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Petrology and Geochemistry of Ste. Dorothée Sill.

R.J.Goldie

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"PETROLOGY AND GEOCHEMISTRY OF A MONTEREGIAN SILL NEAR STE. DOROTHEE, QUEBEC" by R. J. Goldie

ABSTRACT

Rounded bodies of analcite syenite comprise about 2.2 per cent of the Monteregian Ste. Dorothée sill, which was formed by six penecontemporaneous intrusions of alkaline basaltic magma. A combination of vapour phase transport and ionic diffusion through pyroxenes, which had precipitated around carbonate xenoliths, produced "felsic material", richer in Si, Al and alkalis than the basaltic rock. Some "felsic material" was contributed to analcite syenite bodies, and flow structures, formed where "felsic material" and analcite syenite intermingled, demonstrate that they were liquids. Immiscibility of these liquids with the basaltic magma is indicated by the fact that analcite syenite feldspars overlap in composition with those of the basaltic rock, yet sphenes and amphiboles of the two rock types have distinctive habits. Unmixing of a magma into two liquids is accepted as the origin of most of the analcite syenite.

PETROLOGIE ET GÉOCHIMIE D'UN SILL MONTÉREGIEN SITUÉ PRÈS DE STE. DOROTHÉE, QUÉBEC. par R.J. Goldie.

RESUMÉ

Des globules de syenite à analcite forment environ 2.2% du sill monteregien de Ste. Dorothée, formé de six intrusions consécutives de magma basaltique alcalin. Une combinaison de transport à travers une phase aqueuse et de diffusion ionique à travers les pyroxenes, formés par réaction autour des xenolithes à carbonate, a produit un matériel felsique, plus riche en Si, Al, et en alcalis que le magma basaltique. Une partie du materiél felsique s'ajouta aux corps de syenite à analcite; les structures d'écoulement formées où le "materiel felsique" et le syenite à analcite se sont mélangés, montrent qu'ils étaient liquides en même temps.

L'immiscibilité de ces liquides avec le magma basaltique est suggerée par les ressemblances en composition des feldspaths du syenite analcitique et les feldspaths des basaltes. Par contre, les sphènes et les amphiboles des deux types de roches ont les caractéristiques distinctives. La séparation du magma en deux liquides est acceptée comme étant à l'origine de la plupart des globules syenitiques. PETROLOGY AND GEOCHEMISTRY OF A MONTEREGIAN SILL NEAR STE. DOROTHEE, QUEBEC

by

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CHAPTER I: INTRODUCTION

The most complete exposure of the Monteregian Ste. Dorothée sill is in Laurin's quarry, on the west side of the highway north-east of Ste. Dorothée, Quebec (Figure 1). The sill is approximately 5-1/2 m. thick and although composed mostly of a fine-grained mafic "host rock", abundant lenses and rounded bodies of felsic material are present in the upper 2 m. The origin of these bodies has been disputed (e.g. Philpotts and Hodgson, 1968; Mackenzie and White, 1970). The present study was initiated to provide a more detailed description of the Ste. Dorothée sill in terms of its internal structure, petrology and chemistry; and to evaluate the various hypotheses proposed for the origin of the felsic bodies.

The sill was first described by Howard (1922), who classified the mafic rock as a fourchite, and postulated that the felsic bodies originated from a magmatic injection which took place just before the original rock had completely solidified. Clark (1952) considered the felsic bodies to be vesicles or amygdules, and correlated the sill with exposures of similar type in the same area. Philpotts and Hodgson (1968), Hodgson (1968) and Philpotts (1971) classified the felsic material as analcite syenite, gave detailed petrographic descriptions of both rock types, and interpreted their genetic relationship in terms of silicate liquid immiscibility.

References to similar bodies of felsic material in mafic

(commonly lamprophyric) rocks are common. Hypotheses proposed for their origin may be summarized as follows:

- A "felsic magma" was injected into almost completely solidified mafic rock (Howard, 1922).
- 2. A vapour phase selectively leached and transported alkalis, alumina and silica from the basic magma or its crystalline products (Flett, 1935; Pecora and Fisher, 1946; Campbell and Shenk, 1950; Wilshire, 1961; Upton, 1965; Horne and Thompson, 1967; Watterson, 1968).
- 3. Filter-pressing forced a late-phase liquid into vesicles (Ramsay, 1955; Elliott, 1960; R. E. Smith, 1967; Phillips, 1968; Mackenzie and White, 1970; Woodward, 1970).

A vague explanation which could fit either hypothesis (2) or (3) was given by Knopf (1936).

- 4. Kinetic factors prevented assimilation of melted xenolithic material (Reynolds, 1938; Yoder, 1970; Angus, 1971).
- 5. Magma unmixed into two liquids (Flett, 1900; Tomkeieff, 1931, 1942, 1952; Carstens, 1964; Drever, 1960; von Eckerman, 1966; Philpotts and Hodgson, 1968; Hodgson, 1968; Philpotts, 1970, 1971; Ferguson and Currie, 1971.)
- Analcite symite bodies were nucleation centres for felsic minerals (Evans, 1901; Smith, 1946).

Other hypotheses may be applicable. For instance a modification of hypothesis (4) is presented in Section 5.3. 12

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CHAPTER II: MACROSCOPIC FEATURES OF THE SILL, AND THE

SAMPLING PROCEDURE

The top of the Laurin quarry exposure is assumed to represent the upper contact of the sill. The contact with the underlying Beekmantown dolomite is exposed at the base of the cliff (N.H. Gray, pers. comm., 1969), but was always covered with water or ice when visited by me. Although the thickness of the sill may vary by tens of cm., Gray's measurement of it (570 cm.) was used. Successive 5 cm. intervals in two vertical traverse lines, 2 m. apart, were analyzed modally. "Host rock" and "analcite syenite" could not be distinguished in a central zone of "subvertical syenite veinlets" (Philpotts and Hodgson, 1968), but mean percentages (volume) of "analcite syenite" and xenoliths in the remainder of the sill were estimated at 2.28% and 0.64%, with standard deviations (two samples) of 0.53% and 0.98%, respectively (Appendix 1). These results are unsuitable for detailed work because of weathering and irregularities in the rock face, and because it is possible that analcite syenite bodies are not randomly oriented.

More reliable estimates of the proportions of different components were obtained from modal analysis of pairs of sawn slabs, each pair cut from a sample of a 5 cm. interval. Estimates of the modal compositions of successive intervals, down to 275 cm., are presented in Table 1 a, and statistics pertaining to the entire sill are found in Table 1 b.

Although small felsic bodies ("ocelli") are present in

the lowest 15 cm. (Philpotts, 1971), they are not included in this analysis because I was unable to sample that portion of the sill. Assuming the same volume percentages of "ocelli" as in the uppermost 15 cm. of the sill, the adjusted estimate of the volume percentage of analcite symple in the entire sill is still 2.2%.

Five internal contacts, delimited by small, sharp changes in grain size and mineralogical composition, were found in the upper portion of the sill. Their positions vary by as much as 8 cm. with respect to the horizontal. Abundances of mafic phenocrysts mark five horizons ("ledges") in the lower portion of the sill. The concentration of phenocrysts increases gradationally downwards, reaches a maximum at between 0 and 2 cm. from the bottom, and drops sharply at the base (Plate 1). Sawn hand specimens show bases of ledges to be internal contacts, more regular than those in the upper portion of the sill. Such contacts probably resulted from successive intrusions of magma into a previously consolidated, or partially consolidated sill. From hand specimens, at least, there is no reason to consider the successive pulses of magma as having significant compositional differences, and the Ste. Dorothée sill may be considered of <u>multiple type</u> (Daly, 1933). Six intrusive units were recognized, the youngest and innermost was designated 6; other units were numbered accordingly. Irregularities in the upper internal contacts are attributed to the effects of intrusive flow on a relatively soft body of rock. Fragments of upper contact zones seem to have been

partially broken off and assimilated by suceeding pulses of magma. Any liquid, or crystal mush, remaining between fronts of solidification may also have been assimilated.

Point counting was performed so that modal compositions of each intrusive unit could be calculated (Table 2). (Estimates of the volume percentages of analcite symmite in the lower portion of the sill are not included in these calculations because this material cannot be shown to be genetically related to any specific intrusive epidode.)

Horizons defined by flat-topped analcite syenite bodies, analcite syenite bodies linked by small felsic veins, and analcite syenite lenses were observed in the sawn slabs. These horizons and data from the in situ and slab modal analyses are depicted in Figure 2, a pictorial representation of the sill. Photographs of portions of the quarry face appear as Plate 1, and Plates Al-Al0.

CHAPTER III: MINERALS OF THE SILL, AND THE ORIGIN OF THE

ANALCITE SYENITE

The mineralogy of the analcite syenite and of the host rock are summarized in Figure 3, and crystallization sequences deduced from textural relationships in Figure 4.

Analcite in both rock types must have formed by alteration of feldspar, or nepheline, or both (Appendix 5.5). Because of the low lithostatic pressure (about 0.3 kb., Philpotts, 1971) and the abundance of CO_2 (e.g. see Tables 3 to 5), the P_{H_2O} would have been insufficient for liquidus analcite to have formed (Kim and Burley 1971a; Albee and Zen, 1969) even in the presence of K_2O (Peters, Luth and Tuttle, 1966).

Some minerals possess different habits in each rock type (Appendix 4). For example, analcite syenite amphiboles and sphenes are more acicular than those of the host rock. Possible explanations are:

- A. Analcite symite bodies were formed from molten xenoliths.
- B. Analcite syenite bodies were formed by a separate injection of magma.
- C. Amphiboles in both rock types crystallized at different times from a single liquid. Because of changes in the chemistry, though not in the structure of the liquid, analcite syenite amphiboles were relatively enriched in Si and impoverished in Al and Fe (Harry, 1950; DeVore, 1955). The habits

of sphenes may differ for the same reason.

- D. The minerals grew simultaneously in a contiguous liquid, but the water vapour pressure in the analcite sympite was much greater than in the host rock.
- E. The minerals crystallized from two distinct fluids. Characteristic crystal habits are accounted for by differences in the relative attraction of faces of the same crystal for different structural units in each fluid.

Hypotheses A, B, C and D are rejected for the following reasons:

- A. Many slabs and thin sections were examined for evidence supporting this hypothesis. Although it was found that some analcite syenite may have originated by reaction of carbonate xenoliths with the melt (Chapter 5), I agree with Philpotts (1971) that there is no sign of other xenoliths having melted to produce analcite syenite.
- B. As rocks were being sliced, it was observed that most analcite symmite bodies are not interconnected, indicating that the analcite symmite was introduced before the host rock solidified. In terms of hypothesis B, injection of analcite symmite magma must have alternated with intrusion of host rock liquid. Not only is this model unlikely, but the liquids must have been immiscible, and hence

structurally dissimilar (which is hypothesis E) for assimilation not to have occurred.

- C. There is no evidence of consistent differences in the Al, Fe and Si concentrations of analcite syenite and host rock amphiboles (Figure 5), nor of consistent chemical differences between host rock and analcite syenite sphenes (Figure 6).
- D. There is no gradational change in the habits of host rock minerals away from analcite symmetric bodies: in fact, single amphibole crystals which have grown across the contact between the two rock types display both habits, with a sharp break at the contact.

The amphiboles and sphenes must have formed from two structurally distinct fluids which may have been immiscible liquids (hypothesis 5 for the origin of analcite syenite bodies), an immiscible liquid and gas (hypothesis 2), or the residual liquid in the host rock at two different times (hypothesis 3). Hypotheses 1, 4 and 6 are therefore excluded.

Philpotts and Hodgson (1968) reported that feldspars of both rock types are normally zoned from andesine to sanidine. These feldspars must have crystallized simultaneously (reheating during a subsequent intrusive episode is the only mechanism by which host rock and analcite syenite feldspars could have crystallized independently, and is ruled out by the fact that the last formed intrusive unit contains abundant analcite syenite (Figure 2)). With the additional constraints imposed

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by the paragenetic history of each rock type, events must have proceeded as follows if analcite syenite originated by segregation of a late-phase liquid. The residual liquid in the host rock filled vesicles and commenced to precipitate sphene and amphibole about the time that amphibole ceased to crystallize in the host rock. Feldspar subsequently crystallized simultaneously in the main body of the rock and in the segregated fluid. Note that at the time a "late-phase fluid" is presumed to have been segregated, material which would eventually comprise about half the volume of the host rock (modal analysis of Philpotts and Hodgson, 1968) was still liquid. Since it is unlikely that such a mush would have had sufficient strength to permit preservation of the shape of vesicles as they were filled, and it is equally unlikely that sphene and amphibole would crystallize only in restricted portions of a single fluid, hypothesis 3 for the origin of analcite syenite is rejected.

Ideally, the composition of a mineral being precipitated from two immiscible fluids is identical in each fluid at any instant (Bowen 1928, p. 16). (For kinetic reasons, this relationship need not be exact, just as two faces of a growing pyroxene crystal need not have identical compositions (Appendix 5.1).) It is clear that a fluid immiscibility hypothesis can explain the overlap in feldspar compositions. Amphiboles are suitable for a further test of Bowen's relationship, because they possess compositional zoning more intricate than that of feldspars, and, unlike the pyroxenes, there are no significant complications from sector zoning (Plate 2). Although qualitative electron

microprobe traverses of amphiboles from 140-145 cm. are consistent with an immiscibility hypothesis, it is obvious that amphiboles in an analcite syenite body and in the host rock 85-90 cm. below the upper contact did not crystallize in mutual equilibrium (Figure 7). Since either vapour-filled vesicles or bodies of immiscible analcite syenite liquid (Table 10) would have been less dense than the host rock liquid, the analcite syenite body could have floated upwards, traversed the internal contact between intrusive units 4 and 5, and risen 5 to 28 cm. (Figure 2) through the mush of unit number 4 to its present position. The correspondence between electron microprobe traverses on the amphibole from the analcite syenite body, and the amphiboles from 140-145 cm. below the upper contact (Figure 7) supports this explanation; and the structures depicted in Plate 3 provide further evidence. I consider that the large analcite syenite body in this photograph floated upward until it reached the internal contact, where it began to rise diapirically into the more solidified material above. In response, the internal contact was warped upward, and a tongue of the mush above the contact extended downward into intrusive unit number 4 (in the lower right of the photograph). The locally gradational nature of the internal contact resulted from partial assimilation.

Analyses of other minerals are presented and discussed in Appendix 5.

CHAPTER IV: BULK CHEMICAL ANALYSES

IV.1 Method

Samples of hand-separated analcite syenite and host rock were analyzed for Al, Si, P, K, Ca, Ti, Mn, total Fe, Rb, Sr, Zr, and Nb by X-ray fluorescence; for Na and Mg by atomic absorption and for CO_2 and FeO by wet-chemical analysis (Appendix 7). Results (Tables 3 to 5) are depicted pictorially in Figures 8 to 11.

Average compositions of the two rock types in each intrusive unit, and in the entire sill were obtained by considering the composition of any part of the sill to be that of the nearest analyzed interval in the same intrusive unit. Average compositions of each intrusive unit, and of the entire sill, were estimated using the modal analyses in Table 1b. A small amount of missing necessary data was obtained by interpolation (Appendix 8).

At no time were analyses recalculated to 100 per cent, both because unanalyzed volatiles were known to be present, and because recalculation would have increased the amount of inter-element correlation induced by closure.

IV.2 Densities and Viscosities of Liquids with the Compositions of Ste. Dorothée Rocks

Densities of liquids with the compositions of analcite syenite and host rock, at 1100° C, were computed by the method of Bottinga and Weill (1970a) (Table 10), assuming $P_{H_2O} = P_{Total} =$ 0.3 kbar (Philpotts, 1971). Estimates of the water contents and FeO:Fe₂O₃ ratios of the liquids were obtained from mean

 H_2O^+ measurements (Philpotts and Hodgson, 1968; and Philpotts, 1971) and present FeO and Fe₂O₃ concentrations (Tables 3 and 4). (Only analyses which included measurements of FeO were used in the calculations). Errors arising from the last two assumptions are unlikely to be greater than about 3%.

Viscosities of anhydrous liquids with the compositions of analcite sympite and host rock, at 1200°C, were calculated by the method of Bottinga and Weill (1970b, 1972) (Table 11). IV.3: Interpretations

It has been suggested (Philpotts, 1971; Appendix 5.1, this thesis) that the "phenocryst ledges" were formed by sinking of pyroxene crystals. Three alternative hypotheses for their origin are:

- (i) flow differentiation;
- (ii) cooling of the upper contact of each intrusive unit significantly faster than the lower contact;
- (iii) convection.

Flow differentiation is rejected because phenocryst ledges are not symmetrical with respect to internal contacts. If hypothesis (ii) were true, the upper cooling face of each intrusive unit would have grown inwards faster than the lower face, yet in every case (Table 2) there was a greater thickness of the previous intrusive unit below each new injection of magma than above. Finally, the sill was too thin for convection to have operated (Bartlett, 1969).

Within the host rock of each intrusive unit there are

irregular downward increases and decreases in the concentrations of elements characteristic of early and latecrystallizing phases respectively (Figures 8 to 11). (Although estimates of P205 concentrations were found to have been affected by the presence of Ca, corrected values display the same trends as uncorrected values (Appendix 7.41)). This is what would be expected if crystal settling had occurred: the irregularities may be attributed to partial assimilation of material of previous intrusive units, variations in mineral compositions, and varying relative velocities of downward-sinking crystals and inward-growing solidification fronts. A more rigorous test of the hypothesis would be to determine whether or not there are downward increases in pyroxene concentrations. Unfortunately, the compositions of Ste. Dorothée minerals, especially pyroxenes (Appendix 5.1), are too variable to allow "chemical modes" (Perry, 1967, 1969; Chayes, 1968; Gresens, 1969; Bryan, Finger and Chayes, 1969; Bryan, 1969; and Wright and Doherty, 1970) to be determined from chemical analyses.

The density of Ste. Dorothée titanaugites is 3.41 (Philpotts, 1971). Using the data of Robie et al (1966), and linearly extrapolating Skinner's (1966) values of coefficients of expansion, densities of Ste. Dorothée titanaugites and titanomagnetites at 1100°C were estimated as 3.31 and 4.31 respectively. Therefore, provided temperature variations and the load pressure on the sill did not greatly affect differences between mineral and liquid densities, both titanomagnetite and pyroxene would have sunk in liquid of composition similar to Ste. Dorothée host rock (Table 10).

Minor element distributions in the analcite syenite and host rock seem to have been controlled by the mineralogy of each rock type, rather than an initial partitioning of elements between two immiscible liquids (Appendix 9). For example, the strong linear correlation between feldspar composition and feldspar-magma partition coefficients for Sr (from the results of Philpotts and Schnetzler, 1970) indicates that the activity coefficient of Sr in magmas of a wide variety of compositions, and $P_{H_{2}0} \leq 0.5$ Kb, is constant down to temperatures at least as low as those at which plagioclase Ab₅₀An₅₀ precipitates (Appendix 10). Sr would therefore be present in equal concentrations in two coexisting liquids, yet the analcite syenite is richer in both Sr and feldspar (the most important Sr-bearing mineral in the sill) than the host rock.

Rare-earth element (R.E.E.) concentrations in the host rock are similar to, but consistently higher than those in the analcite syenite (Table 12), which may be explained by the greater abundance of sphene and apatite in the host rock. (R.E.E. partition coefficients between both apatite and sphene and a wide variety of rock melts are of the order of 50 (Deer, Howie and Zussman, 1963, 1, 72-73; Gold, 1963; Khomyakov, 1968; and Nagasawa, 1970), whereas partition coefficients between other silicates and magmas are less

than, or approximately equal to one (Onuma, et al, 1968; Schnetzler and Philpotts, 1968; Higuchi and Nagasawa, 1969)).

Providing equilibrium had been maintained between the host rock and analcite syenite, such patterns would be expected if the analcite syenite had formed from a late phase differentiate of the host rock, an immiscible fluid, the "felsic material" within xenoliths (Chapter 5) or nucleation centres for felsic minerals (c.f. Philpotts et al, 1970).

CHAPTER V: CARBONATE XENOLITHS

V.1: Description and Classification

I examined features which appear to be related to carbonate xenoliths in eighty thin sections, and classified them into four types: A, B and C-type bodies, and "mafic aggregates." All are of the order of mm. to cm. in diameter, and type A, B and C bodies are rimmed by greenish augite crystals. The interior of each type A body consists of masses of calcite and calcite-scapolite, each with its own rim of pyroxene crystals similar to those rimming the entire body. Plagioclase, sanidine, analcite, turbid analcite and small accumulations of green augites occupy intervening spaces. Type B and C bodies contain "felsic material" (composed of plagioclase, analcite, turbid analcite and natrolite ± sanidine, fine-grained calcite, green augite, opaque minerals, thomsonite, sphene, micaceous (?) material and brown amphibole), but only type B bodies contain remnants of the original xenoliths.

Green augites composing the rims of the four type A bodies found have pale cores and darker rims; and minor amounts of analcite and fine-grained, nearly opaque grey and dark grey material are present interstitially. The only alteration of the host rock surrounding these bodies is an increase in the turbidity of entire analcite crystals.

The outermost portion of some of the twenty-four type B bodies found (Plate 4) is a zone (less than 0.1 mm. thick) of very fine-grained brown crystals which grades rapidly into an

augite rim, one to several mm. thick. Augites of the outer portion of all rims are colourless to light yellow green or brown; those inside are coarser grained and have similar coloured cores, but change rapidly to darker shades of green at their edges, especially at contacts with the "felsic material." (However, two crystals with a core darker green than the rim were found.) "Felsic material" generally separates augite rims from the carbonate, and may be concentrated at one end of the body.

Every type B body appears to have developed from xenoliths composed predominantly of calcite, sometimes with subordinate dolomite. However, one xenolith is a limy mudstone, and two contain about 50% sand-sized quartz grains in a fine-grained calcitic matrix. Neither of these contains wollastonite, although a minute quantity of the mineral may be present in another, pure limestone xenolith.

Networks of tubular isotropic structures (with average diameters of about 5μ) were observed in the calcite grains of two xenoliths.

The xenoliths are in various stages of fragmentation. At the first stage, they seem to be nearly intact. At the second stage, cracks (usually near the edge of the xenolith) penetrate between and through calcite grains and are filled with "felsic material"; in the third stage, the limestone is brecciated; and at the fourth stage, isolated fragments of calcite are scattered throughout the "felsic material." (Plate 4 shows stages 2 and 3).

Alteration of the surrounding host rock is apparent over 0 to about 5 mm. The usual effects are a decrease in the average grain size of the host rock, with an increase in the amount of analcite, turbid analcite, feldspar and carbonate. Amphibole is always rare, and fine-grained augite crystals resembling those which form the xenolith rims are common.

Two type C bodies, with pyroxene rims identical to those of type B bodies, were found. Their interiors are composed of "felsic material" with augites and opaque minerals more abundant than in type B bodies. Alteration of the host rock around type C bodies is similar to, but more extensive than that associated with type B bodies.

Three "mafic aggregates" (Plate 5) were found. These are glomerophenocrysts of pyroxene (similar in size and optical properties to normal host rock pyroxene phenocrysts), amphibole, sphene, opaque minerals, apatite and plagioclase.

V.2 Analysis of Minerals Associated With Xenoliths

V.21 Pyroxenes

Two pyroxene crystals on the inside of the pyroxene rim of a type C body from 162.5 cm. were analyzed on the electron microprobe (Appendix 3) near their cores and rims. Results are presented in Table 9, along with the allocation of ions into W, X, Y and Z, computed by the program described in Appendix 5.1. Low summations are probably due to inadequacies in the correction procedure (Appendix 5.1).

The two most remarkable features about these analyses are the complete absence of Al, and a marked enrichment in Fe at

the crystal rim. (Al is also absent in several other xenolith rim pyroxenes in a different thin section.) The enrichment in Fe is correlated with a great increase in the intensity of the mineral's colour (from light yellow-green to dark green). V.22 Analcite

Analcite in "felsic material" is compositionally similar to host rock and analcite symple analcites in the same thin section (Tables 9 and A9).

V.3 Interpretations

Ten blisters were found on pyroxene rims which surround type B and C bodies (Plates 7 to 9). The blisters are usually enveloped by one or more selvedges of pyroxene (similar to the main pyroxene rim) concentrically arranged with respect to the breach. "Felsic material" may occur on both sides of the outermost selvedge (Plate 7). The rounded shape of the blisters, and the lack of structural dichotomies in the "felsic material" between blisters and the rest of the bodies preclude the possibility that the "felsic material" was ejected in solid chunks; while the flow structures, and miscibility of "felsic material" with analcite syenite evident in Plate 8 indicate that both the analcite syenite and the "felsic material" were at one time fluid. (It might be objected that the apparent flow structures are the remains of an inner rim formed on the xenolith. However, the flow structures are defined by titanomagnetite crystals, whereas all xenolith rims are composed of pyroxene, none of which shows any alteration to titanomagnetite.) I consider that flow structures are more likely to have been preserved if

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، ۲ the intermingled analcite syenite and "felsic material" fluids were silicate liquids rather than vapours. Holgate (1954) similarly concluded that the felsic or glassy material often found in mafic igneous rocks between the remains of quartzrich xenoliths and their pyroxene rims had condensed from a liquid.

The host rock and pyroxene rims must have been sufficiently rigid to restrain the bodies from tending towards sphericity, otherwise pyroxene rims would not be generally angular. Since textural evidence suggests that the felsic material and the rim pyroxenes formed contemporaneously, rim pyroxenes were probably formed relatively late in the crystallization sequence of the host rock. In the following discussion, amphibole is assumed to have been crystallizing in the host rock, and the $P_{\rm H_{2}0}$ to have approximated the load pressure as type B and C bodies formed. (The failure of the assemblage quartz-calcite to have produced significant quantities of wollastonite cannot be used as a geothermometer. Perhaps the chemical potentials of Si, Ca, or both, were lower in the melt than in wollastonite; or perhaps there was insufficient time for wollastonite to have (The results of Gordon (1971) and Kridelbaugh (1971) been formed. suggest that the kinetics of the reaction are strongly dependent on the composition of the vapour phase.))

Bowen (1928, Chapter 10) showed that incorporation of a xenolith in a magma causes precipitation of crystalline phases in which the melt is saturated. As a carbonate xenolith degassed, the P_{H2O} nearby would have been reduced, accounting 30

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for the absence of hydroxyl-bearing minerals, and the decrease in average grain size of the host rock near xenoliths. Infusion of lime into the magma would have caused precipitation not of amphibole, but pyroxene, equivalent in composition to that which would have crystallized from a dry melt. The pyroxene rim would have acted as a semi-permeable membrane (Holgate, 1954; Roedder, 1956) and allowed outward diffusion of CO_2 . Since the shape of xenolith rims implies that little of this mass transfer was balanced by shrinking of the xenolith, there must have been a corresponding inward movement of material. For $P_{H_{2O}} \approx P_{Total}$, this material would have been mostly "water", rich in elements selectively transported by an aqueous vapour phase: Si, Al, Na, K and Fe (Friedman, 1951; Morey and Hesselgesser, 1952; Morey, 1957; Tuttle and Bowen, 1958; Ovchinnikov and Masenkov, 1960; Orville, 1963; Adams, 1968; Currie, 1968; Martin and Piwinskii, 1969). Inside the pyroxene rim, the increase in P_{CO_2} would have caused much of the dissolved material, including Fe and Al, but not Mg (Holloway, 1971), to precipitate into liquid (if present) and solid phases (Burnham, 1967). Since Al probably entered plagioclase in preference to pyroxene (because of the lower (Ringwood, 1959) and higher $a_{Si}4+$ (Kushiro, 1960; PHAO Le Bas, 1962) of the liquid "felsic material" compared with the host rock liquid), Fe^{2+} and Fe^{3+} would have substituted for Mg^{2+} and Al^{3+} in pyroxene. This partially accounts for the absence of Al and the strong inwards increase in Fe/Mg ratios of rim pyroxenes.

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Other reasons for this enrichment in Fe relative to Mg are:

- (i) MgCO₃ in any dolomite in the xenolith would have broken down before CaCO₃ dissociated (Kracek, 1942);
- (ii) selective transport of ions would have increased with the thickness of the rim;
- (iii) the host rock liquid probably followed the usual trend of increasing Fe with respect to Mg during crystallization.

Type C bodies are probably type B bodies from which all the carbonate has vanished. Pyroxene rims surrounding individual calcite grains in type A bodies may have formed in response to a slow rate of outward diffusion of Ca at lower (possibly subsolidus) temperatures than those at which type B and C bodies formed.

A breach would have formed in a pyroxene rim when the CO_2 concentration built up too rapidly to be relieved by diffusion, or when "felsic material" accreted faster than the rate of decomposition of carbonate. Whether the residual liquid in the host rock and the liquid "felsic material" were miscible or immiscible, CO_2 and Ca would have diffused radially outwards from the breach, and a front of pyroxene crystals would have formed along an isograd in the relative proportions of inwards and outwards moving ions. Varying rates of diffusion would have resulted in a series of such fronts.

The structures depicted in Plate 9 can be accounted for as follows: after the initial pyroxene rim (now the innermost rim) was formed, it was breached, the extruded "felsic material" surrounded the xenolith, and became rimmed with pyroxene. A

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similar process formed the third pyroxene rim and finally, a breach within the second-formed rim led to the eruption of a blister through the outer zone of "felsic material" and the third pyroxene rim into the host rock. Yet another pyroxene rim formed around this lobe.

When metasomatism became important in the sill, porous, partly decomposed limestone xenoliths would have provided sinks for H_2O , accounting for the greater degree of alteration of "felsic material" than analcite sympite.

"Mafic aggregates" probably formed by reaction of carbonate xenoliths with the host rock melt when it was precipitating pyroxene (aluminous titanaugite). Because of the elevated temperatures, carbonate would have degassed rapidly, causing continual breaching of any pyroxene rim that formed, which, together with the relatively low $P_{\rm H_2O}$ of the magma, would have inhibited the formation of "felsic material" by a diffusion process; and ejected into the host rock any that did form.

If all analcite syenite originated by unmixing from the host rock, slowly cooled intrusive units would be expected to have the highest concentrations of analcite syenite. However, intrusive unit number 2, which must have been one of the slowest-cooling units in the sill (it is the secondthickest unit, and $I_2 = ((thickness of the upper portion of$ the unit)/ (thickness of the entire unit)); a measure of theamount of crystal settling presumed to have occurred, is by $far the largest <math>I_i$) has the second lowest concentration of analcite syenite (Table 2).
Significant amounts cannot have been removed by upward flotation, for intrusive unit number 1 is even poorer in analcite symmetrie.

I suggest that: "felsic material", formed by reaction of carbonate xenoliths with the melt, was contributed to the analcite syenite; that the volume of carbonate xenoliths assimilated possesses a monotonic increasing relationship with the amount of felsic material contributed; and that assimilation of carbonate xenoliths accounts for most variations in CO2 concentrations of the host rock. This hypothesis readily explains the relative paucity of analcite syenite in intrusive unit number 2, for the CO2 concentration of the host rock of this unit is greater only than that of intrusive unit number 1. Since "felsic material" is richer in felsic minerals than the average analcite syenite, the hypothesis also explains correlations between concentrations of host rock CO2 and analcite syenite oxides in each intrusive unit (Table 13): these correlations are not readily accounted for by other hypotheses of origin of the analcite syenite. The discovery of an inclusion of pyroxenes, resembling a fragment of a xenolith rim, in an analcite syenite body (Plate 6), and the apparent "bleeding off" of "felsic material" shown in Plate 8 further support this idea.

The objections of Ferguson and Currie (1971) to a xenolithic origin of analcite syenite do not apply to this mechanism; similarly, the first reason given by Philpotts (1971) (that quartzofeldspathic xenoliths do not show signs of alteration to analcite syenite) for rejecting such a hypothesis is also irrelevant.

However, Philpotts showed that the size-frequency distribution of ocelli in the lower contact region of the sill suggests nucleation from the host rock. Although the pyroxene: amphibole ratio in the host rock of the upper contact zone is the highest found in the sill, the ocelli contain mostly volatile-rich minerals (Figure 3) and cavities. Similar bodies are present throughout the upper half of the sill, either as discrete entities, or occupying the upper portions of analcite syenite bodies. An analysis of some "discrete" bodies from 65-70 cm. below the upper contact (Analysis 9, Table 5) indicates that they are composed dominantly of analcite and natrolite. (Volatiles are assumed to account for the low summation of the analysis.) I consider that these ocelli, and presumably those from the lower contact zone, are amygdules, mineralogically and perhaps genetically distinct from the larger analcite syenite bodies.

Philpotts' third objection to a xenolithic origin for the analcite syenite rests on rare earth (R.E.E.) analyses (Philpotts et al, 1970) and the equality of the Sr^{87}/Sr^{86} of the two rock types (Philpotts and Philpotts, 1969). However, providing equilibrium was maintained between analcite syenite and the host rock, this objection is invalid. If limestones with Sr concentrations as high as those of the host rock (which is uncommon (Vlasov, 1964, p. 145)) and with a Sr^{87}/Sr^{86} ratio of 0.715 (limestones of any geological age rarely have higher Sr^{87}/Sr^{86} ratios (Hamilton, 1965, p. 112)), were homogenized with a magma with a Sr^{87}/Sr^{86} ratio of 0.704 (the value

measured by Philpotts and Philpotts, 1969, and typical of Monteregian intrusives (e.g. Hamilton, 1965, p. 116)) in proportions equal to the present volumetric ratio of analcite syenite to host rock, the Sr^{87}/Sr^{86} of the magma would increase by only 0.0002. In comparison, the accuracy of the measured Sr^{87}/Sr^{86} ratio is \pm 0.001 (J. A. Philpotts, written comm., 1970). A similar argument may be applied to R.E.E. concentrations of the two rock types.

For the following reasons it is unlikely that most analcite syenite originated from "felsic material":

- (i) analcite sympite bodies contain more mafic minerals than the "felsic material";
- (ii) pyroxenes resembling those on the rims of xenoliths were found in only two of hundreds of analcite symmetric bodies.

Structures very similar to those surrounding carbonate xenoliths of the Ste. Dorothée sill are often developed on siliceous xenoliths in mafic rocks (a partial list of references is found in Appendix 6), and show a surprising uniformity. In terms of the hypothesis presented above, immersion of a siliceous xenolith in a melt would have led to rapid precipitation of a Si-bearing phase in which the melt was saturated:pyroxene. "Water" would have greatly assisted migration of Si, Al, Na, K and Fe down their respective chemical potential gradients through this pyroxene, producing a fluid, or fluid-crystal mixture, which condensed into an assemblage of dominantly felsic minerals between the

rim and the remains of the xenolith. The green colour of pyroxenes on the inside of the rim is probably due to differential rates of ionic diffusion, which would have caused progressive enrichment in Fe with respect to Mg.

It is remarkable that pyroxene is the only mineral to form such rims. Perhaps other minerals which may form at the junction of xenoliths and basic melts do not act as semi-permeable membranes, and no layer of "felsic material" is formed.

CHAPTER VI: CONCLUSIONS AND SUMMARY VI.1 Origin of the Analcite Symmetry

It was concluded in Chapter 3 that analcite syenite bodies formed from a fluid immiscible with the host rock, and in Chapter 5 that the analcite syenite was at one time liquid. Hypothesis 5 (liquid immiscibility) is therefore tentatively accepted as the origin of the bulk of the analcite syenite, although a significant amount was probably contributed from "felsic material" found around xenoliths. It is evident from mineral parageneses (Figure 4) that, after amphibole had ceased to crystallize, two residual liquids would have had similar, feldspathic compositions, and hence may have become miscible again. This could account for the lack of sharp contacts between the host rock and subvertical syenite veinlets in intrusive unit 6, and between the host rock and analcitefeldspar veins which link some analcite syenite bodies.

Philpotts (1971) also accepted the liquid immiscibility hypothesis, and from structures in the sill calculated the density contrast

(f host rock - f analcite syenite = 0.44 to 0.52 g/cm³) and interfacial surface tension between the two phases, and the ratio of the viscosities of the two phases

(η host rock/ η analcite syenite = 500 to 1000). Computed density contrasts (Chapter 4.2, and Table 10) range from 0.25 g/cm³ to 0.37 g/cm³, in fair accord with Philpotts' figures. Contrary to Philpotts' results, the analcite syenite is calculated to have been the more viscous liquid (Chapter 4.2 and Table 11) at 1200°C. This is not a serious objection to the liquid immiscibility hypothesis, for it must be remembered that the structures studied by Philpotts were formed when the host rock (but not the analcite syenite) had nearly solidified, and that bubbles of gas in the analcite syenite would have reduced its effective viscosity.

The relationship of projections of analcite symmite and host rock analyses into the system SiO₂-FeO-K₂O·Al₂O₃ to the two liquid field (Figure 12) supports the suggestion of Philpotts and Hodgson (1968) that this two liquid field is part of that in the natural system "analcite symmite"-"host rock".

VI.2: Summary

The Ste. Dorothée sill is a 570 cm. thick critically undersaturated alkali basaltic multiple intrusion which was emplaced at about 1100° C, under a load pressure of about 0.3 Kb. Six periods of intrusion are recognized: before each intrusive unit had fully solidified, another pulse of magma forced its way between the fronts of solidification, assimilating and flushing out the remaining crystal-liquid mixture. Aluminous titanaugite, titanomagnetite, sphene, apatite and vesicles nucleated before, or shortly after emplacement, and phenocryst ledges were formed by settling of pyroxene, titanomagnetite and possibly sphene and apatite. As the $f_{\rm H_2O}$ increased, amphibole (kaersutite or aluminium-rich titaniferous hastingsite) began to crystallize, followed by feldspar, which changed continuously in composition from andesine through calcic anorthoclase to sanidine.

About the time that pyroxene ceased to crystallize, the magma encountered a two-liquid field, and droplets which condensed into analcite syenite separated and crystallized pyroxene, amphibole, feldspar, and accessory minerals. These droplets floated upwards and either flattened out against fronts of solidification forming lenses and sills, or rose diapirically through the mush above. As feldspar crystallized, the residual liquid in the host rock once more became miscible with the remaining "analcite syenite liquid", and narrow analcite-feldspar veins with gradational contacts were generated.

Rims of Al-free clinopyroxenes were precipitated on carbonate xenoliths while amphibole crystallized from the host rock. A combination of ionic diffusion and vapourphase transport through these pyroxenes resulted in the formation of crystal-liquid mixtures, rich in Si, Al, and alkalis, inside the rims. Some of this material was added to the analcite syenite, which eventually comprised about 2 per cent of the sill.

Appendix 1: In Situ Modal Analysis

It was assumed for the purposes of this analysis that all light-coloured bodies, apart from xenoliths, were analcite syenite (Philpotts and Hodgson, 1968). The sill was analyzed for host rock, analcite syenite and xenoliths, but because host rock and analcite syenite are intimately related in the central zone of "sub-vertical syenite veinlets," this portion of the sill was omitted. Two traverses, 2 m. apart, were analyzed using a mm. rule. Compositions of each 5 cm. interval were obtained by averaging modal analyses of three parallel, vertical sections 5 cm. apart. Results are presented in Table Al. A major reason for disparities between my pictorial representation of the sill (Figure 2) and those of Philpotts and Hodgson (1968) and Philpotts (1971) is lateral variation. For instance, the central zone of "subvertical syenite veinlets" is 14 cm. thicker in the southern than in the northern section.

Let $V_{c,t}$ = average percentage (volume) of component c in the sill (excluding the central zone). From the results of Table Al,: for the northernmost section,

 $V_{sye,t} = 2.65$ %

 $V_{xen,t} = 0.86\%$

("sye", "xen" = "analcite syenite" and "xenoliths"
respectively,)
for the southernmost section,
V_{sye,t'} = 1.90%
V_{xen,t'} = 0.42%

means and standard deviations are: $V_{sye,t}$, = 2.28%, standard deviation (2 samples) = 0.53 $V_{xen,t}$, = 0.64%, standard deviation (2 samples) = 0.98

A composite section was sampled: samples down to 180 cm. were taken from the northernmost section, all others from the southernmost section. This composite section was treated as if it were one, with a thickness of 570 cm., and with the lower horizons assigned the depths they have in the southern section. 42

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Appendix 2: Modal Analysis of Sawed Specimens

A2.1: Method

Five cm. was once more chosen as the interval size. ... Before performing the analysis, the following points were considered:

- (i) Bodies of analcite syenite range from small (about 1 mm. diameter) spheroids through ellipsoids (several cm. by several dm.) to lenses, of the order of cm. thick, extending across the entire exposure. Xenoliths usually have diameters of the order of mm. or cm.
- (ii) Since many analcite symmetrie bodies are elongated, lineations may exist.

To minimize variation due to component size, the rock area analysed was maximized by performing the analyses on slabs, which were cut vertically to minimize variation caused by horizontal orientation of components. The hypothesis that the variance of the proportion of a component is the same in slabs cut perpendicularly to one another could have been tested to determine the likelihood of the existence of a consistent lineation direction. However, lineations may change orientation with depth in the sill, and many specimens were elongated. To obtain more equidimensional specimens would have been very time-consuming, and would have involved samples taken over a lateral spread of several metres. As a compromise, slabs were prepared as follows: The long axis was drawn on each specimen; then a slab (0.5 to 1 cm. thick) was cut along the section, perpendicular to this line, with maximum area. The two remaining pieces were slabbed along the long axis line to form a composite slab; but both slabs were cut at roughly 45° to the long axis of very elongated specimens. Slabs were sprayed with clear varnish and arbitrarily designated (X) and (Y).

Considerations in choosing the components to be modally analyzed were:

- (i) No slabs had weathered surfaces.
- (ii) Many small spherical bodies seemed to consist almost entirely of analcite, and would probably be more appropriately called amygdules than "ocelli".
- (iii) Carbonate and white silicate material sometimes occurs in intersertal masses as big as some amygdules.
 - (iv) Some portions of some xenoliths resemble analcite syenite.
 - (v) Veins of analcite syenite and of carbonate are present.

The following components were chosen:

- (i) <u>"Analcite syenite"</u>: All veins other than carbonate veins, and all light-coloured bodies with distinct outlines and no reaction rims.
- (ii) <u>Xenoliths</u>: Bodies with rims judged to be kelyphitic, and all other xenoliths.

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(iii) <u>Host Rock</u>: All other rock components, excluding carbonate veins. (Carbonate veins were rarely encountered, and were excluded by not counting any points in (5 mm. x 5 mm.) squares which overlaid them.)

The following method of point-counting is more rapid than using a mechanical stage (Smithson, 1963; Schryver, 1968):

The pattern of a sheet of graph paper with a grid of (1 mm. x 1 mm.) and (5 mm. x 5 mm.) squares was transferred by copying machine to a sheet of clear plastic, which was laid over a slab. The points on which the counting was based were the centres of each (1 mm. x 1 mm.) square that fell in (5 mm. x 5 mm.) squares which entirely covered the slab. Squares were marked with a pen as they were counted.

Chayes (1956, Chapter 11) showed that bias is usually minimized by placing one of the edges of a counting grid at between 30° and 50° to the trace of the layering. Since this would have greatly reduced the counted area, or increased the counting time by increasing the number of (5 cm. x 5 cm.) squares not wholly over the slab; and since layering is much more pronounced on the scale of decimetres than millimetres, I always counted with one grid line parallel to the slab edges.

Boundaries marking small, sharp changes in average grain size and composition were interpreted as internal contacts. Narrow (about 1 mm.) contact zones, finer-grained and more mafic than the rock on either side were sometimes present, but were ignored, and counts above and below contacts were recorded separately. 45

A2.2: Analysis of Results

I assumed that there was some lateral continuity in the sill, and imagined it to be divided into a series of horizontal slabs, 5 cm. thick, which were target populations of which each specimen was a sample.

Errors in defining the top of the sill, of marking the sill rock in situ, and of sawing specimens could have produced a maximum error of 1.5 cm. vertically in the location of the centre of a specimen, and a maximum error in the thickness of the slab of 1 cm. In a "worst possible" situation, 2.5 cm./6 cm. = 40% of an analyzed slab belongs to a neighbouring interval (Figure Al). This error was ignored, because the main uses of this analysis were correlation of modal and chemical compositions, and estimation of the modal composition of the entire sill. Since modal and chemical analyses were performed on samples of the same specimen, relationships between modal and chemical composition are not affected by errors in locating specimens. When less than 5 cm. of an interval was available because of errors in sawing, that portion was assumed to be representative of the entire interval; and when portions of another interval were present in a specimen, only that part of the slab belonging to the interval under consideration was analyzed.

Analcite syenite and xenolith percentages were chosen as the independent variables in the following discussion of variances. Ideally, to test whether the counting plus operator component of variance is less than or equal to binomial

expectation (Chayes, 1956, Chapters IV and V), replicate analyses should have been made of randomly chosen slabs randomly distributed throughout the routine analyses. However, because of weight limitations, only a few specimens were brought back after each visit to the sill. Each slab was allotted a three-digit number, and random numbers were extracted from a table in groups of three until five slabs were specified. After every twenty slabs had been counted, the first slab on the list which was in existence and had not previously had a duplicate count made on it was analyzed.

Results were:

Slabs (in order o	of analysis)	Routin	e Analy	rses	Replica	te Anal	vses
Specimen Number	Slab	Total Counts	β sye, j,k	, ^B xen, j,k	Total Counts	₿sye, j,k	j,k
50-55 cm. 0-5 cm. 65-70 cm. 140-145 cm. 190-195 cm.	Y X X X X	5375 3575 5175 4475 4850	9.860 0.448 8.696 7.061 0.598	0 0 0.246 1.381	5325 3575 5175 4400 4875	10.028 0.476 8.908 6.977 0.656	0 0 0.273 1.316

j is the number assigned each interval, counting downwards from the upper contact; and β c,j,k is an estimate of the volume percentage of component (c) in slab (k).

The variance of any pair of analyses is:

$$\hat{\boldsymbol{s}}^{\circ^{2}}_{c,j,k} = (\boldsymbol{\beta}^{\circ}_{c,j,k} - \boldsymbol{\beta}^{\circ}_{c,j,k1})^{2} + (\boldsymbol{\beta}^{\circ}_{c,j,k} - \boldsymbol{\beta}^{\circ}_{c,j,k2})^{2}$$
$$= 1/2 (\boldsymbol{\beta}^{\circ}_{c,j,k1} - \boldsymbol{\beta}^{\circ}_{c,j,k2})^{2}$$

where β c,j,kl and β c,j,k2 are the routine and replicate analysis estimations of the percentage of component (c) of 47

slab (k) in the interval (j): $\vec{\beta}$ c,j,k is their mean.

The best estimator of the counting plus operator component of variance for this method is the pooled sample

$$\overline{\hat{s}_{c}^{02}} = \underbrace{\sum_{k=1}^{n_{c}} \hat{s}_{c,j,k}^{02}}_{m_{c}} \quad (m_{c} = \text{the number of} \\ \text{values of } \hat{s}_{c,j,k}^{02} \quad \text{used})$$

All values of $\hat{s}^{o^2}_{sye,j,k}$, but only the values of $\hat{s}^{o^2}_{xen,j,k}$ based on non-zero values of $\beta_{c,j,kl}$ were included.

(i.e. $m_{sye} = 5, m_{xen} = 2$).

Thus,

variance

$$\overline{S}^{0}^{2}_{\text{sye}} = 0.00844$$

 $\overline{S}^{0}_{\text{xen}} = 0.0012$

The variance estimate of a binomial distribution is:

$$e_{c}^{o^{2}} = \sum \frac{\overline{\beta}_{c,j,k} (100 - \overline{\beta}_{c,j,k})}{N_{c,j,k}}$$

where $N_{c,j,k}$ = the mean of the total number of counts made on each slab.

Thus,
$$e_{sye}^{0} = 0.1084$$

 $e_{xen}^{0} = 0.0172$

Test 1.

$$H_{1,0}: s_{c}^{o^{2}} < e_{c}^{o^{2}}$$

 $H_{1,1}: s_{c}^{o^{2}} \gg e_{c}^{o^{2}}$

Hypothesis $H_{1,0}$ is tested against the alternative $H_{1,1}$ by a χ^2 test where

$$\chi^2 = (m_c - 1) \frac{\overline{s}_c^2}{\frac{e_c^2}{c}}$$

the region of rejection of $H_{1,0}$ is given by

$$\chi^2 \gg \chi^2$$
 1-a, m_c-1

★ is the risk level, chosen as 0.05.

Test 2.

 $H_{2,0}: \quad \hat{s}_{c}^{0,0} = e_{c}^{0,0}$ $H_{2,1}: \quad \hat{s}_{c}^{0,0} \neq e_{c}^{0,0}$

the region of rejection of $H_{1,0}$ is:

 $\chi^2_{\alpha,m_c^{-1}} \langle \chi^2_c \langle \chi^2_{1-\alpha,m_c^{-1}} \rangle$

again, 🔨 was chosen as 0.05.

Component	χ^2_c	$\chi^{2}_{0.05,m_{c}-1}$	$\chi^{2}_{0.95,m_{c}-1}$	Outcome of Test 1.	Outcome of Test 2.
Analcite Syenite	0.3114	0.711	9.49	Accept ^H 1,0	Reject ^H 2,0
Xenoliths	0.0698	0.0039	3.84	Accept ^H l,0	Accept ^H 2,0

It was therefore concluded that, at the 0.05 significance level, the counting plus operator variance for analcite symmite is smaller than binomial expectation, and that the same variance for xenoliths is not greater than binomial expectation. `<u>~</u>'I

The two main sources of operator plus counting variation are probably the number of (5 mm. x 5 mm.) squares counted, and judgement of the position of the centre of a square. Although a progressive change with time of operator-induced variation could not be allowed for by analyzing the entire collection of slabs in random order, the above statistical analysis indicates that any such variation is unlikely to be significant, and that the counting was under control.

Since each specimen is a sample of a different target population, relationships between the number of counts and the within-specimen component of variance are different for each 5 cm. interval. Thus, it was not possible to devise a technique of weighting the volume estimates derived from different slabs according to the number of points measured on each, to give a minimum variance estimate of the modal proportions of components. As approximately the same number of counts was made on each slab of a pair of slabs (the maximum value of the ratio $N_{\rm OC}$ =

(number of counts made on the slab with the most number of points) (number of counts made on the other slab)

is 2.80, and the mean value, N_{OC} is 1.32), $V_{C,j}$ (the estimated volume percentage of component c in interval j) was approximated by:

 $v_{c,j} = 1/2 (\beta_{c,j,X} + \beta_{c,j,Y}).$

(The number of counts on each of the five slabs analyzed in replicate was recorded as the mean of the two measured values.)

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Because there are few xenoliths or analcite syenite bodies below 275 cm., slab analysis was discontinued there, and the results of the in situ analyses used. Syenite in the lower portion of the sill constitutes about 4 per cent of the total analcite syenite, and the contribution to the total "within traverse" component was assumed to be negligible. However, xenoliths in the lower portion of the sill may make up as much as 20 per cent of the total, and the contribution to the total variance of **xeno**lith percentages must be significant.

Point estimates of the percentage of (c) present in the entire sill $(V_{c,t})$, were obtained by summation of the $V_{c,j}$. The precision of these estimates cannot be determined, because each 5 cm. slab represents a different population and the estimates of variances cannot be averaged. Neither is it possible to determine the accuracy of each $V_{c,t}$, for it is not known how typical of the sill the traverse is.

Appendix 3: Electron Microprobe

Analytical Procedure

All analyses were performed with McGill University's Acton MS-64 electron microprobe, on polished thin sections. The take off angle of the microprobe is 18°; the accelerating voltage was held at 15KV and sample current at 50 nanoampères, during all operations.

The standards used, and number of 10-second counts made on each element, are listed in Table A2. The approximate standard deviation, Si,

(where

$$S_{j} = \sqrt{\left(\frac{1}{1-2} - \frac{(x_{i} - x_{i})^{2}}{n-1} - \frac{\left(\frac{n}{1-1} - x_{i} - x_{i}\right)^{2}}{n}\right)}$$

$$j (j=1, \dots k) \text{ designates each of the k elements}$$

$$n_{j} \text{ is the number of readings made on element}$$

$$number j \text{ in each mineral analysis.}$$

$$x_{i} (i=1, \dots n) \text{ is a typical reading.})$$

of estimated oxide weight percentages is generally less than 1 percent, and always less than 3.5 percent, in accord with the conclusions of Sweatman and Long (1969).

The usual analytical procedure was to make counts on the standard(s), then on two sample locations (or one, if ten 10-second counts were being taken), and again on the standard(s). Five background readings were made on each side of the peak on the standard, and on one or more representative mineral samples.

McGill's revised version of Rucklidge's (1967, 1968) computer program, EMPADR V, was used to correct results. The 52

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program incorporates the following corrections, which are applied iteratively: fluorescence (Reed, 1965), absorption (Duncumb and Shields, 1966) and atomic number (Duncumb and Shields, 1963; Duncumb and de Casa, 1967). W. H. MacLean (pers. comm. to Fox, 1970) has analyzed a U.S.G.S. basaltic glass standard (W7) against a combination of silicate standards and found negligible differences between microprobe and wet chemical analyses for alkali oxides and silica. Larger discrepancies were found for MgO and TiO₂ (1-3% of the oxide weight), and for Al₂O₃, FeO, and MnO (6-10%). It should be noted that the proportion of MnO in this rock is only 0.17 weight per cent, that Fe may have been absorbed by the platinum crucible during fusion, and that the homogeneity of the glass was not checked. Dr. MacLean (pers. comm., 1971) considers the relative accuracy of the electron probe technique to be about 2 per cent for components present in concentrations greater than or equal to 1 per cent in a homogeneous substance, although Dr. G. A. Challis (written comm., 1971) suspects that larger, systematic errors may be induced by the correction procedure during analysis of pyroxenes and amphiboles using standards of significantly different composition.

Appendix 4: Textural Relationships of Minerals

With the aid of masking tape, one half of each thin section was stained to permit distinction of plagioclase and potash feldspar (Rosenblum, 1956), and the other half was stained to distinguish calcite and dolomite (Friedman, Relationships between all minerals seem to be con-1959). sistent throughout the sill.

A4.01: Pyroxene

A4.02: Amphibole

Host Rock

Host Rock

a) Present in two size gen- a) Rare, present in only one erations in some rocks (the coarser-grained crystals range up to 1 cm. average diameter).

pink; some, especially the coarser generation, also possess green-coloured zones, usually the cores, occasionally the rims.

b) Most crystals are light b) Pink, sometimes with green cores.

size generation, and often

appear to be slightly corroded.

Analcite Syenite

Analcite Syenite

a) Present in one size a) The dominant mafic mineral; generation. present in one size generation. b) Crystals are brown, sometimes grading rapidly to green near the crystal edge.

c) Commonly present as rims on opaque minerals or pyroxene. Opaque inclusions are common.

Host Rock

d) The crystals are stubby prisms. Analcite Syenite

d) Crystals range in shapefrom stubby to acicular prisms.

A4.03: Opaque Minerals

Hest Rock

Analcite Syenite

a) The only apparently primary opaque mineral is optically homogeneous titanomagnetite.

b) Crystal rims are often altered to pyrite, occasionally
to hematite. Small crystals are often completely pyritized.
c) Generally equidimensional c) Crystals are usually smaller
euhedra. and less abundant than in the

host rock. Titanomagnetite forms equigranular, usually equidimensional euhedra. Pyrites are equigranular and equidimensional to acicular.

d) Fine-grained titanomagnetite occurs rarely as an alteration product of pyroxene.

A4.04: Plagioclase

Host Rock

Analcite Syenite

a) Usually present in two size generations: large (largest dimension \leq 5 mm: plagioclase crystals are often the coarsest in a thin section) crystals which poikilitically enclose crystals of amphibole, pyroxene, sphene, opaques and apatite (more than half the "crystal" may be inclusions); and smaller (largest dimension \leq 0.1 mm.) lath-shaped, generally inclusion free crystals, often surrounded by analcite.

b) Zoning is normal.

Host Rock

Analcite Syenite

c) May be rimmed with
 c) Potash feldspar rims are
 potash feldspar.
 larger and more common than
 in the host rock.

d) Often highly altered to natrolite and/or analcite.

A4.05: Potash Feldspar

Less common in the host rock than the analcite symple. Found as rims on plagioclase crystals and as clear laths of sanidine in the groundmass.

A4.06: Analcite, Natrolite, and Associated Alteration Products

Much, maybe all, analcite seems to have formed by alteration of plagioclase. A zonation is often present: plagioclase - altered plagioclase - clear, slightly birefringent analcite-turbid analcite. Many small ocelli consist of turbid analcite with a core of clear analcite.

Natrolite also seems to have formed by alteration of plagioclase, and possibly analcite. Two habits are common: sheaf-like, radiating masses; and fine-grained aggregates intimately associated with analcite.

A4.07: Sphene

Host Rock	Analcite Syenite

a) Usually present as
 a) Present as acicular euhedra,
 approximately equidimens commonly with regular, jagged
 ional euhedra.
 edges (resembling saw-blades).
 b) Rare inclusions of opaque minerals and apatite.
 A4.08: Apatite

Acicular; found as inclusions in all other minerals.

A4.09: Carbonate

Host Rock

Analcite Syenite

Usually calcite, less frequently dolomite; a latephase mineral, frequently interstitial with respect to analcite.

A4.10: Serpentine and Chlorite

Minute amounts of serpentine and chlorite are enclosed in a host rock pyroxene crystal from 400-405 cm., and a host rock amphibole crystal from 359 cm. below the upper contact respectively.

Appendix 5: Electron Microprobe Analyses of Minerals, and

Discussion of Results

A5.1: Pyroxene

Eighteen quantitative analyses were made on the electron microprobe using a $1 - 2 \mu$ diameter beam, various standards, and the computer program EMPADR V to make corrections (Appendix 3 and Table A2). Results, expressed in weight per cent oxides are presented in Table A3. (Sketches of the analyzed crystals appear as Figures A2 to A5.)

By approximating the standard deviation of the estimate of weight percentage of each oxide by S_j (Appendix 3) and ignoring the covariances of the elements, the hypothesis that each total of weight percentages does not differ significantly from 100 per cent can be tested. The statistic

$$t_{t} = |100 - \text{Total of Weight Percentages}|$$

$$\sqrt{\left\{\sum_{j=1}^{k} \frac{s_{j}^{2}}{n_{j}}\right\}}$$

has a student's t distribution with

$$\dot{a} \cdot f = (\sum_{j=1}^{k} n_j - k)$$
 degrees of freedom

S_j, t_t, and d.f are listed in Table A3. Except for UCPXI-3, the hypothesis must be rejected at the 95 per cent confidence level, meaning that significant variation, other than that induced by variation in the counts made on each element, was present.

S_i includes:

a) random variation inherent in the counting process,

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- b) sample inhomogeneities and alteration of the sample by the electron beam,
- c) machine drift,
- d) focussing errors,
- errors in peaking up;

and does not include:

- f) variations similar to a) to e) occurring during readings on the standard(s),
- g) unanalyzed oxides,
- h) chemical states of the elements,
- i) errors induced by the correction procedure.

Fe and Ti, which are calculated as FeO and Ti₂O₃, are probably the only elements whose chemical state may cause important errors. Unanalyzed oxides are unlikely to total more than 1 per cent (Deer, Howie and Zussman, 1963, V. 2). I share the view of Challis (Appendix A3) that error (i) is the most important reason for the high average total weight percentages of 191PX-1 and PX-2, and the low total weight percentages of other pyroxenes.

In the following section, these analyses are used without further discussions of errors. The analyses are projected into Ca - Mg - (Fe + Mn) and X - Y - W diagrams in Figures A6 and A7.

Pyroxene chemistry may be treated in terms of ionic substitutions (Clark, Appleman and Papike, 1969). The general pyroxene formula (after Berman, 1937; Hess, 1949; and Kuno, 1955) is:

 W_{1-p} (X,Y)_{1+p} $Z_{2}O_{6}$

A computer program, which operated iteratively, was used to compute ionic distributions according to the assumptions:

- a) Ca²⁺ occupies W; Mg²⁺, Fe²⁺ and Mn(as Mn²⁺) occupy X, Si⁴⁺ occupies Z (Deer, Howie and Zussman, 1963, V. 2), and Na⁺ enters by the acmite substitution (Tomita, 1934, p. 976; Le Bas, 1962).
- b) Ti is present only as Ti³⁺. (Ti⁴⁺ may be present, but the pink colour of the pyroxene indicates that at least some Ti³⁺ is present (Verhoogen, 1962; Burns, 1970, pp. 53-54).)
- c) Charge balance requirements were met, and trivalent ions entered Y by the coupled substitution:

 $x^{2+} + Si^{4+} \longrightarrow y^{3+} + Z^{3+}$

d) In order of preference (Hartmann, 1969), Z^{3+} is occupied by Al³⁺ and Fe³⁺, and Y³⁺ by Al³⁺, Ti³⁺ and Fe³⁺.

Errors in assuming Mn is present only as Mn^{2+} are probably unimportant; but the assumption that Ti is present only as Ti³⁺ is a serious defect. In the absence of other errors, the calculated (Fe²⁺/Fe³⁺) will equal the true value only if the assumption is correct. However, the calculated (Fe²⁺/Fe³⁺) may be shown to be a monotonic increasing function of, and nearly proportional to the ratio

 $((Fe^{2+} + 2Ti^{3+})/(Fe^{3+} + 2Ti^{4+}))$. In comparison, the Fe^{2+}/Fe^{3+} ratio measured by wet chemical analysis is correct only when no Ti^{3+} is present, and increases, with respect to the true value, with **de**creasing Ti^{4+}/Ti^{3+} (Burns, 1970, p. 54). Because of chemical differences between sector zones (Gray, 1970, 1971), qualitative electron microprobe traverses (similar to those performed on amphiboles (Chapter 3)) are generally assymetrical and discontinuous; and correlations between crystals are not possible without crystallographic control. No correlation between compositional differences and the shape of sector zone boundaries could be made. Concentric chemical zoning is also present, hence no average composition of any pyroxenes could be estimated.

The weight percentage of silica in Ste. Dorothée pyroxenes is similar to that of the host rock. Variations in physical and chemical conditions (notably the $a_{S_i}4^+$ of the magma (Kushiro, 1960; Le Bas, 1962); rate of growth of the crystal (Hollister and Gancarz, 1971); lithostatic pressure (Kushiro, 1962; 1965), and the P_{H_2O} (Goldsmith, 1953; Ringwood, 1959)) may have affected the rate of uptake of Si by pyroxenes, and the proportions of other minerals crystallizing at the same time (especially sphene and titanomagnetite), possibly leading the original Ste. Dorothée magma to either a Si-saturated or a Si-unsaturated differentiate by fractional crystallization. This hypothesis resembles that of Beall (1963) and is supported by contrasting trends in Si concentrations in electron microprobe traverses of different crystals, and by the scatter of projections of Ste. Dorothee host rock compositions about the feldspar join in the system Nepheline-Kalsilite-Silica (Figure A8). The ubiquity of analcite may only reflect homogenization by autometasomatism.

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Many pyroxene phenocrysts near the base of intrusive unit number 6 have narrow rims, optically and chemically similar to the crystal cores (e.g. 272.5P X 1 and 272.5P X 2; Tables A3 and A4 and Figures A6 and A7). The following history is postulated: 272.5P X 1 and 272.5P X 2 nucleated in intrusive unit number 5 and were situated near the upper contact at the time of emplacement. Since the macroscopic structures of the sill (Chapter 2) are most easily interpreted by assuming that fronts of solidification grew inward, and the phenocryst ledges are interpreted as resulting from crystal settling (Chapter 4.3), 272.5P X 1 and 272.5P X 2 could have been suspended in a zone of residual liquid when intrusive unit number 6 was emplaced. The pyroxene rims would have been precipitated as the residual liquid was assimilated. This hypothesis is supported by the observation that below the lower contact of intrusive units 5 and 6, abundant rimless pyroxene phenocrysts, of a similar size to those in the phenocryst ledge of intrusive unit number 6 are present. Pyroxenes, with rims resembling those of 272.5P X 1 and 272.5P X 2 were found in a cursory study of thin sections from lower down this unit. Perhaps pyroxenes which had formed in unit number 4 were incorporated into unit number 5.

A5.2: Amphiboles

Amphiboles were quantitatively analyzed on an Acton electron microprobe using suitable standards and the computer program EMPADR V to correct results (Appendix 3).

Two amphibole crystals (one in the host rock and one in the analcite syenite) were chosen from each slide, and each was usually analyzed near the geometric centre, and near the rim. Results are presented in Table A6.

The totals of all analyses fall short of 100 per cent. For example, when the concentrations of all likely components in analyses 13 and 14 are measured, or reasonably guessed, there is still a deficiency of about 2 per cent. Poor carbon-coating of the thin sections, volatilization or improperly analysed standards could not have accounted for the discrepancies, which must have been caused either by unusually large concentrations of volatiles (for example, H_3O^+ replacing alkalies (Bondam, 1967)), or by inadequacies in the correction procedure. (Dr. G. A. Challis (pers. comm., 1971) considers that the latter reason is the more important.)

Ninety-five per cent confidence limits (Student's t) of the weight percentage of each oxide were established using approximate standard deviations (S_j) provided by the computer print-out, and compositions were plotted, oxide by oxide (Figure 5).

A5.3: Iron-Titanium Oxides

Arbitrarily chosen spots on titanomagnetite crystals were analyzed with the electron microprobe, using a $1 - 2\mu$ diameter beam. Fe, Ti, Al and Mg analyses were recalculated using the computer program EMPADR V (see Appendix 3); other elements were determined approximately from:

Concentration of (X) in the sample =

(Peak counts/sec.(sample)) - (Background counts/sec.(sample))
 (Peak counts/sec.(standard)) - (Background counts/sec.(standard))
x (concentration of (X) in the standard.)...Equation Al

Analyses are presented in Table A7 as weight per cent of various elements, following D. J. Smith (1967). Si analyses of the two titanomagnetites from 65-70 cm. prove that Si in wet chemical analyses of titanomagnetite need not originate solely from impurities (c.f. Lewis, 1970).

The fo₂ of magmatic fluid(s) at any time cannot be estimated (Buddington and Lindsley, 1964; Watkins and Haggerty, 1967) because Ste. Dorothée rocks are alkaline (Carmichael and Nicholls, 1967), and because the single spinel phase coexisted with sphene.

Qualitative electron microprobe traverses, similar to those performed on amphiboles (Chapter 3) were made on titanomagnetites from 65-70 cm. below the upper contact (Figure A9), because they were much less pitted than those in the "5-10 cm." and "65-70 cm." thin sections. All crystals traversed seem to possess an outwards increase in Fe and decrease in Ti. (The coefficient of linear correlation between these elements in all quantitative analyses is - 0.82. Intergrowth of crystals, the presence

of submicroscopic exsolution lamellae and subsolidus migration of ions are possible complicating factors.) Since decreasing Ti concentrations in the magnetite - ulvőspinel series are accompanied by replacement of Fe^{2+} by Fe^{3+} , the (Fe^{2+}/Fe_{total}) ratio in the magma must have diminished with time, and the rate of crystallization of sphene accelerated with respect to that of titanomagnetite. This affords a possible explanation of the presence of only one spinel phase: the core formed under a relatively low fe_2 and was shieland from the later liquid (whose higher fo_2 would have helped initiate exsolution (Buddington and Lindsley, 1964; Watkins and Haggerty, 1967)) by a rim of Ti-poor material.

Analcite syenite and host rock minerals seem to have crystallized in mutual equilibrium, but subsolidus processes or accidental inclusion of host rock material by the analcite syenite could be invoked in defence of alternative hypotheses.

A5.4 Pyrites

Electron microprobe analyses (Appendix 3) of cores and rims of pyrite crystals from 207.5 cm. below the upper contact are presented in Table A8.

No evidence of compositional zoning or significant chemical differences between host rock and analcite syenite

pyrites were detected (this is consistent with the inference (Appendix 4.03) that the pyrites are metasomatic), nor was significant departure from the formula FeS₂ found.

A5.5: Analcite, Natrolite and Associated Alteration Products A5.51: Analcite

Clear, unaltered portions of host rock and analcite syenite analcites in a single thin section from 162.5 cm. below the upper contact were analyzed on the electron microprobe. Because bubbling in the mineral could sometimes be observed towards the end of each reading, even though a defocussed beam was used and the spot was moved during each 10-second count, Na and K, the elements most likely to be affected by volatilization, were included among the elements analyzed first.

Results are presented in Table A9. The assumption that the difference between the totals and 100 per cent is made up by water is in accord with the analyses presented by Deer, Howie and Zussman (1963, V. 4). In recalculating the analyses in terms of Ne - Ks - Qz - (CaO·Al₂O₃) there was no significant excess or deficiency of any oxide.

Analyses were projected into the system Ne - Ks - Qz by recalculation to an anhydrous composition with $(Ca0 \cdot Al_2O_3)$ counted as nepheline (Figure Al0); with kalsilite recalculated as nepheline, compositions of host rock and analcite symmite analcites are Ne_{35 \cdot 01} Ab_{64 \cdot 99} and Ne_{38 \cdot 05} - Ab_{61 \cdot 95} respectively.

A5.52: Natrolite

A clear, colourless natrolite crystal which composed

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most of an ocellus from near the upper contact of the sill was analyzed in similar fashion to the analcites (Table AlO). The discrepancy between the total weight of oxides and 100 per cent seems to be rather large to be accounted for by water alone (Deer, Howie and Zussman, 1963, V. 4): perhaps there has been partial substitution of Fe^{3+} for Al^{3+} . In spite of this, the molecular formula deduced from the analysis is much closer to that of natrolite than any other zeolite, confirming the optical identification.

A5.53: Turbid Analcite

The colour of turbid analcite in transmitted light ranges from white to red-brown. The red-brown hue is caused by minute, nearly opaque dark red-brown crystals with a high reflectivity. Qualitative electron microprobe analyses support the identification of this material as hematite: some red-brown turbid analcite has concentrations of Ca, Al and Mg similar to those of neighbouring white turbid analcite, but is much richer in Fe.

In a turbid analcite crystal from an analcite syenite body 127.5 cm. below the upper contact, very small, colourless, acicular crystals (pumpellyite?) grade by decrease in size into flecks which gave the analcite a turbid appearance. Sanidine, natrolite, dolomite and calcite are also possible constituents of turbid analcite.

A5.54: Discussion

Kim and Burley (1971, a, b) showed that, in the system Ab - Ne - H_2O , liquidus analcite cannot form at $P_{H_2O} < 5$ Kb. Not only is it unlikely that the additional components in the 67

natural system could have changed phase relationships sufficiently to permit the crystallization of primary analcite in the Ste. Dorothée sill at $P_{H_2O} \leq 0.3$ Kb. (Peters, Luth and Tuttle, 1966), but CO2 would have had an effect similar to that of lowering the P_{H_2O} (Albee and Zen, 1969). Textural relationships of analcite (Appendix 4.06) also indicate that it was a secondary mineral. Analcite could have commenced to form from (albite + nepheline + vapour) at about 455°, 460°, 470°C, or 520°C (by interpolation in the phase diagrams of Liou, 1971; Greenwood, 1961; Kim and Burley, 1971b, Figure 3; and Yoder, 1954, respectively). Ste. Dorothée analcite compositions plot near the minimum temperature stability limit of analcite in Figure 1 of Kim and Burley (1971a), a temperature-composition diagram for the system Ne - Ab at $P_{H_{2}O} = 2Kb$. Since temperature-composition coordinates of this minimum change very little with P_{H_2O} , it is likely that the compositions of the Ste. Dorothée analcites were close to that of the thermal minimum composition in the system from which they formed, and that the paragenetic history of natrolite, analcite and turbid analcite can be explained in terms of Kim and Burley's diagram. Plagioclase was hydrothermally altered to analcite similar to, or more albitic than its present composition. When the lower boundary of the stability field of analcite was reached, natrolite and turbid analcite began to form at the expense of plagioclase and clear analcite. Formation of analcite ceased at about 100°C, but natrolite (Coombs et al, 1959)

and other minerals may have continued to form at even lower temperatures.

The stability limits of pumpellyite are strongly dependent on the P_{CO_2} (Albee and Zen, 1969).

A5.6: Sphene

Sphene crystals were quantitatively analyzed on the electron microprobe at their geometric centres and near their rims. Since the first series of analyses seemed to indicate the presence of compositional zoning and of unanalyzed elements, sphenes in two other thin sections were analyzed more fully (Table All). Approximate standard deviations (S_j) provided by the computer print-out were used to estimate 95 per cent confidence intervals (Student's t) for the estimates of oxide percentages (Figure 6). Indications of concentric compositional zoning in the first series of analyses are probably due to coincidence: compositional zoning is not apparent within minerals of one rock type, or one series of analyses; nor are significant chemical differences between host rock and analcite syenite sphenes found.

Silica and total weight percentage estimates of Series 1 and 2 analyses are anomalously low compared with Series 3 analyses. Since the Series 1 analyses were performed with the same Si standard (a wollastonite) that was used for the Series 3 analyses; and a different (hornblende) standard was used for Series 2 analyses, I consider it likely that the Si deficiency is real, and that an unknown element substituted for Si in the sphenes from 65-70 cm.
Appendix 6: Partial List of Papers Describing Xenoliths, From Mafic Igneous Rocks, With Outer Rims of Pyroxene Crystals (With Colourless Cores and Green Rims) and Inner Rims of Glass or Felsic Material.

Benson, W. N. 1945: The basic igneous rocks of Eastern Otago and their tectonic environment. Pt. IV. <u>Trans.</u> <u>Roy. Soc. N. Z.</u> 75, 288-318.

Campbell, R., Day, T. C., and Stenhouse A. G. 1932: The Braefoot outer sill, Fife. Pt. I. <u>Trans. Edinburgh Geol.</u> <u>Soc.</u> 12, 342-375.

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Holgate, N. 1954: The role of liquid immiscibility in igneous petrogenesis. J. Geol. 62, 439-480.

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Appendix 7: Bulk Chemical Analyses

A7.1: Preparation of Rock Powders

- A. The lower portions of intrusive units 2 5 were divided into equal intervals of approximately 5 cm. and a chip sample (several hundred grams) was taken from each. Large chips were crushed, and those containing xenoliths, or showing signs of iron staining or weathering were rejected. Most of the dust on the chips was blown off, and the rock was pulverized to -300 mesh in an agate grinder. A sample of the lower portion of each intrusive unit was obtained by mixing equal weights of powder from constituent intervals.
- B. Samples of 5 cm. intervals in which analcite symite was present were sawed with a stainless steel blade into slices about 1 mm. thick. The slices were broken, and pieces of analcite symite and host rock (as defined in Appendix 2) were separated manually. An unavoidable bias of this technique is that large analcite symite bodies are probably over-represented. Samples were washed, crushed and ground as in (A).
- C. Samples from intervals devoid of analcite syenite were crushed in a steel jaw crusher, cleaned by air winnow-ing and ground as in (A).

A7.2: Wet Chemical Analyses

Mrs. S. Horska kindly performed wet chemical analyses on samples available at the time. Ferrous iron was determined by the method of Wilson (1955). Since the average

grinding time in air for samples was one minute, a correction of 0.05 per cent was added to each result (Fitton and Gill, 1970). CO₂ was measured by the procedure of Shapiro (1960). A7.3: Sodium and Magnesium (Atomic Absorption).

0.1 g. of each powdered sample was fused with 0.5 g. of lithium metaborate, dissolved in dilute nitric acid, and diluted to the order of micrograms of Na and Mg per millilitre. These solutions were run against standard solutions on a Perkin-Elmer 403 atomic absorption spectrophotometer using an air-acetylene flame.

A7.4: Major Element Analysis (X-ray Fluorescence)

l g. of each powdered sample was mixed with 2 g. of lithium tetraborate, and fused in a graphite crucible. The resulting glass bead was crushed, ground in a Lemaire grinder with ceramic (85 per cent alumina) plates, pressed into pellets with a boric acid backing in a 30 ton press and left to dry at least 24 hours before analysis.

Analyses were performed on a Philips semi-automatic X-ray spectrometer (PW 1220) with a chromium tube, and analyzing crystals, goniometer positions, collimator type and counters appropriate to each element. Three samples and one standard (U.S. Geological Survey standard BCR-1) were analyzed at a time, taking 3 x 10-second counts on Fe, Ti, Ca, K; 6 x 10-second counts on Si and 3 x 100-second counts on P and Al. 3 x 100-second background counts were made near the P peak; the backgrounds of all other readings were obtained from measurements made by Mrs. L. Newbury on pellets composed entirely of lithium tetraborate from the same batch that I used. This technique is expected to largely compensate for errors due to impurities in the Cr tube and in the flux.

Mean count rates were corrected for dead-time and background, and nominal oxide concentrations were obtained by assuming that the ratios (count rate : concentration) were identical in samples and standard. Mass absorption corrections were applied by a computer program employing an iterative procedure (Gunn, 1967) which requires Na to be determined by another technique, but assumes that Mg is measured by X-ray fluorescence. Instead of modifying the program, the Mg concentration measured by atomic absorption was entered, and it was assumed that the error this produced in the calculated mass absorption coefficients was negligible.

Three main processes may have induced within-specimen, within-instrument variations in estimates of concentrations: (a) Statistical (counting) errors.

(b) Changes in physical parameters of instrument components.

(c) Deterioration of the pellet (Leake et al, 1969).

The relative standard deviation of the net counting intensity is:

$$\boldsymbol{\mathcal{E}}(\boldsymbol{\mathscr{E}}) = \frac{100 \sqrt{2}}{\sqrt{T}} \quad \sqrt{\left(\frac{R_p + R_b}{R_p - R_b}\right)} \qquad \text{Equation A2}$$

where R_{p,b} = peak and background count rates respectively. T = sum of counting times on peak and background positions. (Jenkins and deVries, 1967, p. 97) Although the estimated standard deviations of mean peak readings (Table Al2) provide a guide to the expected precision of estimated concentrations (in the absence of pellet deterioration or "drift" within the spectrometer), they are only approximate, since background readings were assumed, not measured. These values may be compared with replicate analyses performed on three pellets (Table Al3); (i) shortly after they were made and (ii) after a year of storage face down on absorbent paper. Nominal concentrations (C_1 and C_2 respectively) were determined for each element, and the percentage drift, e, defined as:

$$e = \frac{2(c_2 - c_1)}{c_2 + c_1} \times 100\%$$

was determined (Table Al3).

C₁ and C₂ were approximated by mean nominal concentrations. Percentage drifts in the concentrations of elements other than Si and Al are considerably larger than expected. There seems to be no consistency in the sense of variation of each element: any deterioration in the sample pellets must have been matched by deterioration in the standard. (According to Mrs. Newbury (pers. comm., 1971), deviations of this magnitude are characteristic of day to day instrumental drift.) The two most important factors causing within-specimen variation were therefore counting errors and, more importantly, instrument drift.

Leake et al (1969) suggested that different sizefrequency distributions of particles in pellets may contribute to inaccuracies in Fe determinations. Mrs. Newbury

has analyzed two pellets made from the same rock powder: one was prepared as described above, the other was only partially pulverized; and found no discrepancies attributable to the grain size factor in estimates of Si, Al, K and P concentrations. Fe and Ti may be affected by several per cent, Ca by as much as 10 per cent. P results have poor accuracy, mostly because of interference from a Ca escape peak and satellite lines. Al measurements may be affected by contamination from the Le Maire grinder.

Leake et al (1969) compared their X-ray fluorescence estimates of major elements with those determined by neutron activation techniques and found relative errors of less than 1 per cent for major elements other than Al, Fe and P. The accuracy of precise estimates obtained by the above method is probably of the same order (L. Newbury, pers. comm., 1971). A7.41: Interference of Ca Radiation With the P Peak

Mrs. Newbury confirmed my suspicion that Ca radiation interferes with the $PK_{\mathbf{x}}$ peak, and established the following empirical equation:

True % $P_2O_5 = 1.54$ (Apparent % P_2O_5) - 0.0277 (%CaO) Trends of P_2O_5 concentrations are little changed by this correction: for example, the slight tendency for P_2O_5 concentrations to increase downwards within the host rock of each intrusive unit remains. The coefficients of correlation between CaO and uncorrected P_2O_5 concentrations, and between CaO and corrected P_2O_5 concentrations in the analcite syenite

of each intrusive unit are 0.98 and 0.94 respectively; both are significant at the 95 per cent confidence level (5 samples). A7.5: Minor Element Analyses (X-ray Fluorescence)

Powdered silica, to which different quantities of "spex mix" had been added, was used for standards. ("Spex mix" contains equal weight percentages of 49 elements, usually present as oxides.) Pellets were prepared by the lithium tetraborate fusion technique, or by pressing powders in the 30 ton press.

A7.51: Manganese

Pellets prepared by the fusion technique were used. (The pellet representing the host rock from 330-335 cm. below the upper contact was broken before it could be analyzed.) The X-ray spectrometer was equipped with a molybdenum tube: preliminary runs showed that interference from the CrK_{β} peak could be safely ignored, and that Mn concentrations were of the order of 1000 p.p.m. A single, 1000 p.p.m. standard was used, and 3 x 20 second counts were made on peak and background positions. Corrections for dead time, background, and absorption were applied by means of a calculator program developed by Mrs. Newbury (the mass absorption coefficient was determined by taking a weighted sum of the estimated percentages of major oxides in the specimen, with weighting coefficients taken from Heinrich (1966)).

Mean relative standard deviations of the counting procedure were estimated from Equation A2:

 $\epsilon_{\text{host rock}} = 0.38\%$

 $\varepsilon_{\text{analcite syenite}} = 0.44\%$

Leake et al (1969) estimated that the accuracy of their Mn analyses (using a tungsten tube) was about 0.02 oxide weight per cent.

A7.52: Rubidium, Strontium, Zirconium and Niobium

These analyses were performed on pellets made by pressing pure rock powders. (However, because of shortages in the quantity of host rock powder from 0-5 cm. and analcite syenite powder from 97.5 -100 cm. below the upper contact, pellets of these powders prepared by the fusion technique were analyzed.) The Cr tube on the spectrometer was used so that Rb, Sr, Zr and Nb could be analyzed during the same run, and a single standard was employed to save time: preliminary measurements showed that a 200 p.p.m. standard was the best compromise. Optimum count times (for abcut 2 per cent precision) were determined from Equation A2, and samples and standards were analyzed as follows:

> Background position #1 (3 x 20 second counts) Nb (K $_{eff}$) peak (3 x 40 second counts) Zr (K $_{eff}$) peak (3 x 10 second counts) Y (K $_{eff}$) peak (3 x 10 second counts) Background position #2 (3 x 20 second counts) Sr (K $_{eff}$) peak (3 x 10 second counts) Rb (K $_{eff}$) peak (3 x 20 second counts)

(The concentration of Y could not be determined because it is not present in Spex mix.) Readings were corrected for dead-time, background, interference from other peaks, and absorption, with a calculator program that had been developed by Mrs. Newbury (Webber and Newbury, 1971) as follows:

Ratios of intensities of continuous radiation at wavelengths corresponding to peak and background positions were measured on a silica "blank" pellet. The background under each Nb peak is estimated by multiplying the reading at background position #1 by the appropriate ratio; background position #2 is used to estimate Zr, Sr and Rb backgrounds.

The ratio of the intensity of the Sr (K_{α}) peak to that of the Sr (K_{β}) peak at the $Zr(K_{\alpha}$) peak position was determined from a silica "blank" spiked with Sr, and is used in the program to estimate Sr (K_{β}) interference with Zr (K_{α}). Y(K_{β}) interference with Nb(K_{α}) is similarly determined.

It was assumed that the mass absorption coefficient (M / ρ) is inversely proportional to the intensity of continuous radiation at a given wavelength (Jenkins and de Vries, 1967, Chapter 6). Regression coefficients of a line run through a plot of log ((count rate at the background position on the standard) \div (count rate at the background position on a silica blank)) versus log (M / ρ) (from published results) for nine rocks, including six U. S. Geological Survey standard rocks, are used to estimate (M / ρ) .

Because of interfering peaks and the high (d(background intensity)), it is difficult to make a better (d(wavelength))) 79

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estimate than "about 2 per cent" for the counting error, although a comparison of my analyses of U.S. Geological Survey rocks with published analyses (Table Al4) gives an idea of the combined accuracy and precision of the technique. The deviations for Nb are similar to betweenworker deviations reported by Flanagan (1969), but my results are probably more accurate because Ste. Dorothée rocks contain higher Nb concentrations. 80

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Appendix 8: Calculation of the Chemical Composition of

Each Intrusive Unit, and of the Entire Sill.

Interpolations and assumptions made in constructing Tables 6 to 8 were:

- (i) Only analyses 5 to 8 (Table 5) were used in estimating the compositions of the lower portions of intrusive units 2 to 5 respectively.
- (ii) The composition of the sample from 385-390 cm. below the upper contact was assumed to be typical of the analcite sympite of the lower portion of the sill.
- (iii) The FeO concentration in the host rock from 0-5 cm. was estimated by assuming that it had the same Fe²⁺/Fe_{total} ratio as that of analysis number 1, Table 5.
 - (iv) Differences between estimated average compositions of the rock types of the sill and 100 per cent (2.22 per cent, host rock; 3.67 per cent, analcite syenite) can be attributed to experimental errors and unanalyzed components, of which H_2O^+ and S are the most important (Philpotts and Hodgson, 1968; Philpotts, 1971).

Appendix 9: Minor Element Distributions

I propose to demonstrate that a mineralogical control of the trace element distribution is qualitatively consistent with observed patterns.

Trace elements selectively concentrated in the host rock are Mn and probably Zr; Rb and Sr are selectively concentrated in the analcite syenite, and Nb is variable (Tables 6 and 7). Distributions produced by a mineralogical control would be:

<u>Mn</u> would probably be enriched in the host rock because it is most readily camouflaged by Fe^{2+} , Ca^{2+} and Mg^{2+} (for example, Gold, 1963).

Rb Because of its well-known diadochy with K, Rb would be enriched in the analcite syenite.

Sr Feldspar and apatite are the only minerals known to have Sr partition coefficients greater than one (Vlasov, 1964; Walker, 1969; Philpotts and Schnetzler, 1970). Unless the Sr content of apatite is extremely high (which is unlikely, since Sr-Ca diadochy is limited (Eskola, 1922; Nockolds and Mitchell, 1948; Turekian and Kulp, 1956; Vlasov, 1964; Ferguson, 1970)) Sr would be concentrated in the feldsparrich analcite syenite.

<u>Zr</u> has a tendency to concentrate in residual, alkaline melts (Borodin and Gladkikh 1967; Dietrich, 1968; Yagi, 1970; Ferguson, 1970) but may be camouflaged by Fe³⁺ (Wilkinson, 1959). Zr could be concentrated in either rock type.

Nb is concentrated in residual melts (e.g. Butler and Smith, 1962) largely because it forms complexes with CO₂

(Aleksandrov, Trusikova and Tupitsin, 1969). The lack of correlation between CO_2 and Nb concentrations implies that this complexing has not occurred, perhaps because much of the CO_2 was introduced to the magma after the bulk of the Nb had precipitated. Since sphene, which crystallized early and is more abundant in the host rock (Philpotts and Hodgson, 1968) may contain enough Nb (Table All) to account for the Nb content of the entire rock, Nb would be expected to be relatively concentrated in the host rock.

Appendix 10: The Activity Coefficient of Sr in Magmas

With PH20 **4** 0.5 Kb.

Consider a magma from which plagioclase is precipitating. At any instant,

$$D_{Sr} = \frac{Sr_{(p)}}{Sr_{(m)}} = \frac{a_{Sr}_{(p)}}{a_{Sr}_{(m)}} \cdot \frac{r_{Sr}_{(m)}}{r_{Sr}_{(p)}} \cdot (Equation 3)$$

where: D_{Sr} = the partition coefficient of Sr.

Sr , a_{Sr} , γ_{Sr} = concentration, activity and activity coefficients of Sr in the subscripted phase (p = plagioclase, m = melt).

At equilibrium:

Meas

$$a_{Sr} = a_{Sr}$$

 $\mathbf{\hat{r}}_{\text{Sr}_{(p)}}$ is a function of pressure, temperature, and plagioclase composition. Because the composition of plagioclase closely approximates a linear function of temperature of formation for a wide variety of rock types, and partial pressures of water up to 0.5 Kb. (Kudo and Weill, 1970), it can be assumed for volcanic plagioclases that $\Upsilon_{Sr(p)}$ is a function of feldspar composition alone. Equation A3 can be rewritten:

 $D_{Sr} = \Upsilon_{Sr_{(m)}}$, \emptyset (plagioclase composition) where \emptyset is an unknown function. Arbitrarily selecting albite and orthoclase percentages as the two independent variables defining compositions in the system An - Ab - Or:

$$D_{Sr} = \boldsymbol{\gamma}_{Sr} \cdot \boldsymbol{\mathscr{O}}(Ab, Or)$$

Measurements by Philpotts and Schnetzler (1970), who
determined D_{Sr} for 10 plagioclases ranging from

Ab_{3.2}An_{96.7}Or_{0.4} to Ab_{50.5}An_{45.8}Or_{3.6} in volcanic rocks ranging from dacite to alkali basalt, may be related by the multiple regression equation:

 $D_{Sr} = 0.0273 (Ab) + 0.0297 (Or) + 1.152$ (The coefficient of multiple correlation is 0.95). This suggests that γ_{Sr} in melts crystallizing anorthite-rich plagioclase is nearly constant over a wide range of temperatures and rock compositions, and that the function \emptyset is approximately linear. The relationship breaks down for alkali-rich feldspars (see, for example, Carmichael and McDonald, 1961; Berlin and Henderson, 1969; and Philpotts and Schnetzler, 1970)).

Appendix 11: Symbols

All.1:	5	symbols Used in Chapter 2 and Appendices 1 and 2.
с	=	any component: analcite syenite, host rock,
		or xenoliths.
e ²	=	variance estimate of the volume percentage of
6		component c, assuming a binomial distribution.
i	=	designates successive intrusive units, 1 to 6.
' _i	-	T _{u,i} /T _i (q.v.)
j	-	the distance, in cm., of the bottom of an interval
		from the upper contact, divided by the interval
		size: 5 cm.
^m c	=	the number of replicate analyses of component c
		included in later statistical calculations.
^N c,j,k	=	mean of the total number of counts made on each
		slab.
Noc	=	in any interval, the total number of counts made
		on the slab with the largest number of counts,
		divided by the number of counts on the other slab.
Noc	=	mean value of N _{OC} in the entire sill.
κ ²	=	pooled sample variance resulting from replicate
C		counts of component c.
∧o ² Sc,j,k	==	variance of a replicate pair of analyses of com-
		ponent c on slab k in interval j.
$^{\mathrm{T}}$ i	=	Ti,u + T _{i,e} (g.v.)
^T i,u	H	estimated mean thickness of the upper portion of
		the upper portion of intrusive unit i.

<u>'</u>

- Ti,e = measured thickness of the lower portion of intrusive unit i.
- $V_{c,i,u}$ = estimates of the volume percentage of component c,
- V_{c,i,e} in the upper and lower portions, respectively, of intrusive unit i.
- V_{c,j} = estimate of the volume percentage of component c in the jth interval.
- $V_{c,t}$ = estimate of the average volume percentage of component c in the sill, excluding the "central zone".
- $\beta_{c,j,k}$ = estimate of the volume percentage of component c in slab k of the specimen from interval j (k = X or Y).

 $\overline{\beta}$ c,j,k = 1/2 (β c,j,kl + β c,j,k2) β c,j,kl;= are the routine, and replicate analysis estimates β c,j,k2 of the percentage of component c of slab k in interval j.

All.2: Symbols Used in Appendix 5.

d.f. = degrees of freedom.

- t_t = a statistic used in an approximate test of the hypothesis that the sum of weight percentages in

100 per cent.

 x_i (i=1...n) = a typical electron microprobe reading.

<u>Plate 1:</u> <u>The phenocryst ledge 422 cm. below the upper contact</u> (here labelled 414 cm.). Two irregular analcite symmite veins can be seen in the lower portion of the photograph.

Plate 2: Electron microprobe scanning image (350 magnification, Al K_{er} radiation) of a portion of an amphibole in which sector zoning was observed. The dark band near the top of the picture is the Al-poor rim of the amphibole, which grades downwards into material richer in Al. A wedge of turbid analcite is present in the upper left-hand corner. The nearly vertical, dark regions are surface cavities, and the apparent decrease in the intensity of radiation at the bottom is due to defocussing of the beam. A sector zone boundary runs from the lower left to the upper right corner of the photo, but in this picture (and in the pictures of Ti K_{er}, Fe K_{er} and Si K_{er} radiation) there is no apparent compositional difference between sectors.

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Plate l

Plate 2

<u>Plate 3:</u> The contact between intrusive units 4 and 5, 95-100 cm. below <u>the upper contact</u>. (The plane of the photograph is vertical.) Material above the contact is coarser-grained and appears to be more felsic than that below; and the usually sharp contact is gradational at the extreme right of the picture.

Light coloured bodies are composed of analcite syenite; dark, finegrained objects are xenoliths.

<u>Plate 4: "Type B body" from 112.5 cm. below the upper contact</u>. Light yellow green pyroxene (light grey) rims a zone of felsic material (mostly analcite and plagioclase, nearly colourless) and a calcite core (dark grey) which is cracked, veined and brecciated by the "felsic material". (Plain light).





Plate 4



<u>Plate 5: A "mafic aggregate" from 257.5 cm. below the upper contact</u>, most of which is composed of crystals of pyroxene resembling normal pyroxene phenocrysts of the host rock. (Plain light).

<u>Plate 6: Part of an analcite symmite body from 107.5 cm. below the upper</u> <u>contact</u>. The augites which make up the elongate aggregate of fine-grained crystals running across the middle of the picture are optically very similar to those composing the rims of carbonate xenoliths, and are distinct from normal analcite symmite pyroxenes. (crossed nicols).



l cm.

Plate 5

l cm.

Plate 6



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Plate 7

Plate 7: Felsic material, characteristic of the interior of "type B" and "C" bodies, is found on both sides of this "blister" on the rim of a "type B body" from 142.5 cm. below the upper contact. (Plain light.) <u>Plate 8:</u> Intermingling of analcite syenite and "felsic material" in a "type C body" from 107.5 cm. below the upper contact. The feeder vein is connected with an analcite syenite body several mm. away, and flow structures are defined by titanomagnetite crystals."Felsic material, probably mixed with analcite syenite that had entered the xenolith via another vein, has apparently flowed through the breach in the pyroxene rim, mixed with more analcite syenite, then flowed out the "possible exit" into another vein less than 1 mm. thick. (Plain light).



Plate 8



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Imm.



1 mm •

Plate 9: A blister in the side of a "type B body" from 152.5 cm. below the upper contact. Remains of three concentric pyroxene rims can be seen: the blister appears to have formed from a breach in the middle rim. "Felsic material" is light grey, and the carbonate (centre left of the picture) appears patchy. (Plain light.) Plates Al-Al8: Additional photographs of portions of the sill.

Plate Al: <u>A general view of the Laurin quarry exposure of the Ste.</u> <u>Dorothée sill</u>.

Plate A2: <u>The exposed upper surface of the sill</u> showing small, spherical felsic bodies ("ocelli").



Plate Al

Plate A2



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Plate 14 : Part of the vertical quarry face.

Lines show the depth below the upper contact in cm. Light-coloured bodies of analcite symmite are clearly visible. <u>Plates A5 and A6</u>: Just below the number "126" (cm. below the upper contact), <u>a semicontinuous to continuous syenite sill, averaging about 1 mm. thick, can</u> <u>be seen to connect analcite syenite bodies (with flat upper surfaces)</u> <u>separated by several centimetres</u>. Cavities are weathered xenoliths. Note the vertical jointing.



Plate A5



Plate A6

<u>Plate A7</u>: <u>The horizontal symite sill at 190 cm</u>. which forms the upward termination of the "central zone of subvertical symite veinlets". Note the carbonate-filled vertical joints.

<u>Plate A8:</u> <u>Part of the "central zone"</u>. White streaks are syenite veinlets. (13 cm. of the tape is exposed.)


Plate A7



Plate A8

<u>Plate A9</u>: <u>Horizons in the lower portion of the sill</u> (the scale at the right-hand side refers to the depth below the upper contact assigned each structure in Fig. 2).

<u>Plate A10</u>: <u>The syenite sill at 389 cm. below the upper contact</u> (here labelled "382 cm.": the inconsistency is due to minor variations in different portions of the sill). The phenocryst ledge at the base of intrusive unit #4 terminates about 1 cm. below the sill.



Plate A9

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Plate AlO

<u>Plate All: "Type A body" from 142.5 cm. below the upper contact</u>. Calcite crystals are stained pink, the fine-grained green material is mostly augite, and the nearly clear material is feldspar, analcite and turbid analcite. (Plain light).

<u>Plate A12</u>: <u>Part of a "type B body"</u> from 142.5 cm. below the upper contact. Cracks between and through the original, concentrically zoned calcite grains (stained pink) are filled with felsic material and fine-grained light green augite. (Plain light).



l mm.

Plate All

<u>Plate A13</u>: <u>Augite rim on a "type C body"</u> from 162.5 cm. below the upper contact. The features shown are typical of type B and type C bodies. Note especially the inwards increase in the size of the augites. (Plain light).

<u>Plate Al4</u>: Detail of augites from the rim of the body depicted in Plate Al3. Note the inward increase in grain size, and change in colours. (Plain light).



1 mm.

Plate Al4



Plate A15: "Type C body" from 47.5 cm. below the upper contact. The greencored augite crystal depicted in Plate A16 can be seen in the upper lefthand margin (arrowed). (Nicols at 45° to one another.)

<u>Plate A16</u>: <u>An unusual, green-cored augite, from 47.5 cm. below the upper</u> <u>contact</u>, which occurs within the alteration corona of a type C body. (Plain light).



<u>Plate A17</u>: <u>A "mafic aggregate", which appears to have been sheared</u>, composed of pyroxene, (pink-rimmed, green-cored titanaugite) with some hornblende and sphene, from 272.5 cm. below the upper contact.

<u>Plate Al8</u>: <u>A thin section of rock from 147.5 cm. below the upper contact</u>. The "type B body" at centre is composed dominantly of "felsic material" (light grey-brown) and calcite (stained pink); some of which appears to have spewed into the host rock. Above this body is a calcitic mudstone, to the right an analcite syenite body, and below is another "type B body" containing quartz grains. (Crossed nicols).





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Fig. 2: A pictorial representation of the sill.

The proposed correlation of zones within the sill as upper and lower portions of successive intrusive units is shown at right. Numbers assigned each unit (i) refer to the suggested order of emplacement.

Data from 0-275 cm. below the upper contact is from slab analyses; other data was obtained from in situ studies.

Discrepancies between this figure, Fig. I-B (Philpotts and Hodgson, 1968) and Fig. 1 (Philpotts, 1971) are due to minor irregularities in the sill.

Key to Fig. 2. The bars in histograms representing analcite syenite and xenolith volume percentages are the only symbols with quantitative significance.

Meaning:











Used to form histograms representing volume percentages in each 5 cm. interval.

Semi-continuous to continuous syenite sill averaging about 1 mm. thick, connecting analcite syenite bodies separated by several cm.

Mafic phenocryst ledge. Lower contact is sharp, upper contact gradational, with a decrease in phenocryst size and frequency.

Sill of syenite, 1 mm. to 1 cm. thick: continuous over the entire exposure (in the case of in situ analyses) or over the entire slab (in the case of slab analyses).

Internal contact. The vertical range over which the contact is drawn represents the range in positions occupied by the contact. The arrow indicates the coarser-grained, more felsic side of the contact.



Mineral Thin Section	Are 2 generations of	Pyroxene	Hornblende	Opaques	Does plagioclase occur as phenocrysts?	Plagioclase	Potash feldspar	Analcite	Natrolite	Sphene	Apatite	Calcite	Dolomite	Name of the host rock *
UPPER CONTACT			\succ				\sim	\sim	\sim			\sim		F
12.5 cm			\sim	\bowtie		\bowtie	\bowtie	\bowtie	?	\bowtie		\sim		T
30 cm		\sim	\sim	\bowtie		\bowtie		\bowtie	??	\bowtie	\times			T
Just above the contact			\sim	\bowtie		\bowtie	${ \times }$	\mathbb{X}		\sim	\sim			T
Contact zone														
Just being the centect			\sim	\bowtie		$\overline{\mathbf{X}}$		\bowtie		\bowtie	\bowtie			T
CONTACT 57-5 cm.		Γ												
62.5 cm.		\sim	\mathbb{N}	\bowtie		\bowtie		\times	${ \times }$	X	\mathbf{X}	\bowtie		F
CONTACT 75-82 cm														
87.5 cm			\sim	\times		\mathbf{x}		\mathbf{X}	\mathbf{X}	\mathbf{X}	\times	\mathbf{X}	Л	F
CONTACT 95-100 cm		—	T											
107.5 cm.				\bowtie		\mathbf{X}		\mathbf{X}	\times	\times				T
127-5 cm.		\sim	K	$\overline{\mathbf{X}}$	\geq	\mathbf{X}	V	\mathbf{X}	\mathbf{X}	\mathbf{X}	X	$\boldsymbol{\times}$		T
142.5 cm.		\bowtie		\mathbf{X}		\mathbf{X}		\mathbf{X}	\mathbf{X}	\times	\mathbf{X}	\mathbf{X}		T
CONTACT 150-55 cm.														
160 cm		\sim												T
187-5 cm														T
191 cm.		$\mathbf{\Sigma}$												
210-215 cm.			\bowtie	X		X	\mathbf{X}	X	\mathbf{X}	X		\mathbf{X}		T
244 cm.			\triangleright					X	\geq					T
270-275 cm.													7	T
CONTACT 275 cm														
359 cm			\sim	\sim					\sim					F
CONTACT 363 cm														
365-390 cm	\sim											\geq		F
CONTACT 390 cm														
400-405 cm.														T
CONTACT 420 cm.														
435-440 cm.														T
480-485 cm	/													T
CONTACT 516-5 cm.												T		
516 cm	/	\succ	\bowtie	\succ		\mathbf{X}		\times	\geq	\mathbf{x}	\mathbf{X}	\mathbf{x}		T
560 cm	/		\times	\succ		\succ	?	X		\mathbf{X}			\square	T
570 cm	/									\geq				F

Fig. 3: Mineralogy of thin sections.

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Slashes sloping upward and downward to the right indicate the presence of a feature in the host rock or analcite syenite respectively.

Question marks in the right and left of each box indicate the possible presence of a feature in the host rock or analcite symmite respectively. T = teschenite; F = fourchite (Johannsen, 1938). 121

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Fig. 4: (top): Generalized order of crystallization (host rock at left, analcite syenite at right) inferred from thin sections. Shading in boxes shows ranges of uncertainty in the temperature at which a mineral began, or ceased to crystallize.

(bottom): <u>Alteration processes</u> (host rock at left, analcite syenite at right) inferred from thin sections. Products are represented by filled-in boxes whose lengths indicate the range of temperatures over which they could have been formed. Alteration of amphibole and titanomagnetite to hematite and pyrite is not shown.

Fig. 5: Comparison of amphibole compositions.

Compositions were measured at one or two spots ("core" near the geometric centre, "rim" near the edge of a crystal) on each amphibole. The precision of each concentration estimate is depicted by a pair of crosses whose spacing represents 95% confidence limits obtained from an approximate standard deviation (s_j) of electron microprobe readings.

Distances at the top of each column specify the depth below the upper contact of each thin section.

Low total weight percentages of each analysis are probably due to inadequacies in the correction procedure.



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95% confidence limits of the weight percentages of oxides in the "Mineral number 2": +.....+. "Mineral number 3": Ste. Dorothée sphenes. cores and rims of various ř "Mineral number 1": x-• • J 6 KEY: с; Ш



<u>Fig. 6 b</u>: 95% confidence limits of the weight percentages of oxides in the cores and rims of various Ste. Dorothée sphenes.

> "Mineral number I": x-----X "Mineral number 2": +-----+ "Mineral number 3": @-----

KEY:

Fig. 7: Trends of Fe concentrations in four amphibole crystals, determined by electron microprobe traverses.

Crosses represent 10 sec. counts on successive spots along a traverse; circles represent a second traverse at right angles to the first, and triangles a third traverse along a line parallel with, and 2 μ from the first traverse. The horizontal (but not vertical) spacing between readings of different traverses in the bottom two profiles have been adjusted.

The dotted lines were drawn subjectively, and are considered to enclose actual variations with a high degree of confidence. Similar relationships were found among the A1, Ti and Si profiles of the four minerals.

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Fig. 7.

Fig. 8: Major element variations in the host rock.

Crosses represent analyses of 5 cm. intervals, asterisks represent



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analyses of entire lower portions of intrusive units 2 to 5.

Depth below upper contect	Intrusive wait	Element Mn 1500 2000	t concentr Rb 30 40 50 60 70	ations (p. Sr 1900 2000	p.m.) Zr 190 ²⁰⁰ 390 ⁴⁹⁰ 500	N b \$0 100
25	1	Ţ			1	
50	2	1	P		×	
75	3	1		1		
100	4		*			*
125	5	5				Í
150		7				
200	6	7	ĸ	×		ĸ
225		/				
250		†				
275						
300						
325	5					
360			·			
375	4	×				
400	3	ж				
425		¥				
450		<u>}</u>				
475	- ا		×	×	×	×
500						
525		Ţ				
550		L	1	Ţ	Ĭ	Ĭ



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(same symbols as Fig. 8)

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upper conti	intrusive unit	Oxide CO2	concent NazO	trations (1 MgO 10 20 30	weight %) Al203	SiO2 45 50	P205 05 10	K2O 20 30	CaO 5 10 15	Tí O ₂	Fe0	Fe as FezO3
25	1	*	¥				Ъ	a ₁₀	Aur	9 14-14	ħ.	*
٥Ĺ	2		7	L			1	\leq	1	1		1
5	3	1	1	1	1	<u>``</u>	1	<u> </u>	1	1	1	1
٥ł	4	l.	7	7.	7	<u> </u>	Ŧ			7	7	7
5	5							\leq		·	/	
5						. •			_			
00	6		\		· 1	Ι	\mathbf{N}					
50												
75		+						· · · · ·				
00 25	5											
50												
75	4			×	я		8	•			· .	
~	3											
25 -												
75	2									1. 1.		
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Bepth below upper contact	Intrusive unit	Elemen Mn 1500 2000	1t concent Rb 20 40 50 60 70	trations (Sr 1500 2000	p.p.m.) Zr	Nb 50 100
25 -	1	%		*	•Sr ×4	
50	2	J	×	×	×	×
75	3	1		1	1	1
100 -	4	*	*		\$r&	×
125 -	5					
150-		<u> </u>	<u> </u>	*	·····	·····
175 -						
200 -	6	/				
225		-	*		-	
250						
275 -						
300 -						
325 -	5					
350 -						
375	4	_				
400	3					
425						
450 .						
475	2					
500						
525						
550						



(same symbols as Fig. 8)

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 K_2^0 in every rock, hence analyses were recalculated in terms of K_2^0 , Si0₂, and Fe0). All points grouped near the Si0₂ apex represent analcite syenite analyses, those around the line AA' represent host rock analyses. AA' separates rocks from above 215 cm. (above the line) and those from below 215 cm. below the upper contact. (Phase relations after Roedder, 1951.)



<u>Fig. A1</u>: Situation in which the centre of the interval has been located with maximum error.



---- Sector zone boundaries defined by changes in extinction position.

Lines defined by oscillatory zoning, interpreted as representing successive crystal boundaries.

- Location of quantitative electron probe analyses.
- Strike, (and dip direction of cleavages)

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BODT COLOOKS.	Core	Shar	o contact	Rim	Edge
'Hourglass' zone	Green ligh	nter	Light pink	-brown	darker
Rest of crystal	Brown-c	reen	Pink-brov	vn <u>darke</u>	6



Fig. A3: 191PX, a pyroxene from an analcite syenite lens 190-195 cm. below the upper contact.





Fig. A5 A sketch of 272.5PX-2, a pyroxene phenocryst from 270 - 275 cm. below the upper contact. The symbols used are the same as in Fig. A2 N.B. The zoning in this crystal, as defined by differences in colour, birefringence and extinction position, is very patchy. Hence, this diagram shows a generalized picture of the

essential features of the crystal. <u>Body colours</u>: Most of the crystal is brown-pink, with the wedgeshaped sector zones slightly darker, and the rim zone darker again.

Fig. A6: <u>Compositions of Ste. Dorothée pyroxenes in terms of mole</u> <u>proportions of Ca, Mg, and $\Sigma Fe = (Fe^{\overline{III}} + Fe^{\overline{II}} + Mn)$ </u>. Dotted, arrowed lines join successive compositions in one crystal or sector zone; full lines join portions of different sectors that are assumed to have been deposited simultaneously.




<u>Fig. A8</u>: Projection of Ste. Dorothée rock compositions onto the plane Na AlSiO₄ - KAlSiO₄ - SiO₂. Isotherms on the liquidus surface at $PH_2O = 1000 \text{ kg/cm}^2$ from Hamilton and Mackenzie (1965).

X Host Rock. Ø Analcite Syenite.



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Fig. A9 (a and b): Electron microprobe traverses of titanomagnetites

from 50-55 cm. below the upper contact. Each reading is indicated by a cross. Lines join successive readings when Ti and Fe readings change in opposite senses; when counts on Ti and Fe change in the same sense, the crosses are boxed together.

The analcite syenite titanomagnetite is composed of two intergrown crystals whose common boundary is approximately at the central (9th reading from the left) dip in Ti concentrations.





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<u>Fig. A10:</u> Solid solution ranges of natural minerals in the system Ne-Ks-Qz. (After Kim & Burley (1971a)). Circles represent analyses of Ste. Dorothée analcites.



Table 1 : Results of point-counting slabs from the sill:

(a) the modal composition of each 5 cm. interval.

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Table 1A				
DEPTH BELOW UPPER CONTACT (CM.)	HOST ROCK PERCENTAGE	ANALCITE SYENITE PERCENTAGE	XENOLITHS PERCENTAGE	NOC (SEE APPENDIX 2.2)
0- 5	00 5	0.5	0.0	1.08
0 J 5 10	99.J	0.5	0.0	2.09
0- 10	57.4 00.7	0.0	0.0	1,20
10-15	99.7	1 7	0.0	1,10
15- 20	90.4	1./	0.0	1.66
20-23	33.0	0.4	0.0	2.17
25- 30	99.8	0.2	0.0	1.10
30- 35	99.1	1 4	0.0	1.66
35- 40	90.0	7 7	0.0	1.30
40- 45	92.3	7.7	0.0	1 12
45- 50	92.7	12.0	0.0	1 04
50- 55	88.0	12.0	0.0	1.04
55- 60	91.4	0.7	0.0	1 09
60- 65	91.0	9.0	0.0	1 20
65- 70	92.8	1.4	0.0	1 28
70- 75	95.3	4.4	0.5	1 49
75- 80	93.5	0.4	0.0	1 17
80- 85	92.1	/.8	0.1	1.17
85- 90	93.2	0.8	0.0	1 22
90- 95	98.5	1.5	0.0	1 15
95-100	96.8	2.3	0.9	1.07
100-105	93.3	5.1	1.0	1 10
105-110	88.4	11.0	0.7	1 11
110-115	94.6	2.3	3.0	2 90
115-120	99.1	0.5	0.4	1.07
120-125	99.3	0.5	0.2	1.07
125-130	93.8	6.2	0.0	1.20
130-135	91.1	5.3	3.5	1.00
135-140	95.8	4.2	0.0	1.04
140-145	92.9	5.5	1.0	1.45
145-150	87.5	6.3	6.2	1.29
150-155	93.7	2./	3./	1.12
155-160	95.0	2.8	2.3	1.13
160-165	94.4	1.4	4.2	1.49
165-170	64.2	1./	34.1	1.10
170-175	93.9	0.3	5./	1 47
175-180	99.2	0.5	0.2	1 70
180-185	99.5	0.5	0.0	1 16
185-190	99.2	0.8	0.1	1.10
190-195	98.8	0.5	0.7	1 21
195-200	95.1	4.9	0.0	1 /5
200-205	90.0	3.0	0.2	1 08
205-210	97.0	3.0	0.0	1 13
210-215	90.7	3.3	0.0	1 10
213-220	97.0	2.2	0.0	1 41
220-223	90.9	2.0	0.1	1.27
220-235	5/.0 06 0	2.1	1.1	1,59
230-233	70.7 07 5	2.0	0.0	1,18
233-240	5/.J 06 /	2.5	0.4	1.28
240-243	90.4 07 7	2.1	0.2	1.85
245-255	99.5	0.2	0.2	1.62
255-260	00 Q	0.1	0.0	1.13
260-265	99.9	0.2	0.2	1.08
200-205	100 0	0.0	0.0	1.00
270-275	99.4	0.0	0.6	1.60

Table 1 : Results of point-counting slabs from the sill:

(b) statistics pertaining to the entire sill.

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Table	1b
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Component	Host Rock	Analcite Syenite	Xenoliths
Percentage in the entire sill	96.5	2.2	1.3
Percentage in the entire sill less the "central zone"	97.2	1.8	1.0

The number of points (in a rectangular grid, with a 1 mm. spacing) counted in the entire sill, and in the entire sill less the "central zone" were 645,505 and 442,762 respectively.

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<u>Tab</u>	le 2:	Modal A	nalyses	and Di	mensions	of each	intrusive u	nit of the	sill.
i	^T i,u	^T i,1	^T i,t	I _{i .}	V _{sye,i}	^V xen,i	V _{sye} ,i,u	V _{xen,i,u}	V _{xen,i,l}
1	38.75	54.5	93.3	0.416	0.207	0.013	0.499	0.031	0.000
2	18.49	93.5	112.0	0.165	1.377	0.090	8.341	0.006	0.107
3	20.01	32.0	52.0	0.385	2.737	0.219	7.115	0,069	0.313
4	20.20	26.5	46.7	0.433	2.261	0.108	5.227	0.024	0.189
5	55.04	88.5	143.5	0.384	1.774	0.579	4.626	1.765	0.169
6			122.5		1.701	2.128			
			570.0						

where

i = the number assigned to each intrusive unit.

T_{i,u}; T_{i,1} = estimate of the mean thickness of the upper and lower portions respectively, of intrusive unit number i (cm.).

 $T_{i,t} = T_{i,u} + T_{i,l}$

 $I_i = (T_{i,u}/T_{i,t})$; the position in each intrusive unit where it apparently separated to admit the following unit.

"sye" and "xen" are "analcite syenite" and "xenoliths".

V_{C,i} = estimated volume percentage of the subscripted component in each intrusive unit.

V_{c,i,u}; V_{c,i,1} = estimated volume percentage of the subscripted component in the upper and lower portions of each intrusive unit respectively.

Table 3 Compositions of samples of host rock.

(CO₂ and FeO by wet chemical analysis, Na₂O and MgO by atomic absorption; all other oxides by X-ray fluorescence spectrometry.)

Total 1: The total weight percentage of Na_20 , Mg0, Al_20_3 , $Si0_2$, P_20_5 , K_20 , Ca0, Ti as Ti0₂, Mn as Mn0, and Fe as Fe_20_3 .

Total 2: Total 1 plus weight percentages of Rb_2^0 , Sr0, Zr as $Zr0_2$, Nb as $Nb_2^00_5$ and $C0_2$, minus a correction for Fe0.

N.A. = not analyzed.

Depth: The depth below the upper contact of a sample (in cm.).

i = the number of the intrusive unit from which the sample was taken. Table 3 Compositions of samples of host rock

	SiC	2 ^{Ti0}	2 ^{A1} 2 ⁰ 3	Total Fe as ^{Fe} 2 ⁰ 3	Fe0	Mn	Mg0	Ca0	Na20	к ₂ 0	^P 2 ⁰ 5	^{C0} 2	Nb	RЪ	Sr	Zr	Total l	Total 2
Depth i	I	Wei	ght Percer	tages	I	(?PM)	I	Wei	ght Pe	rcentage	25		[P]	PM		ſ	
0-51	44.	60 3.4	4 16.83	11.14	1.00	2274.	2.92	9.32	5.63	2.38	0.72	N.A.	110.1	66.5	1415.	507.9	97.27	97.39
10-15 1	44.	96 3.4	1 16.75	10.93	N.A.	2111.	2.83	9.86	4.95	2.30	0.81	N.A.	N.A.	N.A.	N.A.	N.A.	97.07	N.A.
25-30 1	45.	18 3.5	0 16.96	11.01	5.03	2101.	2.92	9.59	4.96	2.27	0.80	0.38	144.7	48.8	1620.	472.1	97.46	97.40
40-45 2	43.	05 3.5	9 16.06	11.13	N.A.	2158.	3.00	9.73	4.85	2.05	0.86	N.A.	N.A.	N.A.	N.A.	N.A.	94.60	N.A.
50-55 2	44.	92 3.7	0 16.39	11.56	N.A.	2159.	3.03	10.43	5.47	2.06	0.82	N.A.	N.A.	N.A.	N.A.	N.A.	98.66	N.A.
55- 57.5 2	43.	93 3.5	5 15.79	11.36	4.94	1989.	2.90	10.29	5.13	2.25	0.83	1.40	142.6	46.8	1298.	446.9	96.29	97.22
65-703	42.	74 3.7	3 15.75	11.64	4.92	2047.	1.13	11.20	7.76	1.93	0.90	1.90	145.5	40.4	1367.	477.2	97.04	98.49
75-80 3	42.	80 3.7	3 16.32	11.54	5.20	2065.	3.30	11.02	5.00	1.90	0.87	1.20	134.3	36.2	1369.	472.8	96.75	97.45
85-90 4	43.	46 3.5	8 16.15	11.38	5.47	2188.	3.09	10.25	4.99	1.96	0.88	4.70	142.9	39.9	1476.	475.1	96.02	100 20
95-100 4	44.	06 3.6	4 16.13	11.48	N.A.	2158.	2.99	10.69	4.98	2.03	0.91	N.A.	N.A.	N.A.	N.A.	N.A.	97.19	N.A.
95–1 00 5	45.	37 3.3	5 17.59	10.51	4.64	2132.	2.92	9.77	5.07	2.05	0.81	1.00	136.1	40.5	1350.	472.1	97.72	98.30
105-110 5	45.	20 3.4	2 17.08	10.72	5.08	2355.	2.90	10.02	4.71	2.26	0.87	0.65	137.6	44.0	1611.	463.4	97.48	97.68
115-120 5	44.	42 3.6	5 16.13	11.35	N.A.	1941.	2.86	11.00	4.73	2.28	0.90	N.A.	N.A.	N.A.	N.A.	N.A.	97.57	N.A.
125-130 5	43.	42 3.7	3 16.04	11.54	5.54	2100.	2.96	11.30	4.63	2.24	0.93	2.05	131.7	44.4	1349.	424.1	97.06	98 56
135-140 5	44.	23 3.3	6 16.73	10.71	N.A.	2026.	2.93	10.25	4.72	2.33	0.72	N.A.	N.A.	N.A.	N.A.	N.A.	96.24	N A
145-150 5	45.	14 3.4	1 16.42	10.85	5.02	2024.	2.92	10.51	4.42	2.59	0.90	0.58	132.9	50.5	1444.	416.2	97.42	07 52
150-155 5	-43.	03 3.5	3 16.03	11.11	N.A.	1676.	2.36	10.85	4.96	3.05	0.87	N.A.	N.A.	N.A.	N.A.	N A	96 01	N A
155-160 6	44.	66 3.5	0 16.07	10.99	N.A.	1923.	2.90	10.58	4.77	2.29	0.88	N.A.	N.A.	N.A.	N.A	N A	06 80	N.A.
170-175 6	43.	32 3.7	2 15.79	11.70	N.A.	1789.	3.07	10.55	5.01	2.30	0.94	N.A.	N.A.	N.A.	N A	N A	90.09	N.A.
210-215 6	41.	48 3.9	6 14.94	12.56	N.A.	2305.	3.46	11.46	5.03	2.05	1.04	N.A.	128.0	39.7	1465	371 0	90.03	N.A. 06 50
215-220 6	42.	07 3.8	1 15.12	12.27	N.A.	2101.	3.38	11.73	5.79	1.86	1.04	N . A .	N A	N A	N A	J/1.7	90.20	90. <i>52</i>
240-245 6	42.	61 3.8	8 15.03	12.65	N.A.	2130.	3.46	11.31	4.94	1.86	1.86	N.A.	N.A.	N.A.	N A	N A	57.54	N.A.
250-255 6	41.	47 3.9	3 15.01	12.67	N.A.	2147.	3.23	11.47	5.37	1.64	1.04	N.A.	N.A.	NΔ	N A	N A	97.07	N.A.
270-275 6	41.	92 4.1	0 14.56	13.62	N.A.	2104.	3.84	11.91	4.54	1.78	1.08	N.A.	N A	N A	N A	N A	07 60	N.A.
330-335 5	40.	89 4.1	4 14.18	14.65	N.A.	N.A.	3.72	12.58	4.46	1.32	0.94	N.A.	N.A.	N A	N A	N.A.	97.02	N.A.
365-370 4	41.	26 4.0	0 15.09	12.64	N.A.	2077.	3.28	11.89	5.71	1.01	0.97	N.A	N A	N A	N A	N.A.	90.00	N.A.
400-405 3	42.	50 4.0	6 15.20	13.33	N.A.	2035.	3.17	11.96	4.71	1.95	0 9/	N A	N A	N A	N A	N.A.	90.12	N.A.
435-440 2	42.	91 3.4	9 15.93	12.19	N.A.	2157.	3.19	10.59	5.29	1.54	0.80	N A	N A	N A	N A	N.A.	98.08	N.A.
455-460 2	.43.	05 3.6	1 15.62	11.89	N.A.	2204.	3.02	10.47	5.14	1.93	0.85	N A	N A	NA	N A	N.A.	90.30	N.A.
480-485 2	42.	37 3.7	4 15.42	12.26	5.19	2063.	3.23	10.98	5.16	1.74	0.82	1.00	126.2	3/ 3	1220	N.A. 125 1	93.00	N.A.
517-522.5 1	44.	07 3.5	2 16.61	11.41	N.A.	2177.	2.86	10.35	5.28	1 95	0.82	N A	120.2 N A	34.3 N A	1440. N A	403.1	93.99	90.4/
555-560 1	43.	41 3.4	4 16.04	11.23	N.A.	2067	3.38	9.14	4.92	2 18	0.80	N A	128 0	N.A.	N.A.	N.A.	9/.15	N.A.
565-570 1	43.	38 4.1	0 16.12	13.62	6.46	2226.	2.94	11.91	4 55	1 78	0.00	1 02	126.0	40./	1314.	452.0	94.81	95.05
					~			**• >1	4.77	T*10	0.15	1.02	170.0	21.0	T22/*	448.1	99.4 4	100.57

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Table 4 Compositions of samples of analcite syenite (For analytical techniques, and meanings of abbreviations, see Table 3)

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		510 ₂	^{T10} 2	^{A1} 2 ⁰ 3	Total Fe as Fe ₂ 0 ₃	Fe0	Mn	Mg0	Ca0	Na20	к ₂ 0	P2 ⁰ 5	^{C0} 2	Nb	Rb	Sr	Zr	Total l	Total 2
Depth	i :	[Weight	Percen	tages)	(PPM)	I	Wei	ght Per	centage	8		[P]	PM		1	
25- 30	1	51.89	1.75	25.21	4.80	2.22	1352.	0.88	4.13	6.27	3.64	0.16	1.10	140.8	73.2	1482.	308.8	98.90	99.93
30	1	50.83	1.98	19.50	5.04	2.29	1389.	0.92	4.86	6.24	3.82	0.19	N.A.	151.6	58.5	2694.	276.9	93.56	93.62
40- 45	2	50.21	2.18	20.29	5.48	N.A.	1458.	1.25	4.98	6.51	3.23	0.21	N.A.	N.A.	N.A.	N.A.	N.A.	94.53	N.A.
50- 55	2	50.46	2.12	20.93	4.78	2.70	1501.	1.12	5.61	7.24	2.73	0.19	1.80	152.7	61.2	1692.	332.0	95.37	97.06
55- 57.5	2	47.74	2.16	19.10	5.39	2.20	1446.	1.50	5.27	6.35	3.11	0.18	1.50	N.A.	N.A.	N.A.	N.A.	90.99	N.A.
65- 70	3	49.84	1.89	20.76	5.37	2.26	1607.	1.13	5.78	7.76	1.82	0.21	1.70	137.6	31.0	1721.	423.0	94.77	96.43
75- 80	3	50.85	1.63	20.03	4.28	2.06	1544.	0.82	4.75	7.62	2.37	0.14	1.20	130.9	42.3	1650.	410.7	92.69	93.87
85- 90	4	51.91	0.90	24.29	4.01	3.45	1513.	0.46	3.07	8.34	2.48	0.10	0.38	82.0	39.1	3206.	312.1	95.76	96.08
95-100	5	52.70	1.52	22.06	4.26	2.38	1343.	1.28	4.38	6.76	3.15	0.17	0.42	76.3	51.1	2178.	320.4	96.45	96.85
105-110	5	52.91	1.20	20.93	3.70	2.04	1153.	1.13	3.43	6.51	3.55	0.13	0.44	96.6	58.9	2490.	245.4	93.64	94.13
125-130	5	49.90	0.78	21.90	2.83	1.89	1138.	0.89	4.45	7.38	2.83	0.14	1.80	37.9	37.0	1193.	161.2	91.25	92.95
145-150	5	52.35	0.92	21.75	3.27	1.52	1604.	0.38	5.43	7.83	3.56	0.13	2.22	76.3	32.9	1209.	338.2	95.83	98.03
190-192	6	48.87	1.95	20.14	5.49	N.A.	1539.	0.84	7.40	5.89	4.27	0.24	N.A.	155.0	49.1	1304.	595.2	95.29	95.55
210-215	6	49.59	2.37	20.89	6.51	N.A.	1352.	2.16	7.58	6.83	1.85	0.39	N.A.	94.6	26.8	2183.	271.0	98.34	98.66
385-390	?	49.40	2.67	20.77	5.56	N.A.	1388.	1.26	5.93	7.98	2.24	0.26	N.A.	N.A.	N.A.	N.A.	N.A.	96.25	N.A.

Table 5: <u>Miscellaneous analyses</u> (For analytical techniques and meanings of abbreviations, see Table 3).

Key to Sample Numbers:

1: Upper contact, including ocelli. Chip sample (~1000g) taken from $a \sim lm^2$ area of the exposed upper contact surface, to a depth of ~1 cm. Weathered chips were rejected.

2, 3 and 4: (2) is an analysis of host rock from 210-215 cm., and (3) a whole-rock analysis of material from the same interval. (4) is an estimate of the host rock composition, obtained by subtraction of analcite syenite of the composition reported in Table 4 from analysis (3), using the analcite syenite: host rock volumetric ratio of Table 1a. (The host rock composition listed in Table 3 is the mean of analyses (2) and (4).)

5, 6, 7 and 8: mean compositions of the lower portions of intrusive units number 2, 3, 4 and 5 respectively.

9: small spherical bodies (amygdules?) from 65-70 cm. below the upper contact.

Sample Number	510 ₂	^{T10} 2	^{A1} 2 ⁰ 3	Total Fe as Fe ₂ 0 ₃	Fe0	Mn	Mg0	Ca0	Na20	к ₂ 0	P2 ⁰ 5	^{C0} 2	Nb	Rb	Sr	Zr	Total l	Total 2
	I	Weight	: Percènt	tages]	(PPM)	I	We:	ight Per	rcentage	28		[PPM		Ľ	
1	43.44	3.36	16.18	11.47	1.03	1980.1	2.83	10.49	5.98	2.48	0.78	2.64	136.8	59.3	1642.	442.8	97.25	100.06
2	41.54	3.95	15.04	12.56	N.A.	2355.	3.53	11.45	5.02	2.06	1.04	N.A.	123.2	36.6	1444.	423.8	96.48	N.A.
3	41.68	3.91	15.03	12.36	N.A.	2225.	3.34	11.34	5.10	2.03	1.01	N.A.	131.5	42.3	1508.	318.3	96.07	N.A.
4	41.41	3.96	14.83	12.56	N.A.	2255.	3.38	11.47	5.04	2.04	1.03	N.A.	132.7	42.8	1485.	320.0	96.00	N.A.
5	40.10	3.72	15.94	12.07	4.81	2132.	2.94	10.96	5.30	1.90	0.88	N.A.	138.9	33.1	1339.	439.8	94.07	N.A.
6	41.63	3.91	14.65	13.14	3.08	2016.	3.42	11.38	5.11	1.54	0.96	N.A.	126.8	28.0	1285.	428.7	95.99	N.A.
7	40.80	4.02	14.43	12.99	5.57	2188.	3.61	11.98	4.97	1.65	1.01	N.A.	115.4	32.9	1115.	439.6	95.73	N.A.
8	40.10	4.14	13.76	14.07	5.69	1921.	3.88	12.08	4.96	1.27	1.02	N.A.	106.2	25.7	858.	431.6	95.51	N.A.
9	50.46	0.23	24.16	0.97	N.A.	670.	0.06	3.91	9.95	1.12	0.09	N.A.	N.A.	N.A.	N.A.	N.A.	91.03	N.A.

Table 5 Miscellaneous analyses (for analytical techniques and meanings of abbreviations, see Table 3)

Tables 6, 7 and 8: (for analytical techniques, and meanings of abbreviations, see Table 3).

<u>Tables 6 and 7</u>: Estimated average compositions of the host rock (Table 7) and analcite syenite (Table 8) in each intrusive unit (analcite syenite at 385-390 cm. below the lower contact is not included in these recalculations).

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Table 6

i	\$10 ₂	^{Ti0} 2	^{A1} 2 ⁰ 3	Total Fe as Fe 2 ⁰ 3	Fe0	Mn	Mg0	Ca0	^{Na} 2 ⁰	к ₂ 0	P2 ⁰ 5	со ₂	Nb	Rb	Sr	Zr	Total l	Total 2
	I	Weight	t Percent	tages	I	(PPM)	1	Wei	ght Per	centage	2S]	[· 	PPM]	ſ	
1 2 3 4 5 6	44.19 43.29 41.58 42.40 41.73 42.41	3.59 3.71 3.84 3.86 3.90 3.85	16.51 15.97 15.16 15.09 14.81 15.21	11.64 11.96 12.53 12.38 12.91 12.36	5.54 4.83 3.84 5.53 5.50 N.A.	2149. 2132. 2031. 2185. 1973. 2073.	2.99 2.95 2.80 3.40 3.50 3.34	10.12 10.84 11.29 11.36 11.51 11.27	4.99 5.28 5.79 4.98 4.87 5.08	2.11 1.93 1.69 1.78 1.68 1.98	0.79 0.87 0.93 0.96 0.96 1.13	1.19 1.40 1.66 4.70 1.56 N.A.	131.8 139.4 132.7 126.6 116.7 128.0	50.9 35.1 32.3 35.6 33.3 39.7	1431. 1333. 1318. 1254. 1080. 1465.	462.1 440.8 447.3 453.3 433.3 371.9	97.21 97.08 95.87 96.49 96.12 96.90	97.86 98.02 97.22 100.63 97.10 N.A.
Tab	le 7	·																
i	⁵¹⁰ 2	^{Ti0} 2	A12 ⁰ 3	Total Fe as Fe ₂ 03	Fe0	Mn	MgO	Ca0	Na20	к ₂ 0	P2 ⁰ 5	^{C0} 2	Nb -	Rb	Sr	Zr	Total l	Total 2
	I	Weigh	t Percen	tages]	(РРМ)	I	We:	ight Pe	rcentag	es		I		PPM		I	
1 2 3 4 5 6	50.89 49.99 50.12 51.91 51.86 49.08	1.97 2.15 1.82 0.90 1.01 2.07	19.80 20.45 20.56 24.29 21.56 20.36	5.03 5.12 5.07 4.01 3.35 5.79	2.29 2.63 2.20 3.45 1.85 N.A.	1387. 1478. 1590. 1513. 1310. 1483.	0.92 1.22 1.04 0.46 0.83 1.23	4.82 5.33 5.50 3.07 4.44 7.45	6.24 6.85 7.72 8.34 7.21 6.17	3.81 2.96 1.97 2.48 3.32 3.55	0.19 0.20 0.19 0.10 0.14 0.28	1.10 1.76 1.56 0.38 1.41 N.A.	151.0 152.7 135.8 82.0 71.8 137.1	59.3 61.2 34.1 39.1 43.6 42.5	2630. 1692. 1701. 3206. 1680. 1565.	278.6 332.3 419.6 312.1 257.3 499.0	93.85 94.46 94.20 95.76 93.89 96.17	95.00 96.12 95.72 96.08 95.28 N.A.
Tal	ole 8 Es xe	timated	average (#3)	composi	tions of	f the ho	ost rock	(#1) and	d the a	nalcite	syenit	e (#2)	in the e	ntire s	ill; and	of the	entire sil	l, excluding
	Si0 ₂	^{Ti0} 2	^{A1} 2 ⁰ 3	Total Fe as ^{Fe} 2 ⁰ 3	Fe0	Mn	Mg0	Ca0	^{Na} 2 ⁰	к ₂ 0	^P 2 ⁰ 5	^{C0} 2	Nb	Rb	Sr	ŢZr .	Total 1	Total 2
	I	Weigh	nt Percer	itages		I (PPM)	I	We	ight Pe	rcentag	es		·I		PPM		·I	
#1 #2 #3	42.63 50.26 42.80	3.79 1.77 3.75	15.46 20.88 15.58	12.32 4.92 12.16	5.15 2.33 5.08	2076. 1450. 2062.	3.20 1.05 3.15	11.06 5.73 10.94	5.11 6.90 5.15	1.87 3.12 1.90	0.95 0.21 0.93	1.63 1.35 1.63	128.3 122.3 128.2	38.0 45.3 38.2	1304. 1838. 1316.	430.0 381.8 429.0	96.67 95.03 96.63	97.78 96.33 97.75

<u>Table 9</u> Quantitative analyses of xenolith rim pyroxenes and a xenolith analcite from 162.5 cm. below the upper contact.

1. Analyses in terms of weight percent oxides:

Oxide	Minera	al #1	Minera	al #2	Analcite		
	"core"	"rim"	"core"	"rim"			
SiO ₂	49.12	46.07	48.89	46.73	49.56		
Ti02	0.29	0.31	0.28	0.23	N.A.		
A1203	0.00	0.00	0.00	0.00	23.80		
Fe as FeO	15.46	31.15	17.52	31.04	N.A.		
MgO	14.43	5.43	13.95	5.37	N.A.		
Ca0	16.19	14.29	15.52	14.16	0.03		
Na ₂ 0	0.96	1.47	0.94	1.48	13.95		
κ ₂ 0	N.A.	N.A.	N.A.	N.A.	0.23		
Total	96.46	98.72	97.11	99.00	87.58		

N.A.= not analyzed

2. Allocation of the ions of the pyroxenes among W, X, Y and Z positions by the computer program described in Appendix 5.1:

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Table 9 continued

	Minera	1 #1	Mineral #2				
	"core"	"rím"	"core"	"rim"			
(CA W(0.674	0.621	0.646	0.614			
(NA	0.073	0.115	0.071	0.116			
(MG X(FF 2+	0.835	0.328	0.807	0.323			
(MN	N.A.	N.A.	N.A.	N.A.			
(AL V(FE 3+	0.000	0.000	0.000	0.000			
(TI	0.008	0.009	0.008	0.007			
(AL 7(FE 3+	0.000	0.000	0.000	0.000			
(SI	1,907	1.869	1.898	1.890			
FE 2+/							
TOTAL FE.	0.503	0.651	0.532	0.687			
P1 P2	0.253 0.346	0.263 0.394	0.283 0.385	0.270 0.380			
NUMBER OF ITERATIONS	6	7	6	7			

Pl and P2 refer to the rewritten pyroxene formula:

 W_{1-P1} (X,Y) $_{1-P2}$ $Z_{2}^{0}_{6}$

"Core" and "rim" analyses were performed near the geometric centres and near the edges, respectively, of crystals.

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<u>Table 10</u>	Densities of anhydrous liquids with the compositions
	of Ste. Dorothée rocks, at 1100°C (calculated by the
	method of Bottinga and Weill (1970a)).

Depth below upper contact (cm.)	Host rock density (g/cm ³)	Analcite syenite density (g/cm ³)
0- 5	2.53	
25- 30	2.65	2.36
30		2.36
50- 55		2.39
55- 57.5	2.65	2.38
65- 70	2.63	2.38
75- 80	2.68	2.35
85- 90	2.68	2.36
95-100 Intrusive unit #5	2.64	2.36
105-110	2.65	2.33
125-130	2.69	2.32
145-150	2.66	2.32
480-485	2.68	
565-570	2.73	

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Dopth holow the	Host most	Anglaita gyopita
upper contact (or)	HUSL FOCK	wiscosity (poiso)
apper contact (cm.)	viscosicy (poise)	viscosity (poise)
0 5	910	
10 15	010	
25 20	000	 *
25- 50	828	× 4045
	-	4045
40-45	695	3/30
50- 55 EE E7 E	000	39/1
55- 57.5 65 70	003	3040
		4028
		5415
05-90	677	×
95-100 (intrusive unit #4)	044	==
95-100 (intrusive unit #5)	917	5826
105-110	824	7093
125-120	641 570	
125-130	570	6992
135-140	754	
	122	2661
	639	
120-125	698	
1/0-1/5	585	
190-192	-	2445
210-215	407	2375
215-220	446	
240-245	444	
250-255	437	
2/0-2/5	339	
330-335	292	
365-370	437	
385-390	-	3063
	406	
435-440	585	
400-46U	592	
	509	
51/.5-522.5	/1/	
	698	
565-570	457	

Table 11 Viscosities of anhydrous liquids with the compositions of Ste. Dorothée rocks, at 1200°C (calculated by the method of Bottinga and Weill (1970b, 1972)).

* contains too much $A1_20_3$ for Bottinga and Weill's model to apply.

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Table 12 Rare earth elements in an "ocellus", and in the adjacent host rock.

Concentrations are in p.p.m., were measured on a mass spectrograph, and the relative precision and accuracy are both two or three percent. These values were kindly provided by J.A. Philpotts (written comm., 1970).

	Ce	Nd	Sm	Eu	Gđ	Dy	Er	Yb	Lu
Host rock	276	113	20.6	5.99	15.6	10.8	4.67	3.68	0.54
Ocellus	200	81.3	12.9	3.79	10.0	7.32	3.37	2.87	0.45
<u>Ocellus</u> Host rock	.725	.719	.626	.633	.641	.678	.721	.780	.833

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<u>Table 13</u> Significant (at the 0.95 level, 5 samples) linear correlations between the CO₂ concentration of the host rock and concentrations of oxides in the analcite syenite of intrusive units 1 to 5.

Oxide	Correlation Coefficient
c0 ₂	-0.86
Na20	0.82
Mg0	-0.85
A1203	0.96
^P 2 ⁰ 5	-0.85
Ca0	-0.88
Fe0	0.86

		Northern	traverse	Southern	traverse
Interval (cm.) (A-5)-(A) (.	j A/5cm.)	V _{sye,j}	V xen,j	V sye,j	V xen,j
0- 5	1	0	0	2/3	0
5- 10	2	0	0	1 1/3	0
10- 15	3	2/3	0	4 2/2	0
15- 20	4	2	0	2	0
20- 25	5	37 1/3	0	2/3	0
25- 30	6	3 1/3	0	1 1/3	0
30 - 35	7	7 1/3	0	4 2/3	0
35 - 40	8	22	0	2	0
40- 45	9	7 1/3	0	26 2/3	0
45- 50	10	11 1/3	1 1/3	10	0
50 - 55	11	16 2/3*	2/3*	16	0
55- 60	12	22	0	11 2/3	0
60- 65	13	16 2/3	4	2/3	0
65- 70	14	8 2/3	0	36	0
70- 75	15	4	0	6	0
75- 80	16	2	0	18 2/3	0
80- 85	17	6*	0	4 2/3	0
85- 90	18	10	0	2/3	0
90- 95	19	10	12 2/3	4 1/3	0
95-100	20	6	2/3	0	0
100-105	21	3 1/3	15 1/3	2/3	2/3
105-110	22	4	13 1/3	0	1 1/3
110-115	23	5 1/3	17 1/3	0	4 2/3
115-120	24	1 1/3	0	0	0
120-125	25	2	0	0	0
125-130	26	13 1/3	0	7 1/3	0
130-135	27	6 2/3	1 1/3	1 1/3	0
135-140	28	4 2/3	0	2/3	0
140-145	29	2/3	0	1 1/3	3 1/3
145-150	30	8	8 2/3	2/3	1 1/3
150-155	31	2	2/3	0	0
155-160	32	8 2/3	2/3	2/3	1 1/3
160-165	33	0	3 1/3	1	6
165-170	34	2/3	U	2 2/3	12
1/0-175	35	0	0	0	U
1/5-180	36	2/3	U	0	U
180-185	37	0	0	1 1/3	0
185–190	38	0	0	2	0

Table Al Vertical variations in modal composition measured down two traverses of the Laurin Quarry face. (For symbols used, see Table 2).

* calculated by linear interpolation because the interval was too iron-stained to measure.

In the northern and southern sections, average total thicknesses of syenite of 0.5 cm. and 0.6 cm. respectively were found between the base of intrusive unit number 6 and the lower limit of exposure.

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Table A2 Standards used, and number of counts taken in electron microprobe analyses.

- N.B. The name of each mineral standard is followed by its McGill collection reference number.
- 1) Pyroxenes

UCPX1-1 to UCPX2-2

272.5 PX1-1 to 272.5 PX2-4

Element	Standard	No. of 10 sec. counts	Standard	No. of 10 sec. counts
Ca	Augite 41	5	Hornblende 149	5
Na	Albite 28	5	Serandite 138	5
Mg	Augite 41	5	Hornblende 149	5
Fe	Augite 41	5	Hornblende 149	5
Mn	Not analyzed	-	Serandite 138	5
A1	Albite 28	5	Hornblende 149	5
Ti	Ti metal	5	Ti metal	5
Si	Augite 41	5	Hornblende 149	5

191PX1-1 **#** 191PX1-2

Element	Standar	đ	No.of 10 sec. counts
Ca	Augite	41	5
Na	Albite	28	5
Mg	Augite	41	7
Fe	Augite	41	5
Mn	Serandite	138	7
A1	Albite	28	5
Ti	Ti metal		7
Si	Augite	41	7

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2) Amphiboles

	Analyses	Analyses 5 - 8			
Element	Standard	No. of 10 sec. counts	Standard		No. of 10 sec. counts
Ca	Hornblende 149	5	Wollastonite	5	10
K	Not analyzed	-	Orthoclase	22	5
Na	Serandite 138	5	Albite	28	5
Mg	Hornblende 149	5	Periclase	83	10
Fe	Hornblende 149	5	Pseudobrookite	96	10
Mn	Serandite 138	5	Not analyzed		-
Al	Hornblende 149	5	Orthoclase	22	5
Ti	Ti metal	5	Ti metal		5
Si	Hornblende 149	5	Wollastonite	5	10

Analyses 9 - 12

Analyses 13 - 14

Standar	đ	No. of 10 sec. counts	Standard		No.of 10 sec. counts
Augite	41	7	Hornblende	149	6
Not analyz	ed	-	Hornblende	149	7
Albite	28	7	Hornblende	149	7
Augite	41	7	Hornblende	149	6
Augite	41	7	Hornblende	149	6
Serandite	138	· 7	Hornblende	149	5
Albite	28	7	Hornblende	149	6
Ti metal		7	Hornblende	149	7
Augite	41	7	Hornblende	149	7
	Standar Augite Not analyz Albite Augite Augite Serandite Albite Ti metal Augite	Standard Augite 41 Not analyzed Albite 28 Augite 41 Augite 41 Serandite 138 Albite 28 Ti metal Augite 41	StandardNo. of 10 sec. countsAugite417Not analyzed-Albite287Augite417Augite417Serandite1387Albite287Ti metal7Augite417	StandardNo. of 10 sec. countsStandardAugite417HornblendeNot analyzed-HornblendeAlbite287HornblendeAugite417HornblendeAugite417HornblendeSerandite1387HornblendeAlbite287HornblendeLite1387HornblendeAlbite287HornblendeAlbite287HornblendeTi metal7HornblendeAugite417Hornblende	StandardNo. of 10 sec. countsStandardAugite417Hornblende149Not analyzed-Hornblende149Albite287Hornblende149Augite417Hornblende149Augite417Hornblende149Augite417Hornblende149Serandite1387Hornblende149Albite287Hornblende149Albite287Hornblende149Albite287Hornblende149Augite417Hornblende149

3) Opaque minerals

Titanomagnetites

Pyrites

Element	Standard	No. of 10 sec. counts	Standard	No. of 10 sec. counts
Fe	Hematite 80	5	Pyrite 501	5
Ti	Ti metal	5	Not analyzed	-
A1	Albite 61	5	Not analyzed	-
Mg	Periclase 83	5	Not analyzed	-
S	Not detected	-	Pyrite 501	5

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4) Analcites and natrolites

All analyses

Element	Standard	No. of 10 sec. counts
Na	Plagioclase 153	10
К	Orthoclase 29	10
Ω.a	Plagioclase 153	10
A.,	Plagioclase 153	10
Si	Plagioclase 153	10

5) Sphenes

Series 1

Series 2

Element	Standard	No. of 10 sec. counts	Standard	No. of 10 sec. counts
Ca	Wollastonite 5	. 5	Hornblende 149	5
Ti	Ti metal	5	Ti metal	5
Fe	Not analyzed	-	Hornblende 149	5
A1	Not analyzed	-	Hornblende 149	5
Si	Wollastonite 5	5	Hornblende 149	5

Series 3

Element	Standard		No. of 10 sec. counts
Ca	Wollastonite	: 5	5
Ti	Ti metal		5
Fe	Hematite	80	5
A1.	Albite	28	5
Si	Wollastonite	: 5	5

6) <u>Xenolith minerals</u>

Pyroxenes

Analcite

Element	Standard	No. of 10 sec. counts	Standard	No. of 10 sec. counts
Ca	Augite 41	5	Plagioclase 153	10
K	Not analyzed	-	Orthoclase 29	10
Na	Albite 28	5	Plagioclase 153	10
Mg	Augite 41	5	Not analyzed	-
Fe	Augite 41	5	Not analyzed	-
A1	Not detected	-	Plagioclase 153	10
Ti	Ti metal	5	Not analyzed	-
Si	Augite 41	5	Plagioclase 153	10

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Oxide	UCPX1-1 Host rock, Fig. A2		UCPX1-2 Host rock, Fig. A2		UCPX1-3 Host rock, Fig. A2		UCPX1-4 Host rock, Fig. A2	
	wt. %	Std. Dev'n						
si0 ₂	41.69	0.89	39.07	0.19	42.72	0.53	39.46	1.18
Total Ti as Ti ₂ 0 ₃	1.53	0.17	. 3.34	0.37	1.37	0.13	3.00	0.17
A1203	9.12	0.42	9.81	0.48	8.09	0.44	9.81	0.40
Total Fe as FeO	19.67	0.61	15.12	0.27	20.35	0.65	16.23	0.64
Total Mn as MnO	N.A.		N.A.		N.A.		N. A.	
Mg0	8.00	0.21	10.62	0.27	9.34	0.32	10.69	0.25
Ca0	16.82	0.35	17.02	0.20	16.59	0.50	16.88	0.21
^{Na} 2 ⁰	0.78	0.11	0.45	0.11	0.66	0.11	0.63	0.14
Total	97.61		95.43		99.13		96.71	
(1st column)t _t (2nd column)d.f.	4.30	28	13.27	28	0.99	42	5.07	28

Table A3 Electron microprobe analyses of pyroxenes

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0	UCPX2-1 Host rock, groundmass crystal		UCPX2-2 groundm	UCPX2-2 Host rock, groundmass crystal		X1-1 Host Fig. A4	272.5PX1-2 Host rock, Fig. A4	
Oxide	wt. %	Std. Dev'n	wt. %	Std. Dev'n	wt. %	Std. Dev'n	wt. %	Std. Dev'n
SiO ₂	39.75	0.83	42.82	0.29	43.49	0.44	42.94	0.25
Total Ti as Ti ₂ 0 ₃	3.72	0.25	2.62	0.25	3.44	0.29	1.87	0.34
A1203	10.54	0.39	6.65	0.35	7.42	0.36	7.60	0.31
Total Fe as FeO	14.80	0.64	14.58	0.50	7.10	0.27	10.39	0.27
Total Mn as MnO	N.A.		N.A.		N.A.		N.A.	
Mg0	11.57	0.34	12.41	0.45	11.13	0.14	8.46	0.09
Ca0	17.20	0.30	17.35	0.40	21.02	1.73	22.60	0.95
Na ₂ 0	0.38	0.03	0.56	0.09	0.49	0.06	0.30	0.15
Total	97.96		97.00		93.98		94.65	
(lst column)t _t (2nd column)d.f.	3.70	28	7.09	28	7.20	32	10.54	32

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Oxide	272.5PX1-3 Host rock, Fig. A4		272.5P rock,	X1-4 Host Fig. A4	272.5P rock,	X1-5 Host Fig. A4	272.5PX1~6 Host rock, Fig. A4	
	wt.%	Std. Dev'n	wt. %	Std. Dev'n	wt. %	Std. Dev'n	wt. %	Std. Dev'n
sio ₂	44.30	0.43	42.71	0.62	39.81	0.57	41.56	0.22
Total Ti as Ti ₂ 0 ₃	3.54	0.44	3.81	0.26	3.19	0.45	5.26	0.43
A1203	6.68	0.22	9.50	0.26	10.61	0.34	9.81	0.14
Total Fe as FeO	6.81	0.24	7.46	0.14	11.41	0.23	7.04	0.24
Total Mn as MnO	0.35	0.08	0.25	0.06	0.56	0.05	0.24	0.04
Mg0	11.95	0.37	10.60	0.34	7.24	0.16	10.56	0.22
Ca0	22.97	0.25	22.71	0.26	22.38	0.23	23.17	0.48
Na ₂ 0	0.58	0.02	0.73	0.17	0.51	0.19	0.57	0.13
Total	97.19		97.78		95.71		98.19	
(lst column)t _t (2nd column)d.f.	7.54	32	5.70	32	10.69	32	5.20	31

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Table A3 continued.

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Oxide	272.5PX2-1 Host rock, Fig. A5		272.5PX2-2 Host rock, Fig. A5		272.5P rock,	X2-3 Host Fig. A5	272.5PX2-4 Host rock, Fig. A5	
	wt. %	Std. Dev'n	wt. %	Std. Dev'n	wt. %	Std. Dev'n	wt. %	Std. Dev'n
SiO ₂	41.67	0.33	42.10	0.24	48.30	0.40	43.99	0.36
Total Ti as Ti ₂ 0 ₃	4.92	0.62	4.90	0.44	2.60	0.12	3.49	0.35
A1203	10.14	0.10	10.85	0.21	5.72	0.18	7.40	0.87
Total Fe as FeO	7.10	0.32	7.03	0.47	6.31	0.10	6.60	0.16
Total Mn as MnO	0.08	0.01	0.20	0.03	0.22	0.03	0.26	0.05
Mg0	10.22	0.10	10.59	0.28	12.93	0.18	11.27	0.24
Ca0	22.05	0.23	22.66	0.64	22.44	0.37	22.65	0.25
Na ₂ 0	0.50	0.05	0.53	0.10	0.49	0.06	0.52	0.11
Total	96.68		98.86		99.03		96.18	
(lst column)t _t (2nd column)d.f.	9.10	32	2.65	36	3.49	32	7.94	32

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Table A3 continued.

Oxide	191 PX-1 syenite,	L. Analcite , Fig. A3	191 PX-2 syenite,	191 PX-2. Analcite syenite, Fig. A3		
	wt. %	Std. Dev'n	wt. %	Std. Dev'n		
si0 ₂	39.11	0.28	38.58	0.50		
Total Ti as Ti ₂ 0 ₃	4.04	0.13	5.21	0.19		
A1203	10.84	0.24	10.60	0.54		
Total Fe as FeO	18.00	0.44	18.11	0.72		
Total Mn as MnO	0.43	0.04	0.27	0.04		
MgO	9.91	0.24	10.03	0.48		
Ca0	17.82	0.16	17.65	0.36		
Na20	0.90	0.13	0.91	0.06		
Total	101.05		101.36			
(1st column)t _t (2nd column)d.f.	3.57	40	2.65	40		

 t_t and d.f. are statistics used to approximately test the hypotheses that the summations differ significantly from 100% (Appendix 5.1).

N.A. not analyzed.

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Table A4 Calculated ionic distributions in pyroxenes

PX. #	1	2	3	4	5	6	7	8	9
	UCPX1-1	UCPX1-2	UCPX1-3	UCPX1-4	UCPX2-1	UCPX2-2	272.5PX1-1	272.5PX1-2	272.5PX1-3
(CA W(0.709	0.722	0.687	0.706	0.708	0.720	:0.891	0.969	0.942
(NA	0.059	0.034	0.050	0.048	0.028	0.042	0.038	0.022	0.045
(MG	0.469	0.627	0.538	0.622	0.622	0.717	0.657	0.504	0.682
X(FE 2+	0.343	0.129	0.327	0.117	0.100	0.138	0.089	0.182	0.000
(MN	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.017	0.011
(AL	0.064	0.004	0.021	0.000	0.004	0.000	0.067	0.076	0.000
Y(FE 3+	0.304	0.371	0.332	0.407	0.376	0.297	0.146	0.165	0.215
(TI	0.051	0.112	0.045	0.099	0.121	0.086	0.103	0.063	0.115
(AL	0.360	0.453	0.348	0.452	0.473	0.304	0.279	0.282	0.302
Z(FE 3+	0.000	0.000	0.000	0.007	0.000	0.037	0.000	0.000	0.003
(SI	1.640	1.547	1.652	1.542	1.527	1.659	1.721	1.718	1.696
FE 2+/ TOT. FE	0.530	0.258	0.496	0.221	0.210	0.291	0.378	0.524	0.000
P1	0.232	0.244	0.263	0.246	0.264	0.238	0.071	0.009	0.013
P2	0.231	0.244	0.262	0.252	0.263	0.275	0.071	0.008	0.026
# OF ITERATIONS	6	6	6	5	5	6	5	6	0

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Table A4 continued.

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	10	11	12	13	14	15	16	17	18
	272.5PX1-4	272.5PX1-5	272.5PX1-6	272.5PX2-1	272.5PX2-2	272.5PX2-3	272.5PX2-4	191PX-1	191PX-2
(CA W(0.927	0.952	0.947	0.912	0.915	0.899	0.938	0.718	0.710
(NA	0.056	0.037	0.042	0.037	0.039	0.036	0.039	0.066	0.066
(MG	0.602	0.429	0.601	0.588	0.595	0.720	0.650	0.556	0.562
X(FE 2+	0.000	0.106	0.000	0.031	0.000	0.107	0.026	0.052	0.035
(MN	0.008	0.019	0.008	0.003	0.006	0.007	0.008	0.014	0.008
(AL	0.054	0.077	0.026	0.070	0.069	0.058	0.037	0.000	0.000
Y(FE 3+	0.238	0.273	0.224	0.198	0.222	0.090	0.187	0.466	0 452
(TI	0.123	0.107	0.170	0.161	0.156	0.082	0.114	0.129	0.166
(AL	0.373	0.420	0.415	0.391	0.413	0.194	0.300	0.481	0 460
Z(FE 3+	0.000	0.000	0.000	0.000	0.000	0 000	0,000	0.401	0.409
(SI	1.627	1.580	1.585	1.609	1.587	1.806	1.700	1.471	1.449
FE 2+/ TOT. FE	0.000	0.280	0.000	0.135	0.000	0.545	0.123	0.092	0.062
P1	0.017	0.011	0.011	0.051	0.046	0.065	0.023	0 216	0 222
P2	0.024	0.010	0.029	0.051	0.048	0.065	0 023	0.240	0.225
# OF	0	5	0	4	0.040	5	6	U.204	0.305
ITERATIONS	·	-	0	7	U	J	4	2	4

 P_1 and P_2 refer to the rewritten pyroxene formula W_{1-P_1} $(X,Y)_{1} P_2$ $Z_2^{0}_{6}$.

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	Ion	Mean concentration (per 6 oxygens)	Standard Deviation
W	(Ca ²⁺	0.832	0.114
vv	(Na	0.044	0.012
	(Mg ²⁺	0.599	0.080
X	(Fe ²⁺	0.099	0.102
	(Mn ²⁺	0.007	0.006
	(A1 ³⁺	0.035	0.032
Y	(Fe ³⁺	0.276	0.107
	((Ti ³⁺	0.111	0.037
	(A1 ³⁺	0.373	0.082
Z	(Fe ^{3†}	0.010	0.023
	(si ⁴⁺	1.618	0.092
Fe	2 ⁺ /Fe _{Total}	0.230	0.196

Table A5 Means and standard deviations of ionic proportions of pyroxenes in Table A4.

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	1	2	3	4	5	6	7	8	9	10	11	12	13 [†]	14
Si0 ₂	37.36	37.32	35.57	35.70	37.52	37.49	36.70	38.34	36.56	37.67	37.54	37.16	39.52	37.70
Ti as ^{TiO} 2	4.90	3.25	5.86	6.14	3.65	3.90	4.98	2.32	3.34	2.97	4.33	2.68	3.30	2.59
A1203	14.90	13.54	15.26	15.04	12.36	13.66	13.14	11.36	16.22	15.10	16.07	14.30	13.54	16.02
Total Fe as FeO	11.75	15.90	12.17	16.49	15.51	17.16	13.77	22.01	13.22	15.75	12.68	17.40	15.46	13.29
Total Mn as MnO	0.48	0.74	0.57	1.08	N.A.	N.A.	N.A.	N.A.	0.60	0.71	0.50	0.96	0.71	0.56
Mg0	9.12	6.81	8.71	6.14	6.13	5.84	7.00	3.47	11.65	10.70	11.64	8.20	7.37	9.29
Ca0	11.30	10.71	11.31	11.08	13.13	12.86	12.94	11.71	9.24	9.11	9.83	9.24	11.69	11.84
Na20	2.51	2.35	2.22	2.66	2.25	2.25	1.92	2.36	2.73	2.59	2.49	2.26	2.27	2.54
к ₂ 0	N.A.	N.A.	N.A.	N.A.	1.47	1.58	1.42	1.87	N.A.	N.A.	N.A.	N.A.	1.65	1.54
Total	92.32	90.63	91.68	9432	92.03	94.74	91.86	93.45	93.56	94.59	95.09	92.18	95.51	97.76

Table A6 Quantitative electron microprobe analyses of amphiboles.

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Table A6 continued.

The most likely reason for the low summations is that the correction procedure is inadequate (Appendix 3).

N.A. = not analyzed.

[†] Dr. W.H. MacLean kindly performed the major element analyses of numbers 13 and 14, whose totals do not include the following measured trace element concentrations: Zr as ZrO₂, 0.045% and 0.045%; ZnO, 0.034% and 0.107%; SrO, 0.16% and 0.14%, and Cl, 0.2% and 0.005% respectively.

Significant quantities of any other elements betweeen atomic numbers 11 and 56 are not present.

All analyses were classified according to the scheme of Leake (1968), in preference to that of Phillips (1965), to permit the inclusion of K and to allow comparisons with the analyses of Frisch (1970). The modifier "alumino-" is used in parentheses when there is \geq 0.9 and <1.0 octahedral Al per 48 hydrogen equivalents (assuming 16 tetrahedral sites per 48 hydrogen equivalents) and is marked by an asterisk when octahedral Al is \geq 1.0 and <1.1 atoms per 48 hydrogen equivalents.

Analyses made on the same crystal are bracketed. Distances refer to the depth below the upper contact from which samples were taken.

1) (Alumino-) Kaersutite; core of a host rock amphibole, 190-95 cm.

(2) <u>Alumino*-titaniferous magnesian hastingsitic hornblende</u>, rim of a host rock amphibole, 190-95 cm.

(3) <u>Kaersutite</u>, core of an analcite syenite amphibole, 190-95 cm.

(4) Ferrokaersutite, rim of an analcite syenite amphibole, 190-95 cm.

5) <u>Titaniferous magnesian hastingsitic hornblende</u>, core of a host rock amphibole, 65-70 cm.

<u>Titaniferous magnesian hastingsite</u>, rim of a host rock amphibole,
 65-70 cm.

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Table A6 continued.

- 7) <u>Titaniferous magnesian hastingsite</u>, core of an analcite syenite amphibole, 65-70 cm.
- Amphibole on the titaniferous ferro-edentic hornblende and titaniferous hastingsitic hornblende boundary, rim of an analcite syenite amphibole, 65-70 cm.
- 9) <u>Alumino*-titaniferous ferroan pargasite</u> (assuming that K≥0.04 atoms per formula unit); core of a host rock amphibole, 50-55 cm.
- 10) (Alumino-) Titaniferous ferroan pargasite (assuming K≥ 0.11 atoms per formula unit); rim of a host rock amphibole, 50-55 cm.
- 11) <u>Kaersutite</u> (assuming K≥ 0.07 atoms per formula unit. It is probable that the addition of K would actually take this analysis into the ferroan pargasite field); core of an analcite syenite amphibole, 50-55 cm.
- 12) <u>Alumino*-titaniferous magnesian hastingsite</u> (assuming K≥ 0.11 atoms per formula unit); rim of an analcite syenite amphibole, 50-55 cm.
- 13) <u>Alumino*-titaniferous hastingsitic hornblende</u>, about three-quarters of the way from the core to the rim of a host rock amphibole, 65-70 cm.
- 14) <u>Alumino-titaniferous ferroan pargasite</u>, about three-quarters of the way from the core to the rim of analcite syenite amphibole, 65-70 cm. If analyses 13 and 14 are recalculated on a 23 oxygen, 2(OH,F,Cl) basis (Robinson, 1970), assuming an Fe0:Fe₂0₃ ratio of 0.367 (the mean value for the 46 hastingsites listed by Leake (1968), and including the trace elements, the totals become 98.12% and 97.76% respectively. The resulting ionic formulae and reclassifications are:

Table A6 continued.

13:
$$(Na_{0.732} \quad K_{0.350} \quad Ca_{2.175}^{2+} \quad Sr_{0.015}^{2+}),$$

 $(Fe_{1.618}^{2+} \quad Mg_{1.830}^{2+} \quad Mn_{1.001}^{2+} \quad Zn_{0.040}^{2+}),$
 $(Fe_{0.537}^{3+} \quad Al_{1.246}^{3+} \quad Ti_{0.414}^{4+} \quad Zr_{0.004}^{4+}),$
 $(Al_{1.414}^{3+} \quad Si_{6.586}^{4+} \quad O_{23}^{2-}, ((OH^-, F^-)_{1.944}Cl_{0.054}^{-}))$

(Alumino-titaniferous ferro-edenitic hornblende).

14:
$$(Na_{0.776} \quad K_{0.325} \quad Ca_{2.102}^{2+} \quad Sr_{0.014}^{2+}),$$

 $(Fe_{1.383}^{2+} \quad Mg_{2.296}^{2+} \quad Mn_{0.078}^{2+} \quad Zn_{0.013}^{2+}),$
 $(Fe_{0.459}^{3+} \quad Al_{2.378}^{3+} \quad Ti_{0.323}^{4+} \quad Zr_{0.004}^{4+}),$
 $(Al_{0.750}^{3+} \quad Si_{6.250}^{4+} \quad O_{23}^{2-}, ((OH^-, F^-)_{1.999}, Cl_{0.001}))$

(An amphibole on the alumino-titaniferous ferroan pargasitic hornblende and alumino-titaniferous ferroan pargasite boundary). •

	5H1	5H2	5H3	5H4	5H5	5H6	5H 7	5H8	5H9	5H10
Fe wt. %	61.54	53.45	57.87	63.40	62.11	64.69	52.12	60.43	59.30	60.38
Ti wt. %	8.73	12.05	8.78	1.44	6.78	1.71	12.51	7.61	6.39	7.25
Fe:Ti	7.05	4.44	6.59	44.03	9.16	37.83	4.17	7.94	9.28	8.33
	5S1	552								
Fe wt. %	51.59	55.99								
Ti wt. 🖁 %	11.12	9.14								
Fe:Ti	4.64	6.13								

Table A7 Electron microprobe analyses of titanomagnetites.

5H, 5S series: host rock and analcite syenite titanomagnetites, respectively, from 5-10 cm. below the upper contact. Sulphur was undetectable in each mineral.

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	65H1	65H2	65H3	65H4	65H5	65H6	65H7	6581	6582
Fe wt. % Ti wt. % Al wt. % Mg wt. % Fe:Ti	69.71 3.41 0.45 0.00 20.44	70.78 1.21 0.45 0.00 58.50	59.07 5.08 0.65 0.00 11.63	62.34 1.59 0.44 0.00 39.21	62.90 5.17 0.52 0.11 12.17	53.31 11.25 0.27 0.00 4.74	64.34 1.46 0.48 0.00 44.07	65.30 2.22 0.26 0.00 29.41	65.56 0.89 0.43 0.00 73.66
	6583	6584	6585	6586	6587	6558	6589	65810	65811
Fe wt. % Ti wt. % Al wt. % Mg wt. % Fe:Ti	58.62 6.36 0.31 0.05 9.22	59.70 7.19 0.43 0.00 8.30	65.96 0.88 0.38 0.00 74.95	62.80 3.78 0.79 0.09 16.61	65.88 2.90 0.45 0.00 22.72	65.50 0.88 0.43 0.00 74.43	58.46 8.02 0.42 0.00 7.29	65.72 3.45 0.88 0.00 19.05	65.90 3.45 0.76 0.09 19.10
	65812	65S13							
Fe wt. % Ti wt. % Al wt. % Mg wt. % Fe:Ti	64.02 4.27 0.88 0.13 15.24	65.06 0.88 0.34 0.00 73.93							

65H, 65S series: host rock and analcite syenite titanomagnetites, respectively, from 65-70 cm. below the upper contact.

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Table A7 continued.

One titanomagnetite from each rock type was checked for S, Ni, Co, Cu and Si. Results were: S - undetectable, Ni, Co and Cu each -1000 ppm., Si <1000 ppm. in each mineral. The host rock and the analcite syenite minerals had about 72 ppm. and 60 ppm. Nb respectively. ļ

<u>Table A8</u> Electron microprobe analyses of pyrites from 207.5 cm. below the upper contact.

	Host rock Pyrite #1		Host rock Pyrite #2	Analcite syenite pyrite		
	Core	Rim	🗧 Core	Core	Rim	
Fe(wt.%)	46.43	45.82	46.38	45.74	46.00	
S(wt.%)	53.55	53.63	52.08	53.49	53.60	
Total	99.98	99.45	98.46	99.23	100.19	

Results of qualitative analyses for Ni, Co, Cu and Si were the same for every spot: Ni <100 ppm; Co <1000 ppm; Cu and Si were not detected.

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Oxide (wt.%)	l. Host rock analcite	2. Analcite syenite analcite
Si0 ₂	54.02	54.68
A12 ⁰ 3	23.13	24.60
Ca0	0.13	0.31
Na20.	13.77	14.38
к ₂ 0	0.21	0.26
Total	91.26	94.24

Table A9 Electron microprobe analyses of analcites from 162.5 cm. below the upper contact.

a) Recalculation of analyses on the basis of 6 oxygens per formula unit (assuming differences between totals and 100% to be made up by water):

1. Na_{0.986} K_{0.0098} Ca_{0.0053} Al_{1.006} Si_{1.994} · 0₆ (1.076H₂0) 2. Na_{1.000} K_{0.0118} Ca_{0.0120} Al_{1.040} Si_{1.961} · 0₆ (1.040H₂0) b) Recalculation of analyses in terms of molecules mepheline, kalsilite, quartz, and (Ca0 Al₂0₃): 1. Ne_{49.32} - Ks_{0.49} - Qz_{49.95} - (Ca0 Al₂0₃)_{0.25}

^{2. Ne}_{50.70} - $Ks_{0.61}$ - $Qz_{48.09}$ - (Ca0 A1₂ O_3)_{0.61}

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Table A10 Electron microprobe analysis of natrolite in an ocellus from near the upper contact.

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	Si	Al	Ca	Na	K	Total	0	Assumed ^H 2 ⁰	
Oxide wt %	44.41	21.94	0.24	14.74	0.43	81.76		18.24	
Molecular proportions*	24.947	14.523	0.143	16.057	0.306		80	34.17	

* Assuming 80 oxygens, and a deficiency in the total weight percentage made up by water.

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Table All Electron microprobe analyses of sphenes.

<u>Coding</u>: Host rock (HOST) and analcite syenite (SYE) sphenes were analyzed near their geometric centres (C) and rims (R). Each crystal of each rock type in each series of analyses was arbitrarily numbered (1 to 3).

Series 1: Sphenes from 65-70 cm below the upper contact.

Oxide wt.%	HOST #1(C)	HOST #1(R)	HOST #2(C)	HOST #2(R)
si0 ₂	28.72	29.20	28.54	29.03
TiO ₂	35.53	33.44	36.96	34.55
Ca0	29.69	29.83	29.32	29.56
Total	93.94	92.47	94.82	93.13
Oxide wt.%	SYE #1(C)	SYE #1(R)	SYE #2(C)	SYE #2(R)
Si0 ₂	28.27	29.25	28.26	28.67
Ti0 ₂	35.46	33.99	34.58	34.18
Ca0	29.69	30.20	29.33	29.55
Total	93.42	93.44	92.17	92.40

Series 2: More sphenes from 65-70 cm. below the upper contact.

0xide	wt.%	HOST (C)	HOST (R)	SYE (C)	SYE (R)
	si0 ₂	28.56	28.97	29.06	29.13
	Ti0 ₂	36.94	35.58	35.84	34.88
	^{A1} 2 ⁰ 3	1.50	1.64	1.49	1.75
Fe as	Fe0	1.04	0.95	1.00	1.44
	Ca0	28.20	28.27	28.18	28.49
Total		96.24	95.41	95.57	95.69

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In all series 2 analyses, Na was undetected, and Nb was estimated at 2010 ppm (HOST1(C)) and 1470 ppm (SYE1(C)) from the approximate relationship, Equation A1, Appendix 5.3.

Series 3: Sphenes from 207.5 cm. below the upper contact

0xide	wt.%	HOST #1(C)	HOST #1(R)	HOST #2(C)	HOST #2(R)	HOST #3(C)
	SiO ₂	31. 21	31.69	32.06	31.88	31.70
	Ti0 ₂	35.83	35.22	35.67	33.67	34.30
	A12 ⁰ 3	1.56	1.90	1.67	1.67	1.70
Fe as	Fe0	1.08	1.15	1.08	1.13	1.10
	Ca0	30.09	29.92	30.20	29.5 9	30.16
Total		99.77	99.89	100.68	97.94	98.95
Oxide	wt.%	HOST #3(R)	SYE #1(C)	SYE #1(R)	SYE #2(C)	SYE #2(R)
	Si0 ₂	32.06	30.56	31.34	31.22	32.78
	Ti02	35.48	35.90	35.69	36.44	34.88
	A12 ⁰ 3	1.78	1.74	1.84	1.48	1.83
Fe as	Fe0	1.04	1.25	1.19	1.09	1.20
	Ca0	29.80	30.02	30.19	29.56	29.30
Total		100.16	99.46	100.26	99.79	99.99

Oxide	wt.%	SYE #3(C)
	SiO ₂	31.82
	TiO ₂	35.93
	A12 ⁰ 3	1.56
Fe as	Fe0	1.06
	Ca0	29.08
Total		99.46

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Element	ε(host rock)	<pre>e(analcite syenite)</pre>
Fe (as Fe ₂ 0 ₃)	0.13%	0.26%
Ti (as TiO ₂)	0.09%	0.19%
Ca	0.07%	0.10%
K	0.15%	0.12%
Р	0.83%	1.06%
Si	0.37%	0.35%
A1	0.23%	0.22%

<u>Table A12</u> Estimated standard deviations of peak readings (x-ray fluorescence spectrometry).

Table A13 Changes in x-ray fluorescence measurements of concentrations over a 12 month period.

Element	e% <u>(</u> A)	е% (В)	e% (C)	e% (D)
Fe	2.44	-0.02	1.23	0.03
Ti	-0.51	7.02	3.77	7.88
Ca	4.60	-2.40	3.50	1.58
K	0.60	0.33	0.47	0.38
Р	22.78	-0.96	11.87	3.52
Si	-0.58	-0.53	0.56	-0.35
A1	-0.77	0.48	0.63	-0.16

The percentage change, $e = \frac{2(C_2 - C_1)}{C_2 C_1} \times 100\%$

where C_{1}, C_{2} are nominal concentrations determined at the start and end of the 12 month period.

A,B,C: analcite symmite from 127.5 and 67.5 cm. below the upper contact, and mean values, respectively

D: host rock from 437.5 cm. below the upper contact.

Table A14 Comparison of x-ray fluorescence measurements of trace element concentrations in U.S.G.S. standard rocks with published values. (Values are in p.p.m.)

BCR-1

Element	f	P	F	G
Nb	(negative)	7.7	34.1	9±1
RЪ	46.0	49.4	48.6	51±1
Sr	313.9	337.4	335.	348±2
Zr	183.6	175.7	185.	182±9

AGV-1

Р	F	G
11.7	21.7	11±1
63.3	69.	70±1
659.1	664.	641±4
208.5	227.	230±9
	P 11.7 63.3 659.1 208.5	P F 11.7 21.7 63.3 69. 659.1 664. 208.5 227.

f: "fused pellet" analysis
P: powder pellet analysis
F: Reported by Flanagan (1969). Zr: mean concentration estimates; Nb, Sr and Rb: isotope analysis.

G: Goodwin's (1971) x-ray fluorescence measurements.

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