to four crystals of rod perthite were chosen from each thin section. A medium power lens with a grid occular was used; the phases under the grid intersections were counted. Albite rims which often formed about the perthite crystals were not counted. A total of forty-one crystals were point counted. The crystals were chosen so that the grid covered the entire crystal. The results of the study are shown in figures 2-6 and 2-7. The percent microcline was calculated for each crystal and histograms were prepared using divisions of 10 per cent

Fig. 2-6 Distribution of potassium feldspar in perthites of the wall rock, Princess Quarry (Based on analysis of 41 crystals)

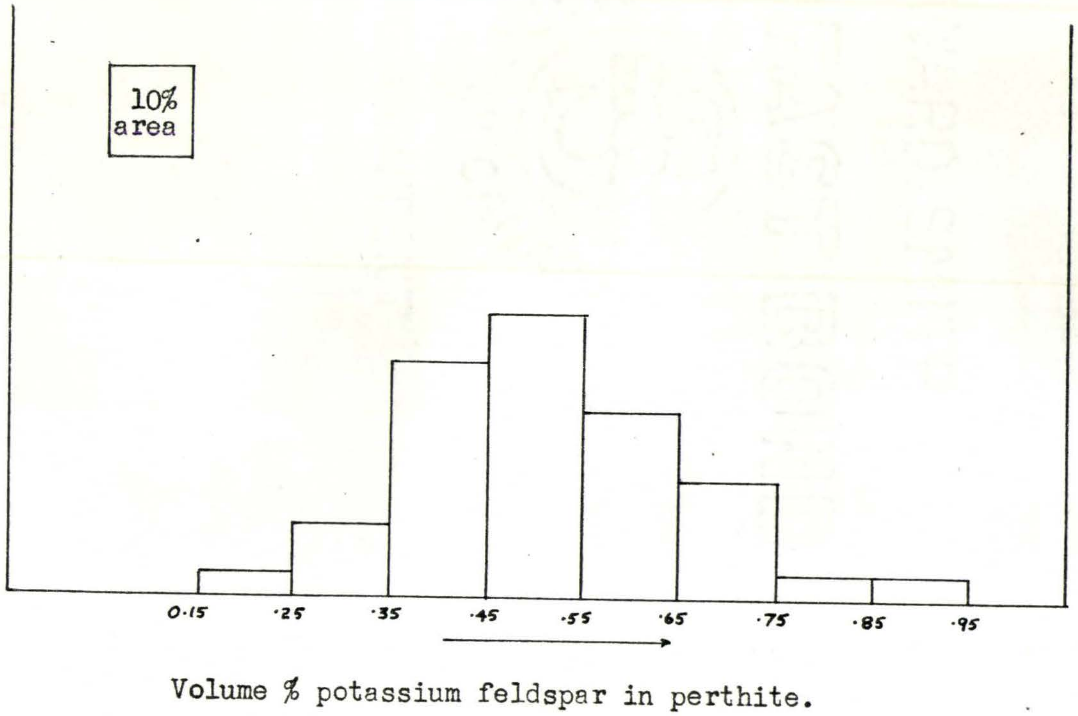
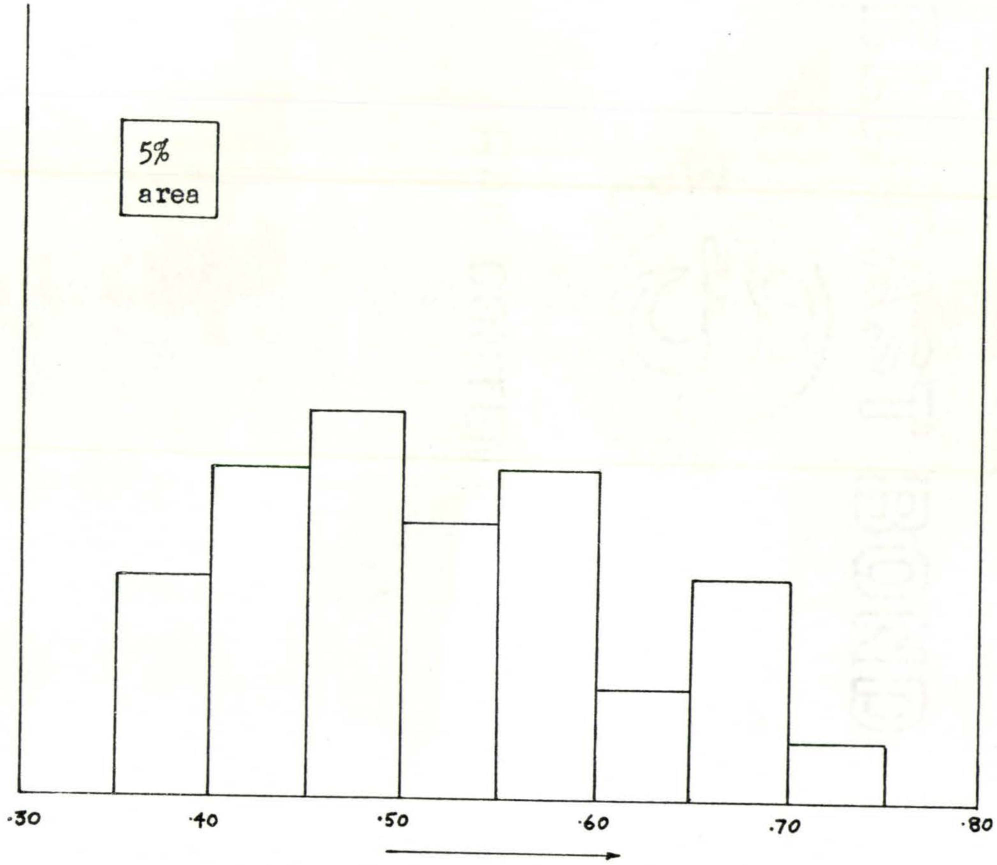


Fig. 2-7 Distribution of potassium feldspar in perthites of the wall rock, Princess Quarry. (based on analysis of 35 crystals)



Volume % potassium feldspar in perthite.

Table 2-10: Modal estimates of potash and plagioclase feldspar in wall rock, Princess Quarry.

Slide #	%Potash Feldspar	%Plagioclase Feldspar
3-3	6.2 (—)	-
1-3	28.2 (17.4)	3.1
1-5	25.8 (24.0)	5.4
1-8	28.8 (21.5)	7.1
1-1	23.0 (—)	9.4
1-6	24.4 (16.6)	11.1
1-4	20.2 (15.7)	11.9
1-7	10.4 (7.5)	15.2
1-2	18.6 (16.5)	17.2
2-2	12.2 (4.7)	23.4
3-2	9.4 (7.7)	24.3
2-1	8.0 (5.6)	25.6
3-1	1.4 (0.3)	32.2

*Values in brackets are estimates of perthite content of total rock. The unbracketed number represents the total amount of potassium feldspar, perthite being treated as one phase.

and 5 per cent microcline (figs.2-6,2-7 respectively). In addition modal analyses were made for each section using 500 counts per section.

The histograms indicate that quite a wide spread in the percent microcline in the rod perthites exists. An approximately normal distribution is indicated with the mean at 49.9 volume per cent microcline, and 50.1 volume per cent albite.

The results of the modal analyses for feldspar given in table 2-10 indicate that a complete gradation exists between potash-deficient and potash-rich nepheline gneiss. In a preceeding section, it was made clear that the predominant feldspar in the veins was microcline and perthite and that in the nepheline gneiss was oligoclase. Combining this information, the author would suggest that contact potassium metasomatism has produced the variation that has been measured. The distance that each sample was taken from a vein was not measured, therefore isopleths defining zones of equal amounts of potash feldspar can not be determined with the data available. It does appear however that the sections studied covered in a random manner the entire variation of potash feldspar in the wall rock.

The histogram in figure 2-6 illustrates the variation in the volume percent microcline for all forty-one rod perthites studied. Using statistical formulas from Dixon and Massey (1957, p.102) the standard deviation (s) of this distribution was calculated to be 14.1 per cent. To determine whether the variance within thin sections was different from the variance of the entire sample population, the variance for each thin section was calculated and a pooled variance determined. The pooled variance (Sp^2 : Dixon and Massey, p.109) equals 61.08 giving a pooled standard deviation Sp = 7.8 per cent. These results indicate that the variance within thin sections is much less than between thin sections. To estimate the maximum value of the standard deviation attributable to experimental error the binomial distribution variance $\sigma^2_{A_x}$ was calculated for all forty-one determinations, and from this value σ_{A_x} was determined to be 7.7. It is evident that since Sp and σ_{A_x} are almost equal, then the variance of the volume per cent microcline in perthites from one thin section is attributable to experimental error and therefore the amount of microcline in perthite crystals within one thin section, statistically speaking, is uniform. Between thin sections however, there are probably real differences in the proportion of microcline in the rod perthites. In terms of the bulk compositions of the perthite crystals; within one thin section all of the perthites have the same composition, but different thin sections contain perthites of different bulk compositions. The variation in the bulk composition determined here suggests strongly that a distinct concentration gradient for potassium existed in the wall rock at the time of formation of the perthites. This supports the conclusions arrived at in the previous section on modal analyses.

The migration of potassium into the wall rock appears to have been promoted by both a temperature and concentration gradient. Orville (1963) has demonstrated that potassium will migrate down a temperature gradient (e.g. into the wall rock zone). Sodium migrates in the opposite direction. Also it is theoretically well established that ions will move in response to strong concentration gradients. The hot aqueous hydrothermal solutions in the veins were apparently quite rich in potassium relative to the cool nepheline gneiss country rock. It appears that both temperature and concentration of the pertinent cations played significant roles during the migration of potassium into the wall rock. It remains to be established whether replacement or exsolution formed the rod, and patch perthites, and what is the role that temperature and bulk composition played in determining the final proportions of albite and microcline in each perthite crystal.

The simplest explanation for variation in the proportions of microcline and albite in the perthite crystals is variation in the extent of replacement of a parent plagioclase phase. Potassium was incorporated into oligoclase in the wall rock to varying degrees, hence the variation in the present crystals of potash feldspar. Almost total replacement of of sodium by potassium in oligoclase resulted in the formation of separate microcline crystals. Within and adjacent to the vein zones microcline would be expected to be most abundant, and this is what is observed .

We may also inquire whether the rod and patch perthites were formed during the replacement process per se, or rather during subsequent exsolution. If exsolution is the mechanism by which they formed, then the system must have been at quite a high temperature. Experimental work in the alkali feldspar system (Bowen and Tuttle, 1950) indicates that at

1000 bars PH_2O the top of the solvus occurs at around 660°C. At 5000 bars PH_2O the liquidus-solidus curves intersect the solvus at approximately 715°C (Yoder, Stewart and Smith, 1957). Since the bulk composition of many of the perthite crystals average near the composition corresponding to the top of the solvus it would be impossible for perthites to form by exsolution without first forming a liquid phase if the system were at 5000 bars PH_2O. Also for pressures of 5000 and 1000 bars PH_2O, the temperature necessary to form homogeneous feldspars is between 660°C and 720°C. Most investigators would agree that the temperature of hydrothermal or even most pegmatitic fluids never rise that high. If replacement is the mechanism which formed the perthites then much lower temperatures could be involved to explain the same phenomena. The presence of patch perthites possibly supports the replacement theory. Also, Robertson (1959) has presented strong evidence that rod perthites can be formed by replacement processes.

The evidence presented above is largely indirect but in the author's opinion it supports the replacement theory for the origin of the perthites.

Temperature alone plays an important role in the formation of the perthites. It is at least one factor which promotes the migration of potassium into the wall rock. Also along any one isopleth of constant potassium content temperature variations in the wall rock may be considered to have caused some variation in the proportions of albite and microcline which form individual perthite crystals. To illustrate this idea two bulk compositions ($Or_{25}Ab_{75}$ and $Or_{50}Ab_{50}$) were chosen in the alkali feldspar system. Using Barth's (1951) solvus, the proportion of albite and microcline which would form at four temperatures were calculated. The results are given in table 2-11. Thus in order to generate variations in the modal percent of exsolved albite from once homogeneous feldspars of the suggested compositions it would have been necessary for exsolution to have been stopped at temperatures ranging from 700°C to 400°C within a zone not more than 1 foot wide. It is not believed possible that such steep temperature gradient could have existed within this zone. Also since potassium feldspar formation is associated only with subsolidus reactions forming sodalite, it is not likely that a very high $\partial T/\partial X$ gradient existed. There is in fact no reason why the final exsolution temperature should not be approximately uniform throughout the wall rock despite the initial temperature gradient that may have been imposed by injection of a pegmatitic magma or hot hydrothermal solutions.

Table 2-11: Volume percent of Or and Ab exsolved from crystals of given bulk composition according to Barth's (1951) solvus for the alkali feldspars.

Temperature (°C)	$Or_{25}Ab_{75}$	$Or_{50}Ab_{50}$
700°	Ab=76.5 Or=23.5	11.8 88.2
600	Ab = 72.2 Or = 27.8	28.6 71.4
500	Ab = 74.5 Or = 25.5	38.5 61.5
400	Ab = 76.4 Or = 23.6	43.6 56.4

The writer's proposed mechanism for the formation of microcline and perthite follows. Potassium rich solutions have migrated from the veins into the wall rock. The diffusion into the wall rock has proceeded to varying degrees along cracks, fissures and grain boundaries promoted by temperature and concentration gradients. Isopleths of equal potassium content in the wall rock are probably very irregular due to the mechanisms of movement of the solutions. Reactions between these solutions and oligoclase in the veins and wall rock resulted in the formation of microcline and microcline perthite according to the equation below.

$$\underset{\text{Albite}}{Na\,Al\,Si_3O_8} + K^+ = \underset{\text{Microcline}}{(K, Na)\,AlSi_3O_8} + Na^+$$

Experimental evidence and the presence of patch perthites suggest that replacement rather than exsolution formed microcline perthite and microcline.

b) Sodalite.

Van Peteghem (1961) synthesized sodalite of natural compositions at temperatures and pressures ranging from 150°C - 750°C and 10,000 - 30,000 p.s.i. Anderson (1963) studied the stability of hydroxyl sodalite ($6Ne \cdot 2NaOH$) at 1 kilobar and determined its maximum temperature of formation to be approximately 520°C - 540°C. Current experimental work by Anderson (pers. commu.) indicatesthat sodalite of natural composition can be formed at 800°C and 1 kilobar PH_2O, and 700°C and 2 kilobar PH_2O in the system $Na\ Al\ Si\ O_4 - NaCl - H_2O$ without any signs of liquid in the system. The information above suggests that natural sodalite can form over a very wide range of temperatures and pressures.

The equation below represents the type of reaction envisaged to occur for the formation of sodalite.

$$\underset{\text{Nepheline}}{6(Na_{.75}K_{.25})\ AlSiO_4} + (3.5\ Na^+ + 2Cl^-) = \underset{\text{Sodalite}}{6NaAlSiO_4 \cdot 2NaCl} + 1.5K^+$$

There is no evidence that the reaction is pressure dependent. As yet there is no experimental evidence of a correlation between a physical or chemical parameter, and the temperature or pressure of formation.

In the Princess Quarry petrographic evidence strongly suggests that sodalite replaces nepheline on a volume for volume basis. The reaction envisaged has been given in the previous paragraph. Note that in addition to chlorine, exdess sodium must be present in the system to form sodalite. Also potassium is liberated from nepheline in the reaction. The sodalite front described earlier presumably represents the maximum depth of penetration of chlorine-bearing solutions into the country rock. Rarely the zone bounded by this front swells from its normal thickness of 1-2 inches to more than 6 inches (e.g. plate 8). This may result merely from a locally lower abundance of nepheline in the country rock permitting the Cl^- ions to penetrate farther before being consumed by reaction with nepheline.

In the veins and wall rock of the Princess Quarry there is no petrographic evidence suggesting that sodalite replaces microcline or vice versa. The reaction suggested for the formation of microcline and perthite indicates that excess sodium is released to the fluid phase as potassium feldspar is formed. When chlorine-rich solutions react with nepheline, potassium is released to the fluid phase as sodalite is formed. There appears to be a connection between the formation of potassium feldspars and sodalite from oligoclase and nepheline respectively. Combining the two equations given previously for the formation of sodalite and potash feldspar we have:

$$\underset{\text{Albite}}{NaAlSi_3O_8} + \underset{\text{Nepheline}}{3(Na_{.75}K_{.25})AlSiO_4} + (NaCl)_{aq} = \underset{\text{Microcline}}{(Na_{.25}K_{.75})\ AlSi_3O_8} + \underset{\text{Sodalite}}{3NaAlSiO_4 . NaCl}$$

We see that sodium released to the fluid phase in the formation of microcline may be used along with chlorine to form sodalite from nepheline. Also potassium released from nepheline may be used to form microcline. The equation indicates that excess potassium in the fluid phase over that liberated by sodalitization is not required to form microcline ($Or_{75}Ab_{25}$) from albite.. In portions of the wall rock this situation may in fact have existed. Note however that microcline and microcline perthite are abundant phases of the wall rock outside of the sodalite zone. The absolute proportions of the four minerals in the above equation in the veins of the quarry are not known, therefore it is impossible to state with reasonable accuracy whether sufficient potassium was released from nepheline to form all the microcline and microcline perthite in the veins and wall rock. Certainly this mechanism probably contributed significant amounts of potassium to the system. The writer believes however that at least part of the potassium which went to form potash feldspar was derived from solutions from an extraneous source.

(c) Character of the Hydrothermal Solutions.

From the information presented in the previous paragraphs it is possible to enumerate some of the properties of the fluid phase which caused the formation of sodalite and potassium feldspar. K_2O and Cl were at least two of the most abundant components in the hydrothermal solutions. Na_2O was also abundant but relative to the Na_2O/K_2O ratio in the system which formed the primary nepheline pegmatite assemblage, it was probably lower during this period of alteration. Also water undoubtedly formed a significant portion of the fluid phase.

The study of fluid inclusions in pegmatite and hydrothermal minerals may help to indicate the composition of the solutions. This study has been actively pursued most recently by Roedder (1960,1963) and Balitskii and Lyubafeyev (1962) among others. The results of these studies indicate that Na, K, Ca and Mg and Cl,$SO_4^=$, CO_2 and HCO_3^- are the most abundant cations and anions respectively in these inclusions. The studies have established that a very wide range in concentration of salts such as NaCl and KCl can be expected in inclusions from minerals from different deposits. In some studies there has been some correlation between low-temperature origin and very high salinities, up to 50% NaCl concentration in a few cases, suggesting that the concentration of salts in the fluid inclusions reaches a maximum at low temperature. Very strong brines however have been found in fluid inclusions from presumably high-temperature pegmatite minerals.

The relevant point pertinent to this study is that concentrated brine solutions rich in halides such as NaCl and KCl commonly occur as fluid inclusions. In some instances at least, this enrichment is present in the pegmatite stage but it is most frequent in hydrothermal minerals. It is probable then that many hydrothermal fluids are weak to concentrated brine solutions. Such solutions would satisfy the requirement for a solution enriched in K and Cl capable of replacing a nepheline-albite assemblage with a sodalite-microcline assemblage. As yet, the minimum concentration of NaCl in an aqueous solution necessary to form sodalite from nepheline has not been determined. Anderson (per commu.) however suspects that only very low concentrations (e.g. less that 1.0 mole per cent NaCl) would be adquate at hydrothermal temperatures and pressures.

Recent experimental investigations concerning the formation of sodalite from nepheline (Van Peteghem, Anderson), and potassium feldspar from albite or oligoclase (Orville, 1963) indicate that an aqueous fluid of suitable composition will react at sub-solidus temperatures with the solid phases to form new minerals. Also, Orville (1963) illustrated in his work involving reactions between sodium and potassium feldspars and a fluid phase, that far below solidus temperatures the fluid phase is (1) capable of acting as the medium through which ions may pass in response to temperature or concentration gradients; and (2) capable of acting as the transporting medium for ionic species. These facts indicate that a fluid phase of the correct composition is capable of producing sodalite and microcline from nepheline and albite.

The temperature and pressure of formation of sodalite and potash feldspar is unknown. The indirect evidence listed below possibly suggests that their temperature of formation was between 300°C and 450°C.

1) a replacement origin for microcline and microcline perthite.

2) sodalite can form at such temperatures with relative ease.

3) fluid inclusion studies possibly suggest that the most concentrated brine solutions are formed at temperatures equivalent to hydrothermal and lower temperatures.

Estimates of pressure during the period of hydrothermal alteration are much less definite than those of temperature. Sodalite is known to be stable at pressures up to two kilobars. The alkali feldspars can be formed at water vapour pressures of at least 5000 bars. Assuming that the fluid phase was supercritical and at a temperature near 450°C, then work by Sourirajan and Kennedy (1962) on the system NaCl - H_2O indicates that an aqueous solution containing 10 weight per cent NaCl has a critical pressure of 550 bars. Since the fluid is undoubtedly more complex chemically than that discussed above, this value for the critical pressure is obviously only an estimate. The critical pressure of the fluid does however place a lower limit on the total pressure of the system (assuming Pfluid = Ptotal).

2) Formation of Additional Hydrothermal Minerals.

a) Magnetite and Calcite.

In the veins of the quarry both of these minerals occur as inclusions and as small veins in cracks in sodalite. They also occur as segregated masses of various sizes. These textures would suggest that both minerals formed throughout the sodalite forming process. However both minerals are common in nepheline pegmatites. Much of both the calcite and magnetite of the Princess Quarry texturally resembles that in sodalite-free nepheline pegmatites. Therefore it is possible that both phases were members of the primary pegmatite assemblage in the Princess Quarry and have simply been recrystallized during the phase of hydrothermal alteration.

In the wall rock, magnetite is invariably associated with lepidomelane. Textures suggest that at least some magnetite has formed from the oxidation of an iron rich biotite according to the type of reaction given below.

$$K\,Fe_3^{+2}AlSi_3O_{10}\,(OH)_2 = Fe_3O_4 + KALSi_3O_8 + H_2$$

It is possible that some microcline in the wall rock has formed by this reaction. It is not evident whether this reaction occurred during the formation of the primary pegmatite assemblage or later during the hydrothermal alteration. Quantitatively however, the amount of lepidomelane converted to magnetite could not account for all the microcline in the wall rock.

Calcite is an abundant interstitial mineral in the wall rock. Comparison of modal analyses for calcite for samples from the wall rock and country rock are approximately identical. This indicates that the calcite in the wall rock cannot be attributed to CO_2 metasomatism of the nepheline gneiss.

(b) Cancrinite.

In the wall rock cancrinite is found associated with calcite and nepheline. The reaction envisaged to form cancrinite is given below.

$$\underset{\text{nepheline}}{3NaAlSiO_4} + CaCO_3 = \underset{\text{cancrinite}}{3NaAlSiO \cdot CaCO_3}$$

It is noteworthy that when sodalite is abundant cancrinite is present in only small amounts or absent. This situation is realised at the Princess Quarry. In contrast, at Cancrinite Hill, one half mile south of the Princess Quarry, cancrinite is abundant but sodalite forms approximately $\frac{1}{4}$ of the total amount of carbonate and chloride enriched feldspathoids. At the Princess Quarry calcite is present in large amounts, and presumably the system was saturated with respect to CO_2, nevertheless sodalite forms. The equation below represents the possible situation being concidered.

$$\text{Cancrinite} + Cl^- = \text{Sodalite} + CO_2$$

Note that since sodalite often occurs with cancrinite but not vice versa, low P_{Cl_2} displaces this reaction to the right. In the Princess Quarry cancrinite undoubtedly formed at the same time as sodalite but in much smaller amounts due to the factors indicated above.

(c) Pyrite and Pyrrhotite.

Pyrite and pyrrhotite are scarce in the Princess Quarry. On the basis of their textural relations it is concluded that they formed later than potash feldspar and sodalite.

In a previous section Arnold's (1962) pyrite-pyrrhotite geothermometer was described and used to determine a temperature of formation for these minerals. The temperature determined was approximately 475°C. However the discussion made clear that this value was probably unreliable since pyrrhotite in this deposit is monoclinic rather than hexagonal.

(d) Zeolite A.

Zeolite A has formed both in the veins and wall rock from the decomposition of nepheline and sodalite by reaction with hot aqueous solutions. The equations below indicate the types of reactions envisaged to have occurred.

$$\underset{\text{nepheline}}{4NaAlSiO_4} + 2SiO_2 + 4H_2O = \underset{\text{natrolite}}{2Na_2Si_3Al_2O_{10} \cdot 4H_2O}$$

And

$$\underset{\text{sodalite}}{6NaAlSiO_4 \cdot 2NaCl} + 3SiO_2 + 6H_2O = \underset{\text{natrolite}}{3Na_2Si_3Al_2O_{10} \cdot 6H_2O} + (2NaCl)_{aq}$$

Burley (1956) studied the physical stability of natrolite in the system $Al_2O_3 - SiO_2 - Na_2O - H_2O$. He established that the maximum and minimum temperatures of formation of synthetic natrolite were 270°C and 100°C respectively, at pressures from 0.67 to 2.0 kilobars PH_2O. Above 270°C natrolite decomposed to analcite, nepheline hydrate, and a vapour phase. Hey's (1930,1932a,b,1933) investigation of many of the common zeolites indicates that dehydration occurs most commonly between 300-400°C at

1 atmosphere. These facts indicate that zeolite A probably formed below 300°C. It is concluded that zeolite A was the last mineral to form in the veins and wall rock of the quarry.

3) Origin of the Hydrothermal Solutions.

The source of the hydrothermal solution which has formed among other minerals, microcline and sodalite, remains to be determined. This solution was probably a late-stage fluid remaining after the crystallization of an igneous rock. A possible source may have been the granite-syenite complex intruded less than one-half mile north of the quarry (see map 1-A). Further study of this and other intrusive igneous rocks of the Bancroft area may shed more light on this problem.

The presence of large amounts of sodalite in the quarry suggests that the fluids, whatever their origin, must have been strongly enriched in chlorine. Correns (1956) illustrated that Cl is widely distributed in igneous and sedimentary rocks in amounts not exceeding 0.1 per cent. Shaw (1960), in a discussion of the origin of Cl-rich scapolite stated that one possible source of chlorine in the Grenville was from halite in metasedimentary evaporite sequences. Brown and Engel (1956) have found such evaporite deposits containing halite, gypsum and anhydrite in the Grenville rocks of the Adirondacks. Anatectic and metasomatic processes acting on such metasediments may have caused the incorporation of large amounts of Cl in plutonic granites and syenites such as those adjacent to the nepheline gneiss lenses in the Bancroft area.

Another alternative is worth considering however. Roedder (1960, 1963) has adequately illustrated that primary fluid inclusions in hydrothermal minerals are not uncommonly very concentrated brine solutions. Of the anions in these solutions chlorine is more often than not the most abundant. This study is only in its infancy but the possibility exists that hydrothermal solutions from most igneous granites (e.g. the one adjacent to the Princess Quarry) contain sufficient chlorine to form sodalite from nepheline. Sodalite is not a common mineral possibly because only rarely do chlorine-rich solutions infiltrate undersaturated nepheline-bearing alkaline rocks. It is suspected by the writer that most late-magmatic fluids contain sufficient chlorine dissolved in their vapour or liquid phases to form sodalite from nepheline. For sodalite to form, the mineralogy of the host rock rather than the composition of the foreign fluids appears to be the critical factor.

VII Conclusions.

A) History of the Princess Quarry.

The events which are considered signigicant to the development of the sodalite deposit are listed in chronological order below in an attempt to relate the regional geology with the formation of the veins in the quarry.

1) Formation of nepheline syenite gneiss by nephelinization and/or magmatic processes.

2) Pegmatization of the nepheline gneiss resulting in formation of sodalite-free nepheline pegmatites. This process is directly connected with the nephelinization and/or magmatic processes which formed the nepheline-rich host rock.

3) Assimilation and intrusion by granitic and syenitic plutonic material resulting in recrystallization of portions of the nepheline gneiss along tension fractures to form nepheline pegmatite assemblages similar in mineralogy to those formed in part (2).

4) Infiltration along tension fractures in the nepheline gneiss by hot, aqueous fluids charged with potassium, sodium and chlorine in particular, and partial replacement of the pegmatite assemblage formed in part (3) to form sodalite and microcline.

5) With falling temperature, the precipitation of calcite, magnetite and sulphides and the alteration of earlier formed feldspathoids to zeolites by hot aqueous solutions.

6) After the complete formation of the vein minerals, a period of shearing

which produced the mylonitic and cataclastic textures presently observed in a few of the veins in the Princess Quarry.

It remains unclear whether calcite and magnetite formed during the period of formation of the primary pegmatite minerals or during the later hydrothermal alteration of this primary assemblage. It is also unknown, what length of time elapsed between the two stages of formation of the veins in the Princess Quarry. The distinct differences in mineralogy between stages I and II does indicate that the solutions which caused the hydrothermal alteration came from a source other than the nepheline syenite host rock. If this were not the case one would expect to find microcline and sodalite quite abundant in many of the sodalite-free nepheline pegmatites. The writer would suggest that the fluids responsible for the formation of sodalite and microcline from nepheline and albite respectively came from adjacent granitic and syenitic material. The chlorine in these fluids possibly was incorporated into the parent granitic material by anatectic or metasomatic processes acting upon evaporite sequences. Also, possibly the enrichment is only an apparent one; most late-stage magmatic granitic liquids probably contain certain amounts of chlorine which would form sodalite if they contacted nepheline-bearing rocks. In this latter situation, the controlling factor is the mineralogy of the host rock. The writer favours the second alternative.

VIII Recommendations for further study.

A more complete study of the effects of potassium metasomatism would undoubtedly be of value. The determination in one section through the wall rock zone perpendicular to a vein, of the modal percentages of potash and plagioclase feldspars, modal determinations of the amounts of albite and microcline forming individual perthite crystals as a function of distance from the vein zone, and the determination of the compositions of the sodic and potassic feldspars would be profitable. A similar study on the distribution of sodalite and nepheline would also be worthwhile.

Aside from this particular sodalite deposit, a detailed examination of the occurrence of sodalite in an alkaline igneous intrusive (e.g. Ice River or Magnet Cove) would be particularly worthwhile in view of the confusion which has arisen concerning the classification of magmatic and hydrothermal sodalite. One might look for textures and structures which indicate a hydrothermal origin for sodalite such as those described in this thesis.

It would also be interesting to extend Roedder's studies of fluid inclusions to include data on the concentration of anions and cations in inclusions in pegmatite and hydrothermal minerals associated with undersaturated alkaline intrusives, and to compare this data with similar data from known granitic sources. This study would be yet another attempt to establish the exact differences between the residual liquids of peralkaline and granitic magmas. Such a study holds particular significance for an anion such as Cl which, even though it may be present in significant concentrations possibly largely bound up in various soluble complex metallic anions, is incorporated into only a very few mineral structures.

Appendix I : Plates 1 - 17

Plate #1. Nepheline pegmatite, Goulding Keene Quarry, York River.

N = Nepheline; P = Plagioclase (An_5); Bi = Biotite

Plate #2. Sodalite rimming and replacing euhedral nepheline crystals

growing perpendicular to joint faces into open cavities.

Plate #3. Mylonitized vein sodalite with large inclusion of nepheline adjacent to mylonitic material. Note reaction rim of zeolite (?) about large nepheline crystal. S = Sodalite.

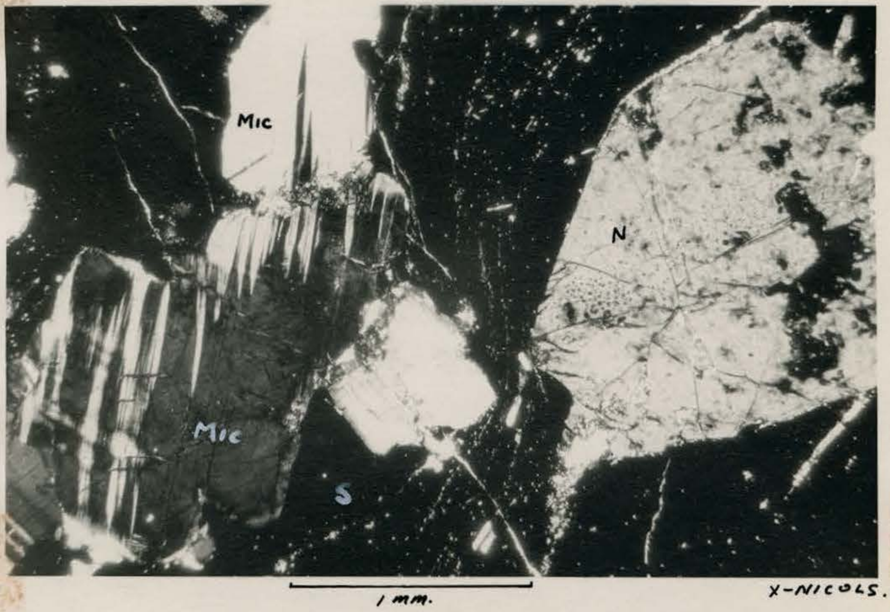


Plate #4. Non-mylonitized vein sodalite enclosing microcline and euhedral nepheline. Note small white inclusions of zeolite. Mic = microcline.

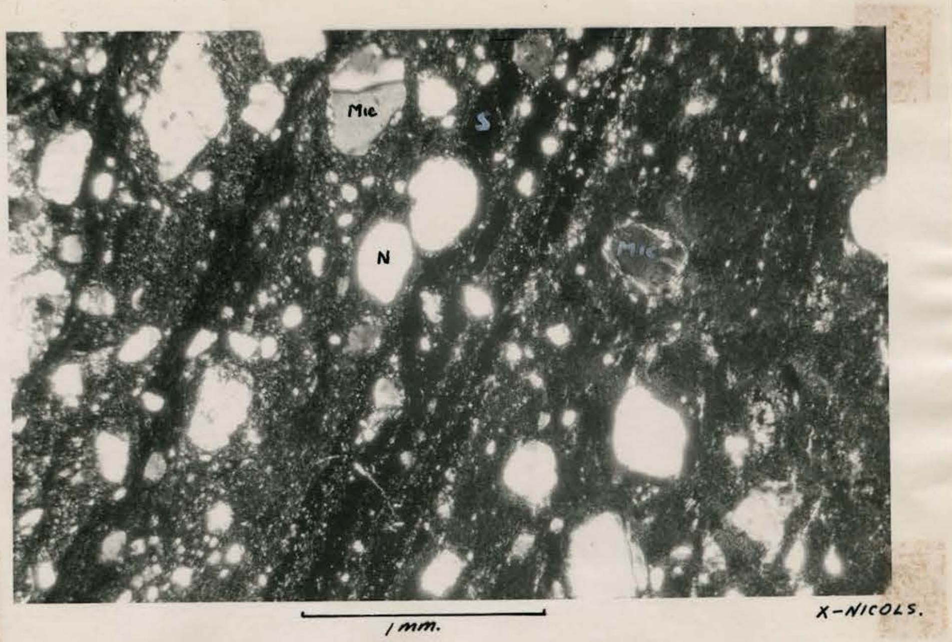


Plate #5. Mylonitized vein material illustrating distinctive linear trend: the minerals are sodalite, nepheline and microcline.

Plate #6 Small euhedral crystals of nepheline and microcline associated with a large crystal of microcline.

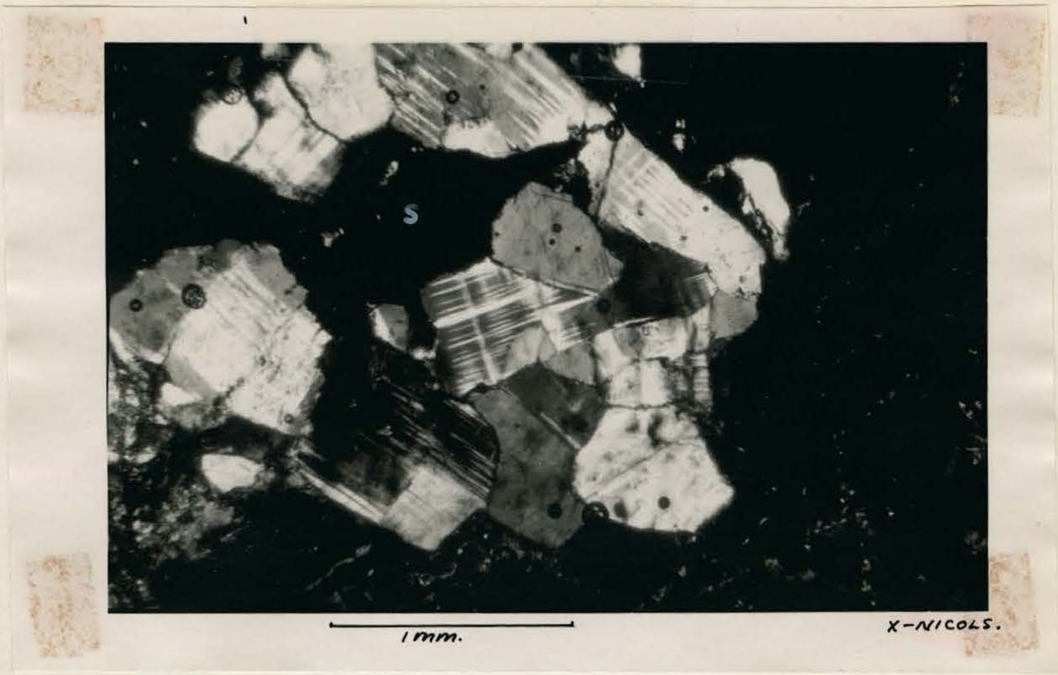


Plate #7. Vein sodalite with microcline inclusions. Textural evidence does not suggest which mineral formed first.

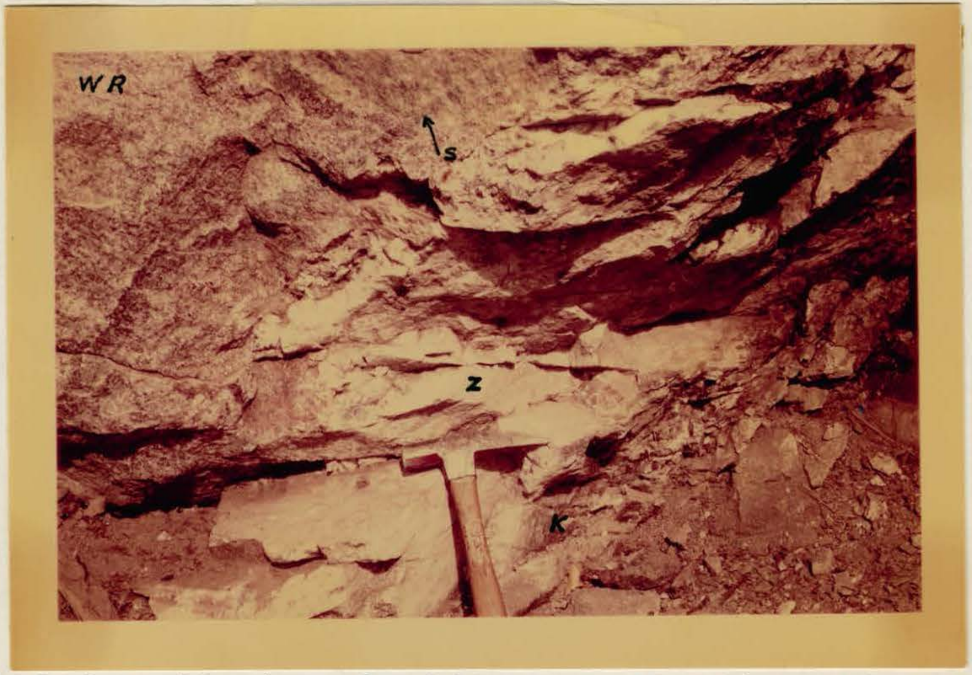


Plate #8. Zeolite alteration of sodalite vein. Note blue sodalite front in adjoining wall rock and kaolinized potash feldspar in lower right portion of vein. Z = zeolite; k = kaolinized feldspar W.R. = wall rock.

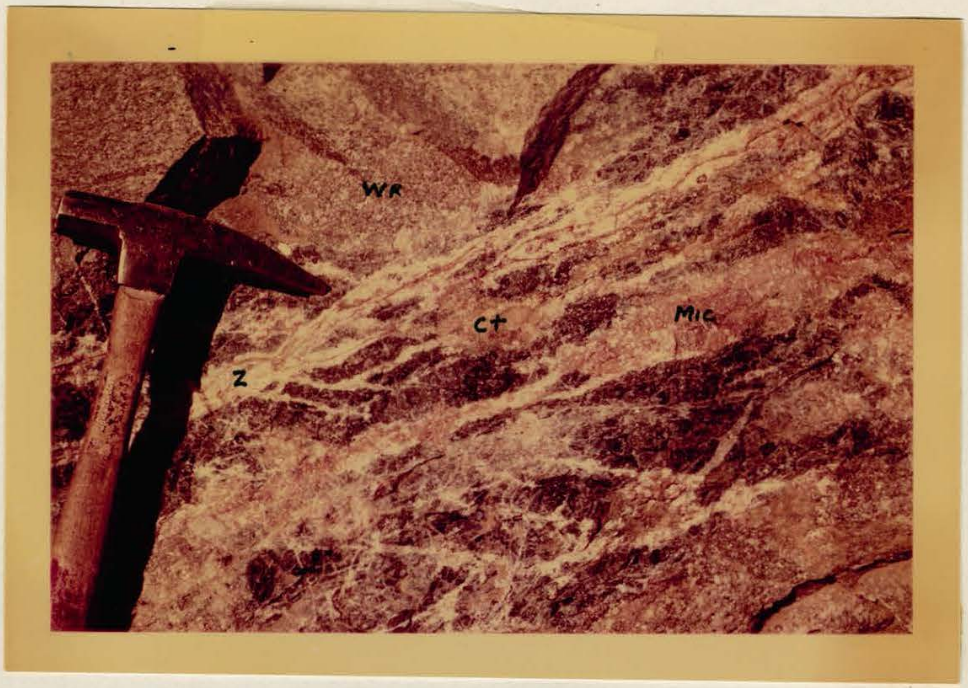


Plate #9. Sodalite vein in nepheline gneiss; sodalite contains pods of calcite, linear zones of microcline, and pink to white veins of zeolite A. Calcite = Ct.

Plate #10. Vug type structure in parts of veins; note zeolite front in wall rock on left side of photograph.

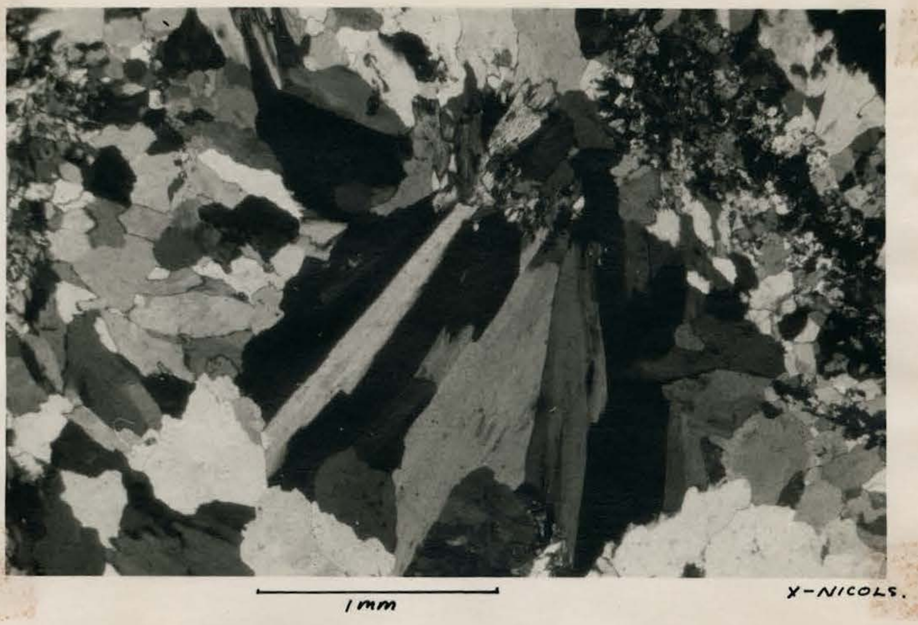


Plate #11 Fan-shaped aggregates of prismatic crystals of zeolite A.

Plate #12. Rod perthite: albite rods and rims in microcline ground mass associated with nepheline and twinned oligoclase. Ab = albite; Olig = oligoclase.

Plate #13. Interstitial recrystallized zone: microcline perthite, magnetite, biotite, oligoclase and calcite enclosed by large anhedral crystals of nepheline. Mt = magnetite.

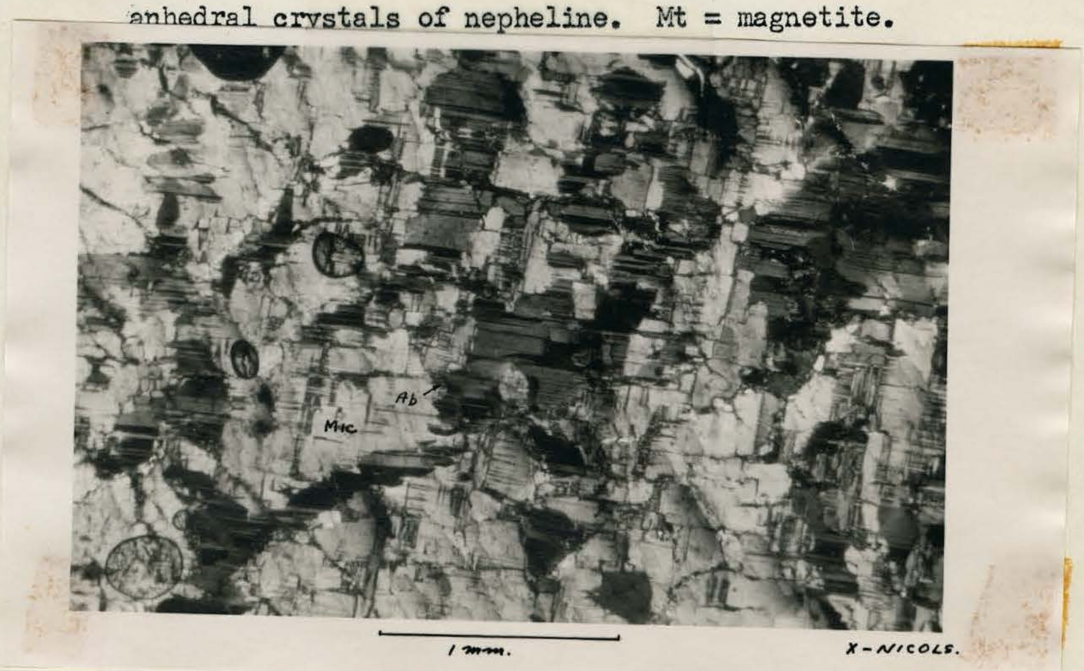


Plate #14. Patch perthite: twinned albite (An_5) in tartan twinned microcline ground mass.

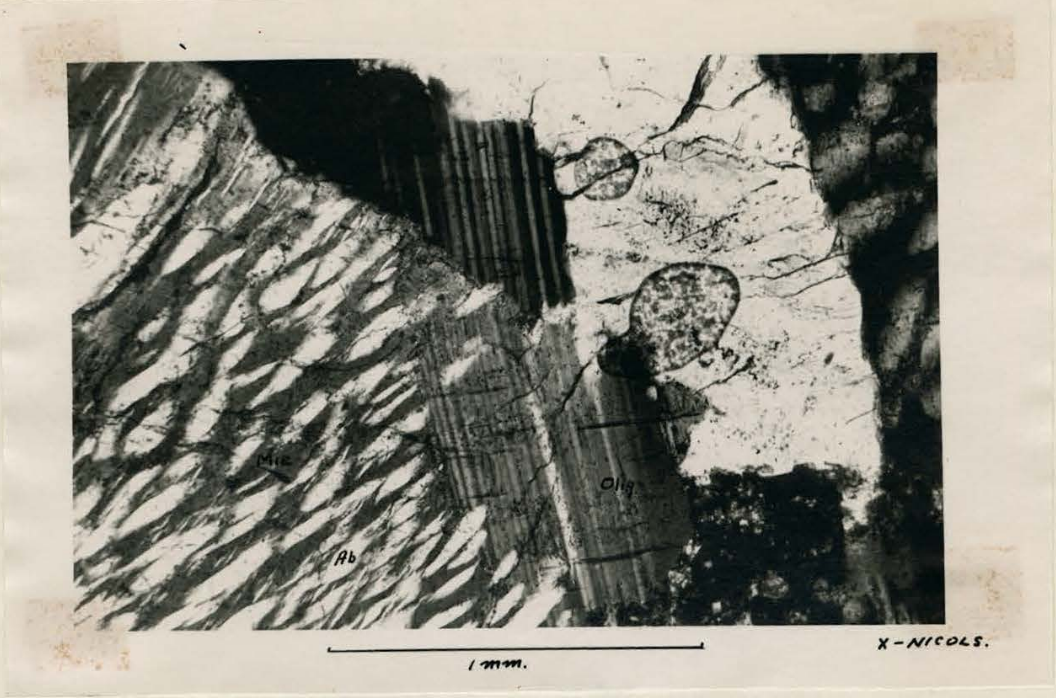


Plate #15. Microcline perthite with albite rods intruding (?) a more calcic twinned plagioclase (An_{8-10})

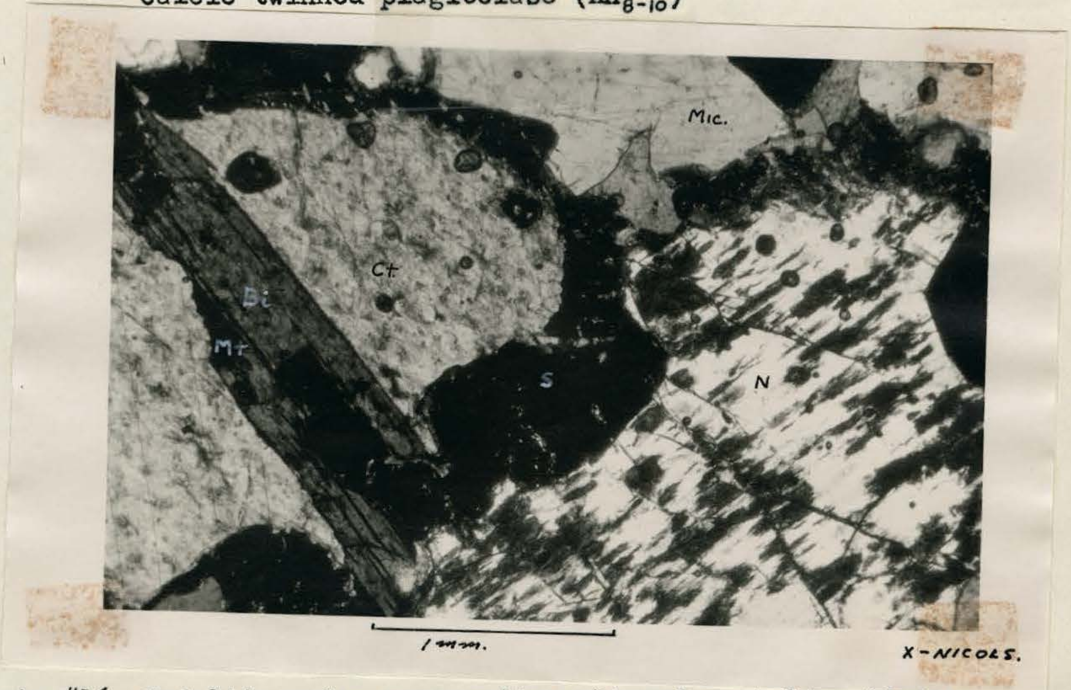


Plate #16. Sodalite veins surrounding altered nepheline, biotite, magnetite, calcite and microcline.

Plate #17. Sheared vein in upper pit of Princess Quarry; note dark mylonite material adjacent to blue sodalite.

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PRINCESS SODALITE QUARRY

BANCROFT, ONTARIO

SCALE 1·0 IN· = 160 FT·

16 0 16 32 48

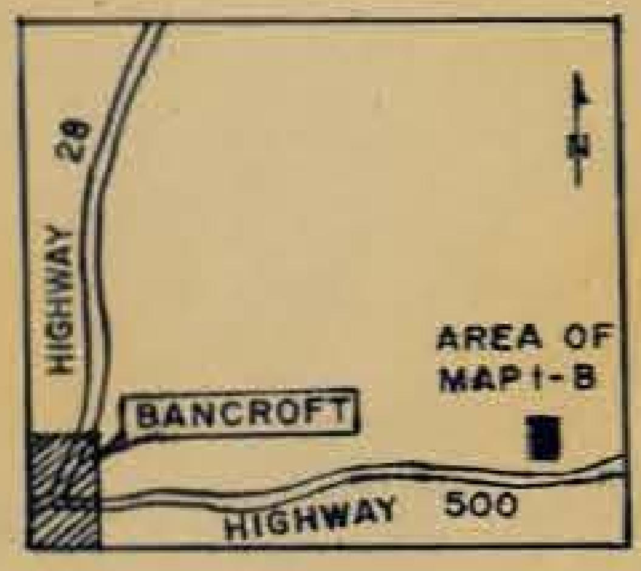
LEGEND

SODALITE-BEARING VEIN	■
ALKALI FELDSPAR VEINS	▦
SODALITE-FREE NEPHELINE PEGMATITE	▩
NEPHELINE SYENITE GNEISS	▨

SYMBOLS

SHEAR ZONE (inclined)	∿
SHEAR ZONE (assumed)	∿∿
BOUNDARY OF ROCK OUTCROP	╌
GEOLOGIC BOUNDARY	─
QUARRY	⌒
JOINT (inclined)	┴
JOINT (vertical)	┼
GNEISSOSITY (inclined)	┴
GNEISSOSITY (vertical)	┼
LINEATION (plunge unknown)	→
CONTOUR LINES	⋯
B·M· ELEVATION ZERO	A·

INDEX MAP TO GEOLOGICAL MAP OF PRINCESS QUARRY



MAP No· 1-B