# A STUDY OF THE MINERALOGY AND PETROLOGY OF THE ICE RIVER COMPLEX, YOHO NATIONAL PARK

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## Abstract

The Ice River Complex is an alkaline ultramafic intrusion located 23 kilometres south of Field, B.C. in the Ottertail and Vermilion ranges of Yoho and Kootenay National Parks. It occupies sill-like structures, with a total exposure of approximately 30 square kilometres, in upper Cambrian limestone (Ottertail Formation) in the core of the Porcupine Creek Anticlinorium.

Two distinct series are present: an early intrusion of jacupirangite, ijolite, and urtite emplaced with a carbonatite rich in mafic silicates and oxides, and a later syenitic series, associated with a zeolite and feldspar bearing carbonatite. Radiometric datings average at 245 mya. A combination of field and laboratory studies was directed toward describing the relationship between these two suites by elucidating the differentiation trends in them. A detailed discussion of field relations and mineral assemblages of the major rock types precedes consideration of the chemical evolution of the complex.

Syenitic rocks are consistently seen to intrude ultramafic (ijolitic) rocks, and were emplaced at different intrusive centres, which contraindicates derivation of the presently exposed rocks by in situ differentiation of a

homogeneous magma. The liquidus phases of the ultramafic rocks (principally perovskite and magnetite) would have been in disequilibrium with those of the syenites (sphene present), and a hypothesis invoking liquid immiscibility near the liquidus, as an explanation of the observed petrographic dichotomy, must therefore also be rejected. Strong parallelism of differentiation trends, including pyroxene composition (varying from titanaugite to hedenbergite and acmite in both suites) and mineralogical evidence of continuous equilibrium between silicate melt and the associated carbonatite suggest the syenitic series is a product of differentiation of an unexposed alkaline ultramafic magma, such differentiation occurring by the exsolution of perovskite, magnetite, and titanaugite and a silicocarbonatite, resulting in higher silica activities and reduced volatile contents in the differentiate (syenites). The widespread occurrence of dikes of pyroxenite and syenite to the northwest and regional development of synmetamorphic sodalite - cancrinite - albite - calcite viens indicate the presence of other, unexposed alkaline intrusions.

Mesoscopic layered textures in the ultramafic rocks bear strong resemblances to those occurring in other basic intrusions, notably the Skaergaard intrusion. Such layerings are best described as resulting from in situ crystallization in the presence of non-equilibrium chemical, thermal, and density gradients, which result from supercooling in the magma prior to the onset of localized, rapid nucleation of mafic silicates (pyroxenes). Layered textures which can be confidently ascribed to gravitative or convective accummulation of phenocrysts occur only immediately above the floor of the intrusion (lineated pyroxenites and perovskite - apatite cumulates).

Late stage (near-solidus) liquid immiscibility between an Fe, Ti rich liquid precipitating melanite and a basic to alkaline liquid precipitating a Ti poor grossular-andradite garnet or aegirine and natrolite, pectolite, and cancrinite is described. Melanite invariably occurs as rims and splotches on mafic substrates and is sometimes oscillatorily zoned; alternating bands of melanite - zeolite on the order of one centimetre wide also occur. Arguments are presented to the effect that the immiscibility is metastable, and may be an example of a natural chemical oscillator.

The nature of the silicate melt - carbonatite immiscibility, which is an equilibrium process, is discussed from the point of view of the shape and position of the solvus. The consolute point must be nearer the silicate side of the system, since textural and mineralogical indications of continuing immiscibility in the carbonatite are very common, but are nearly lacking in the conjugate silicate liquids.

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# A STUDY OF THE MINERALOGY AND PETROLOGY OF THE ICE RIVER COMPLEX, YOHO NATIONAL PARK

## Introduction

The Ice River Complex, located 23 kilometres south of Field, B.C. in Yoho National Park (figure 1) is one of the world's major alkaline intrusive bodies, and is the easternmost intrusion in the Cordillera. The exposed igneous rocks extend across the Ottertail and Vermilion ranges and are dissected by the Ice River and Moose Creek. Access is rendered difficult by the mountainous topography and by regulations imposed by Parks Canada. In addition to the noteworthy geology and mineralogy of the area, it is a sensitive grizzly bear habitat.

The igneous rocks occur in two separated bodies: an elliptical mass of pyroxenite centred on Sharp Mountain (figure 2) and a larger body of pyroxenite , ijolite, and nepheline syenite comprising the mountains and ridges of the Ice River valley. The total exposure amounts to approximately 30 square kilometres. The complex occupies the core of the Porcupine Creek Anticlinorium (Price et al, 1978), although the magnitude of folding in the immediate vicinity of the complex is much reduced compared to that on line with the antiformal axis to the northwest (Currie,1975). The country rock is comprised of middle to upper Cambrian and lower Ordovician shales and carbonates of the Chancellor and Ottertail formations and the McKay Group (Allen, 1914), with most igneous rocks occurring in sill-like structures in Ottertail limestone. Post-intrusive folding and faulting in the Mesozoic was largely restricted to the less competent sedimentary rocks, leaving the complex relatively unaffected. Glacial erosion has produced spectacular exposures ideal for field study.

The age of the complex has not been determined with precision. Gussow and Hunt (1959) after studying contact relations near the head of Shining Beauty Creek reported that major thrusting had occurred at or near the contact, and that a regolith was preserved, overlying the roof of the complex. They concluded that the igneous rocks are a sample of Precambrian basement, and that the sedimentary rocks immediately above the "regolith" are also Precambrian. Kaersutite from the syenite at Sodalite Creek has yielded a potassium-argon age of 421 +/- 11 million years (Gussow, personal communication) which may be erroneously young due to re-setting of the radiometric clock during metamorphism.

However, published conclusions by all other investigators (eg., Currie, 1975; Gussow and Price et al, 1979) disagree with this interpretation, and state that the contact is demonstrably of an intrusive nature, except where deformation and metamorphism have locally obscured its features. Currie (1975) assessed potassium-argon dates he obtained from phlogopite and whole-rock rubidium-strontium dates obtained by Rapson (1963) and gave a best estimate of the age of the complex as 245 million years. Descriptions of contact metamorphic structures, textures, and mineralogies are given by Rapson (1963).

The Ice River Complex is a highly differentiated intrusive body. The range of rock types present is encompassed by ultramafic pyroxenite (jacupirangite) through nepheline syenite and sodalite syenite; a large plug of carbonatite also occurs within the ultramafic rocks on the west side of the Ice River (Garnet Cirque). An interpretation formulated by Allen (1914) is that all rocks present were derived from a homogeneous magma, which differentiated by gravitative accumulation of successively less dense solid phases. Allen did not recognize the igneous nature of the carbonatite, believing it to be a limestone inclusion. His model was elaborated upon by Campbell (1961) who attempted to trace the differentiation trends of the complex by projections into the system $SiO_2$ - $NaAlSiO_4$ - $KAlSiO_4$.

Currie (1975) concluded that the ultramafic (ijolitic) and syenitic portions of the complex represent two separate differentiation series derived from different magmas. He further concluded that these magmas were an immiscible conjugate pair of liquids, which separated from a lamprophyric magma at some unknown depth, the ijolitic liquid intruding and solidifying first.

This study of the Ice River Complex was directed towards resolving the syenite - ijolite relationship by elucidating the differentiation trends in each. During the course of the investigation, new and hitherto unpublished observations on the geology and mineralogy of the complex were made which permit a more accurate definition of these trends than was possible before. It will be proposed that there are two separate silicate liquid differentiation trends, as deduced by Currie, but that these are very closely related, and did not result from silicate - silicate immiscibility. The observed trends in mineralogy and bulk rock composition are more readily explained by differentiation of an alkaline ultramafic liquid, with the parental magma corresponding to the present ultramafic rocks and the differentiate to the syenite suite. An immiscible carbonatite was intruded simultaneously with both rock types, and the differentiation trends can also be traced through its variable mineralogy.

In the short time available to conduct field studies, only selected portions of the complex could be visited. This paper therefore draws heavily on observations by Allen and Currie, who have produced the definitive works on this area, and both authors will be referenced in an informal manner.

## Access and Investigative Methods

The mouths of the valleys of the Ice River and Moose Creek can be accessed by a rough logging road in the valley of the Beaverfoot River (Crozier Road); a fire road running parallel to the Ottertail Range leading directly from the Trans-Canada highway to the Ice River is also available, but this lies within Yoho National Park, and special permission must be obtained from Park authorities to use it. By the summer of 1983, it had fallen into disrepair and was not traversible by four wheeled vehicles. An excellent pack trail leads up the Ice River valley, but only very old foot paths or animal trails are to be found in the Moose Creek valley. Outcrop can only be reached by arduous and frequently treacherous climbs up steep mountain creeks or through dense bush.

Field studies were conducted sporadically during the summer months of 1981-1983. Whenever possible, traverses were conducted along streams cutting through the igneous rocks, since these afforded the best exposures. Traverses were selected on the basis of accessibility and potential for yielding information on syenite-ijolite relations. Fifty one specimens were collected (table 1, figures 4-8) and were extensively studied in thin section. When necessary, mineral identifications were confirmed or established by x-ray diffractometry, energy dispersive spectrometry, and miscellaneous chemical methods. Mineral separations were effected by the use of a magnetic separator, heavy liquids, and selective solvents. Electron microprobe analyses of the minerals in 19 specimens were performed on an ARL SEMQ instrument, using standard correction techniques following the method of Bence and Albee (1968).

## Field Relations and Petrography

The Ice River Complex presents difficulties to the field geologist, due to the considerable variety of rock types present. Rapid fluctuations in mineral content, grain size, and texture on a scale of cm to tens of metres make consistent interpretations and identification of mappable units difficult. The purpose and scope of this study were such that a new geologic map was not made; the map published by Currie was used as a guide, and was found accurate enough in its major aspects. However some details, particularly in regards to the ultramafic rocks, are highly interoretive, and inconsistent with the data collected.

The igneous rocks are readily divided into two portions on the basis of field relations and petrography: an early series of alkaline ultramafic intrusions generally lacking feldspar and containing appreciable quantities of biotite and perovskite (melteigites to urtites) and a later syenitic series, containing alkali feldspar, and amphibole and sphene instead of oiotite and perovskite. The syenitic rocks are consistently seen to intrude the ultramafic rocks; both suites were apparently emplaced simultaneously with a carbonatite of highly variable composition. The carbonatite of the ultramafic suite is very iron rich and contains large quantities of oxides and silicate minerals; that of the syenitic suite is essentially bimineralic, consisting mainly of natrolite and calcite.

Allen considered the entire intrusion to have been emplaced at one site centred under Manganese Mountain, forming a sill-like mass in Ottertail limestone thinning towards all edges. Currie observed that the ultramafics of

Sharp Mountain are discordant, and primary igneous layering there defines a pipe-like structure. Therefore, at least two intrusive sites can be recognized, corresponding to the spatial separation of the syenites and ultramafics (figure 3). The relationship between the Aquila Ridge and the Sharp Mountain ultramafic rocks is unclear; Currie considered them to be formerly connected by a lopolithic extension which was later disrupted by the syenites. The ultramafic rocks at Sharp Mountain are extremely inaccessible and were not studied.

Because of the coarse grained nature of most specimens, meaningful point count data could not be collected on modal percentages of minerals. What is more relevant to a discussion of the petrography of these rocks are the values of several intensive variables (silica activity, iron enrichment, etc.) which the assemblages define.

## Ultramafic Rocks

The Aquila Ridge ultramafic rocks form a sill like body 2500 feet thick with both large and small scale structures oriented subhorizontally, ie., approximately parallel to the contacts. These structures consist of a large, elongated central mass of carbonatite in Garnet Cirque, and a variety of primary layerings in the silicate rocks, defined by changes in mineralogy, texture, and grain size. A compositional variation across the sill is present, with the lowermost rocks rich in titaniferous and aluminous clinopyroxene, perovskite, and phlogopite (biotite melteigite to biotite ijolite) and the uppermost rocks rich in nepheline, acmitic hedenbergite, sphene, and calcite (urtite). This cryptic variation is greatly complicated by smaller scale variations, thus, urtitic schlieren are common in lower ijolites. Currie mapped a series of well defined, layered rhythmic repetitions across the sill, but this author could not observe the continuous bands that Currie recognized, which were largely based on interpretive petrographic study.

Five types of layering were noted:

(1) tabular, horizontal bodies of medium to fine grained equigranular ijolite of variable thicknesses on the order of one to tens of metres (figure 10)

(2) alternating bands 5-10 cm wide of pyroxene rich and nepheline rich material, parallel to dike contacts (figure 11)

(3) irregular segregations of pegmatitic pyroxene and nepheline (figures 12,13)

(5) horizons 1-3 metres thick consisting of thin, mafic rich bases with spindly pyroxene nucleating on such bases and growing perpendicular to them (figure 14)

(5) small scale layering (0.5-2 cm) with zeolitic bands alternating with dark melanite rich bands. These may be single or compound in layers up to 15 cm wide. (figure 15)

While such textures are common, the bulk of the ijolitic rocks have unlayered, isotropic features (eg., figure 16).

The silicate rocks near the base of the Aquila Ridge sill are very rich in perovskite, with some patches consisting of little but euhedral perovskite and apatite; these are interpreted to be cumulate rocks due to their panidiomorphic texture. More commonly, the basal ijolites consist of coarse grained and irregular purplish titanaugite and euhedral perovskite enclosed poikilitically by crystals of phlogopitic mica, with nepheline forming a matrix of variable volume. The mineral grains are randomly oriented in all cases noted. The basal ijolites are intersected by numerous carbonatite dikes, which produced white to pink or reddish zeolitic (natrolite) alteration in the silicate rocks, with the original textures largely preserved.

Minor phases in the basal ijolites are magnetite, pyrrhotite, and rare euhedral grains of diopside (figure 17). Feldspar is completely absent. The diopside is usually associated with optically isotropic melanite, which is almost entirely anhedral; rare grains show incomplete development of faces, and these are partially resorbed and oscillatorily zoned (alternating pale purple to deep wine red) (figure 18). The melanite is invariably a late mineral, forming thin rims on mafic silicate minerals and perovskite. A second set of late minerals is pectolite +/- natrolite +/- cancrinite + an andradite-grossular garnet, invariably euhedral, colourless, and weakly birefringent (figure 19). Sphene, not otherwise present, may also be associated with these minerals. Although usually spatially separated, the melanite-diopside and grossular-pectolite residua can be found within the same cavity, with the two garnets apparently stably coexisting (figure 18). Calcite can occur with either type, and is usually contiguous with other calcium rich minerals (melanite or sphene).

Moving vertically across the sill, the total content of nepheline increases and the pyroxene changes to a pale green hedenbergite. Perovskite is gradually replaced by sphene, which initially occurs as thin rims on perovskite, and finally as euhedral wedges. Simultaneously with the appearance of euhedral sphene, alkali feldspar occurs as rare interstitial and nonperthitic grains. The biotite content steadily decreases, with the mica becoming progressively iron rich.

Melanite continues as a ubiquitous phase, losing its purplish tinge and becoming a dark red brown as the iron content increases; it forms extensive rims on mafic minerals and also an interstitial phase (figure 20). Opaque schorlomite also appears, with the same textural relations, but diopside is no longer present. The coexisting alkaline residua also change character, with natrolite becoming more prominent, and the andradite-grossular garnet being replaced by aegirine. In rocks containing sphene and alkali feldspar, sodalite appears with natrolite and cancrinite. The tabular bodies of equigranular ijolite previously noted contain discrete globules of these minerals about 0.1 mm or less in diameter, enclosed in nepheline (figure 22); this feature, together with the equigranular and panidimorphic nature of these tabular bodies, is interpreted to result from dynamic disturbances during crystallization (vida infra). It is also strongly indicative of late stage liquid immiscibility, with an alkaline or syenitic (zeolitic) liquid phase separating near the solidus (the globules are common in nepheline, but absent from pyroxene or other early crystallizing phases). The conjugate liquid would correspond to the iron and titanium rich schorlomite-melanite, which also occurs in forms highly indicative of existing as a discrete, late forming liquid (figures 20,21).

The middle ijolites contain spectacular examples of primary layering. Of these, the most prominent are the tabular ijolite bodies and the layered dikes. The third type, with spindly pyroxene oriented normal to the direction of layering, is less common. Extremely long and narrow crystals of hedenbergite 20x0.5 cm radiate from multiple nucleation sites on a one cm base of magnetite-perovskite. The pyroxene is enclosed by nepheline, with the alkaline residua minerals developed interstitially. The mafic base, at least in some cases, corresponds to the lower contact of an ijolite dike; the acicular texture is weakly developed in layered dikes, which exhibit symmetrical rhythmic repetitions of light and dark silicates.

The fifth type of layering occurs mostly in areas with extensively developed reddish or pinkish alteration of nepheline, referred to as hydronepheline by Allen. This alteration is not associated with carbonatite dikes, but rather with local concentrations of zeolitic rocks. The textures are frequently pegmatitic in such areas, with single crystal nepheline blocks up to 30 cm wide. As noted, the layering consists of repetitions of alkaline and melanite residua, usually composite. Single repetitions may be found in the tabular ijolite bodies.

The uppermost ultramafic rocks are principally urtitic (greater than 60 % nepheline) with deep green pyroxene. Although the optical properties of the pyroxene suggest it is acmitic, microprobe analysis reveals only a moderate increase in sodium content (approximately 3 % $Na_2O$). As a rule, the urtites are extremely coarse grained, and consist of a maze of dikes 10 metres or less across, which can only be identified from a distance; their contacts are obscured at close range by their pegmatitic textures. The layering so prominent in middle ijolites is only weakly developed, and consists of simple textural variations: the zeolitic type is absent. Currie noted common development of alkali feldspar and wollastonite in urtites, and they are also characterized by late crystallizing primary calcite and highly birefringent cancrinite (figure 23). Biotite, an important mineral in nearly all ijolites, is relegated to a secondary role, occurring as flecks in or rims on pyroxene.

The carbonatite occurring with the Aquila Ridge ultramafics is of three types: a black-weathering, iron rich variety, a buff-weathering calcite rich type associated with it, and a red-weathering type. The red-weathering type is presumed to be later than the other two, since it cross-cuts the buff variety (figure 25).

A flow differentiated dike of black carbonatite 20 cm wide occurring in the middle ijolite sequence was carefully studied. At the contact with the ijolite, fluidal textures are preserved as streams of amorphous elemental carbon in a matrix of tetranatrolite. The carbon is variously impure; one segregation qualitatively analyzed with an energy dispersive spectrometer contained large amounts of cerium, manganese, and iron. At locations removed from the contact, the carbon is intimately associated with grass-green berthierine occurring in angular interstices between laths of manganese rich calcite. Spherical aggregates of berthierine, frequently joined by thin "necks", are present in calcite (figure 27) and in interstices with a complex iron rich matrix of uncertain mineralogy (figure 28). This texture is strongly indicative of immiscibility between an iron rich silicate liquid and the carbonate liquid. The berthierine also occurs in discrete bands parallel to the contact.

The centre of the dike consists of phenocrysts of siderite in a matrix of calcite. Equant and slightly rounded crystals of siderite one cm wide are also found in the berthierine rich regions. At one point, the dike swells to a width of 30 cm, with the centre occupied by a lenticular mass of the buff weathering carbonatite which is nearly pure calcite. A very sharp contact reinforces the impression of liquid immiscibility described above.

Other minerals occurring in the dike are: an iron rich biotite, generally forming anhedral masses associated with berthierine; equant crystals of aegirine, which is also present as large numbers of needles in calcite; two zeolites (natrolite and the rare barium zeolite edingtonite); perovskite; ilmenite; and very minor sphalerite. No other sulphides were recognized, although pyrite is present in small quantities in the calcite segregation.

The black carbonatite associated with the basal ijolites is very similiar to the above description, except that natrolite is more prominent (figure 29) and perovskite is extremely common (about 10 % by volume), occurring as perfect pseudo-octahedra up to 1.5 cm wide. This is consistent with the large quantities of euhedral perovskite present in the contiguous silicate rocks.

The red carbonatite is similiar to the black, but important differences exist. The content of non-carbonate minerals is much reduced (less than 10 %) and siderite is absent, as is any zeolite mineral. The rare earth element minerals present are pyrochlore and xenotime; the serpentine present is distinctly yellow-brown rather than green, and textures indicative of liquid immiscibility are only weakly developed.

The main body of carbonatite in Garnet Cirque was not studied, but descriptions by Currie and Rapson (1964) indicate it consists principally of the buff-weathering type. Pyrite is present in local concentrations up to 5 %.

The ultramafic rocks at Buttress Peak are only superficially similiar to those at Aquila Ridge. At and near the lower contact with the sedimentary rocks, a prominent orientation in titanaugite (lineation) is developed; the rock is nearly pure pyroxene, and the crystals are highly idiomorphic (figure 31). The rock is also anomalous for containing large perovskite and euhedral sphene. These features are strongly indicative of flow differentiation, particularly since perovskite and sphene are mutually exclusive under conditions of equilibrium crystallization. Melanite is rare or absent, and no zeolitic minerals are present.

The ultramafic rocks above the contact are severely brecciated by leucocratic syenite, and exposures are discontinuous (figure 30). Currie mapped the same sequence of rhythmic repetitions in this area that he did at Aquila Ridge, but this also is highly interpretive, since insufficient ultramafic rocks are available to map in such detail. A sample of one included block well away from the contact contains minerals and textures similiar to the middle ijolites of Aquila Ridge, but the pyroxenes are more acmitic; it is also noteworthy that the titanaugite of the cumulate contact rock is enriched in iron relative to that of the basal ijolites, and contains abundant exsolved ilmenite. The Buttress Peak ultramafics also bear significant quantities of calcite, similiar to the Aquila Ridge urtites. From the field and petrographic evidence, it is evident that the processes of formation and the composition of the magma which produced the Buttress Peak ultramafics were somewhat different than that at Aquila Ridge; the distinct iron enrichment indicates they are probably later forming.

Syenitic Rocks

The syenitic suite encompasses rocks ranging from fine grained amphibole jacupirangites to coarse grained nepheline syenite and sodalite syenite. The mafic members of the suite bear little or no feldspar, but are readily differentiated from analogous members of the ultramafic suite by containing sphene instead of perovskite, and a titanium rich alkali amphibole rather than phlogopite; biotite, when present, is usually subordinate. These mineralogical distinctions persist in all members of the syenite suite, and rocks transitional from the amphibole jacupirangite to nepheline syenite are common. Therefore,

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although the former are not true syenites, their petrographic continuity to and spatial association with true syenites requires a common term.

The syenites occur mainly as an irregular mass centred on Manganese Mountain, with the feldspar and sodalite rich varieties concentrated in the centre; an extension across the Ice River to Aquila Ridge provides a link with the ultramafics there. A weak primary layering in the nepheline syenites defines a pipe-like structure in the core. The surrounding rocks are a complex breccia of mafic members of the suite and sedimentary and ultramafic inclusions laced with viens and dikes of pale nepheline syenite (figures 32-34). Minor occurrences of syenitic rocks are to be found between ultramafic rocks and country rock at both Sharp Mountain and Garnet Mountain, according to the mapping of both Currie and Allen.

Three major intrusive events of syenite can be identified both at Buttress Peak and Aquila Ridge, with identical rocks occurring at both localities (figures 32,34); they constitute the series amphibole jacupirangite - amphibole foyaite - nepheline syenite, intruding in that order. The most mafic member of the triad is generally texturally anisotropic, with strong alignment of mafic minerals producing a well lineated and foliated fabric. The orientation of this fabric was randomized by later intrusions, but bears striking similiarities to that of the ultramafic pyroxenite of Buttress Peak, in that it is panidimorphic and the volume of intercumulate (sic) nepheline is very small.

The amphibole jacupirangites are characterized by fine grain size (generally less than 3 mm) and subequal amounts of kaersutite and titanaugite, identical in composition to that of the titanaugite of the basal ijolites. Apatite and sphene are very prominent accessories; nepheline is usually minor, irregular, and interstitial within the mat of mafic minerals. Magnetite is a minor phase, but sulphides are notably absent. A peculiar variation of this material contains discrete blobs 1-3 mm across of bluish white nepheline, arranged in laminae parallel to the foliation of mafic minerals (figure 35).

Rocks transitional between the amphibole jacupirangite and nepheline syenite are highly variable in texture, but bear a consistent mineralogy. Pale green hedenbergitic pyroxene, frequently with purplish cores partially replaced by kaersutite, exist independently, in glomeroporphyritic mats with, or poikilitically enclosed by idiomorphic kaersutite crystals. Nepheline is idiomorphic, and alkali feldspar occurs as irregular interstitial grains or less commonly as laths; it is usually nonperthitic. In one specimen (81-IR-12) rare grains of plagioclase feldspar are present, normally zoned from An37 to An25. Late developing sodalite exists in interstices and as lobate embayments replacing nepheline, and moderately birefringent cancrinite-vishnevite is also freqently present. A fine grained alteration of alkali feldspar of uncertain mineralogy (natrolite?) is commonly developed. Layering, though less prominent than in the jacupirangites, is present in the form of elongated glomeroporphyritic mats and streaked out inclusions of amphibole jacupirangite.

The leucocratic nepheline syenites are extremely variable with respect to texture and mineral content. Most commonly they are comprised of an isotropic interlocking network of white to pale green or grey laths of highly perthitic alkali feldspar, frequently coexisting with plagioclase feldspar An0 or more rarely microcline. Sodic hedenbergite and barkevikite are usually present in subordinate amounts, as are sphene and occasionally pale yellow-brown melanite. Sodalite is an essential mineral, but a continuous gradation to sodalite syenite is not observed. The sodalite syenite occurs as irregular and discontinuous stringers, with streams of deep green aegirine and a variety of sulphide minerals which remain largely unidentified. Pyrite occurs with the deepest blue varieties, but the sodalite may be nearly colourless or have a pale green tinge.

A rare variety of syenite contains a deep purple fluorite in association with euhedral crystals of sodalite (not otherwise noted) and pyrochlore. The purple fluorite is confined to those grains in direct contact with the pyrochlore, and it may be assumed that the colour is due to destruction of the fluorite crystal lattice by radioactive components of the pyrochlore. A whole-rock gamma ray spectrum of this material indicates it contains approximately 250 ppm of uranium.

The carbonatite associated with the syenites is radically different from that occurring with the ultramafic rocks, in that the only silicate minerals present in it are feldspar (pure albite) and zeolites. The presence of edingtonite provides an important link with the black siliceous carbonatite of Aquila Ridge, but it is relatively rare, and natrolite is the usual zeolite. The carbonate present is pure calcite; siderite and manganese rich varietites are absent. A strong tendency to coarse grain size and vuggy textures predominates.

According to Currie, the natrolite-calcite rocks occur in sheet-like bodies at or near the contact of the mafic breccia with ultramafic and country rocks. Dikes of carbonatite are also very common at the contact between the breccia and the nepheline syenite. The country rocks above the breccia roof at Aquila Ridge have been subjected to considerable metasomatism, with large crystals of natrolite and minor aegirine and calcite forming vuggy growths in a highly altered feldspar pegmatite.

Lamprophyres

Many black weathering lamprophyric dikes are present in the igneous rocks and contiguous country rocks; a green weathering type with large phenocrysts of phlogopite is very common in the float along creeks cutting through ultramafic rocks at Aquila Ridge, though this was not found in outcrop. The former type very often swarms with inclusions (figure 36) now altered to fine grained mats of chlorite and calcite.

Petrographically, the lamprophyres are distinct from any plutonic rock in the complex. They contain shattered and corroded phenocrysts of olivine and augite, or weakly pleochroic titanaugite, in a fine grained groundmass of pyroxene, pale orange phlogopite and calcite, with small, irregular grains of alkali feldspar. Several of the pyroxene grains have rounded cores and faceted overgrowths of later pyroxene, indicating a complex crystallization history.

The field relations indicate that most of the dikes were emplaced after the main mass of syenite, and are concentrated around the southern contact and the roof. Analyses given by Currie show that the lamprophyres are considerably enriched in nickel and chromium and deficient in barium, zirconium, niobium, and cerium relative to the plutonic rocks. Currie considered the lamprophyres to be samples of the primary ijolitic liquid, but the evidence is against this, and they are likely to remain as enigmatic as any lamprophyre is.

## Mineralogy

Allen provided an extensive list of the minerals he identified in the igneous rocks and associated metamorphosed country rocks; the extreme variety and unusual compositions of these minerals are typical for alkaline complexes. The following discussion focusses on the occurrences and properties of these minerals relevant to a description of the differentiation trends of the complex.

### Oxides and Related Minerals

Magnetite is present in all igneous rocks except sodalite syenite, urtite, and carbonatite; ilmenite appears

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only as small blades in silicocarbonatite. Magnetite is predictably most common in the mafic members of each suite, occurring as rounded or irregular grains, frequently surrounded by a mat of green aegirine. It occurs in unusually large local concentrations in fluorite - pyrochlore syenite, forming slightly rounded octahedra up to 5 mm wide.

The magnetite of the syenite suite is very heterogeneous to the electron microprobe, presumably due to exsolution of hematite/ilmenite. Magnetite in the ultramafic rocks is homogeneous, though normally zoned from Us45 to Us25; analyses are given in tables 2 and 3. X-ray diffraction analysis of the highly magnetic components of an ijolite (82-IR-17) reveal that some exsolution has occurred, since minor peaks of ilmenite and giekelite are present.

An unusual mixture of amorphous oxides and elemental carbon is present in the base of the silicocarbonatite, intimately associated with tetranatrolite (figure 26) and also berthierine. A clean separation of the natrolite-oxide mixture produced the x-ray pattern only of the natrolite; although iron Ka radiation was used, the background level was virtually zero. Microprobe analyses of opaque clots in berthierine produced an analysis equivalent to that of the berthierine, but with a weight total more than 10% lower than an analysis of clean berthierine. The presence of elemental carbon is confirmed by soaking the material in organic solvents; the residue after drying is sticky. One qualitative analysis by energy dispersive spectrometry of a discrete patch revealed the presence of large quantites of manganese and cerium and moderate amounts of iron. Impure iron oxides are also found with the carbon by the same method.

Pyrochlore is present in some rocks of both suites. It occurs as pale brown octahedra in red carbonatite, together with xenotime, and as deep yellow brown octahedra associated with purple fluorite in a very rare type of syenite. The yellow variety is uraniferous, as indicated by gamma ray spectroscopy and contiguous purple fluorite.

Perovskite and Sphene

Allen noted the presence of perovskite in several igneous rocks, as well as in skarn rocks, but he describes the mineral as very rare, and also as occurring with feldspar. This is inconsistent with the mutual exclusion of perovskite and feldspar with respect to silica activity (Nicholls et al, 1971). Currie reported only one ambiguous occurrence of perovskite but from his descriptions of the ultramafic rocks, it is plain that he mistook it for a dark sphene.

Perovskite only occurs in the feldspar free portions of the ultramafic rocks, but in those it is abundant, forming up to 10% by volume of the lower ijolites and melteigites and associated carbonatites. It occurs as perfect pseudo - octahedra, with (001) terminations, and also as dodecahedra, both up to 1.5 cm across. These large crystals show complex growth patterns, including hopper growth, and are riddled with white, yellow, and green apatite. In thin section, the euhedral forms are dark chestnut brown, with complex lamellar twinning and low birefringence (about .012) (figure 37). In homogeneous ijolite (tabular ijolite) the perovskite has a distinct purplish cast, is rounded or irregular in outline, and displays both normal and oscillatory zoning.

An opaque variety is present in many ijolites, but is always irregular and surrounded by a rim of translucent perovskite with very high relief which displays the lamellar twinning. It differs from the translucent variety in containing about 12% rare earth elements, compared to about 6% in the latter (table 4). Energy dispersive spectrometry reveals these are principally Nb, Ce, and Sm, with very minor quantities of Nd and Y indicated. Microprobe traverses across opaque perovskites reveal the presence of normal zoning, the total REE content decreasing towards the rim. In rare examples of ijolite where subidiomorphic sphene began crystallizing shortly after perovskite, both minerals are very impure, particularly the sphene, which is dark and iron rich.

Sphene is the characteristic accessory mineral in feldspar bearing ijolites and in all syenitic rocks except sodalite syenite. It is also associated with the basic residua in biotite melteigite, although it is never present as a pre-immiscibility mineral in these primitive rocks; in rocks transitional to feldspar bearing ijolites, it commonly forms thin rims on perovskite and can pseudomorph it.

The amphibole jacupirangites and foyaites contain large quantities of sphene as honey-yellow to orange-yellow euhedral wedges, oriented parallel to the layered fabric. The total content of sphene in syenitic rocks closely parallels that of pyroxene and amphibole.

## Sulphides

The only sulphide identified in the ultramafic rocks was pyrrhotite, which forms small (less than 2 mm) irregular and disseminated grains. Sulphides are absent from urtite and all syenitic rocks except sodalite syenite.

Pyrite is present in the buff carbonatite; Currie noted local concentrations up to 5% in the central carbonatite plug. The silicocarbonatite contains a few small grains of sphalerite, but no other sulphide was found.

At least two sulphides occur in the sodalite syenite. The deepest blue varieties of sodalite are associated with pyrite. The other mineral, a non-magnetic, silver-grey sulphide or arsenide, remains unidentified. Small sulphide bodies occur in metasomatized country rocks; a small deposit at Shining Beauty Creek was formerly worked for pyrite, galena, chalcopyrite, and others (Allen, page 230). A lamprophyre sill on the east face of Zinc Mountain contains substantial quantities of pyrrhotite (Currie, page 9).

## Garnet

A titanium andradite (melanite) is present in all samples of ijolitic rocks, varying in quantity from small, insignificant flecks on pyroxene to a major interstitial mineral which may comprise 15% of the rock. Its appearance in thin section is highly variable, ranging in colour from very pale purple-pink to deep purple-brown or red-brown; an opaque schorlomite with intense purple reflection is also present. Non-opaque melanites are completely isotropic, and occasionally are oscillatorily zoned.

The textures of the melanite indicate that the mineral precipitated from an iron and titanium rich interstitial liquid, which preferentially adhered onto the surfaces of other mafic minerals, although rarely it is found between grains of nepheline (figure 20). The intense purple colour is undoubtedly due to the presence of $Ti^{3+}$, but the red-brown colour colour has been shown to be due to $Fe^{2+}$ (Huggins et al, 1981). Deep red-brown melanite reverts to a pale golden yellow when heated in an oxidising atmosphere, and the presence of these reduced ions is a definite indicator of very low oxygen fugacities. Golden brown melanite appears in the nepheline syenites (though absent from more mafic members of that suite) but commonly as subidiomorphic grains not associated with pyroxene or other mafic minerals, in contrast to the mineral in the ultramafic rocks (figure 38).

A grossular-andradite garnet is also present in the primitive ultramafic rocks, associated with basic or alkaline minerals (pectolite, cancrinite, and natrolite). This garnet is optically complex, being colourless and anisotropic (with a birefringence of about .006) and exhibiting a complex form of sector twinning. The mineral strongly resembles corundum in appearance, and it is likely that it is the corundum which Allen identified in biotite melteigite. Although polymineralic, the vugs and cavities containing the grossular also give the impression of having originated as a discrete liquid phase, particularly since the basic minerals are not disseminated throughout the rock. As discussed previously, these textures indicate late stage immiscibility between an iron rich melt and a basic to alkaline melt.

The existence of contiguous grains of melanite and grossular - andradite implies the existence of a solvus between the two minerals, which is substantiated by the difference in structure indicated by contrasting optical properties. Microprobe analyses (table 5) indicate that the compositions of coexisting garnets differ in the distribution of Al (much greater in the grossular) and Ti-Fe (greater in the melanite), although anisotropic garnet in basic cavities may contain up to 19% total iron. Without having conducted Mossbauer or electron paramagnetic resonance spectroscopy, it is not possible to assign structural roles or formulae to these garnets. A microprobe traverse across an oscillatorily zoned melanite (figure 39) indicates that Ti assumes the structural role of Si, and Fe of Al. On the basis of the Mossbauer study by Huggins et al (1981) a tentative assignation of structural formulae has been made (table 6).

Biotite and Berthierine

Biotite is an essential mineral of the melteigites and ijolites, and is an important accessory in amphibole jacupirangites, melteigites, and foyaites. A progression from phlogopitic mica to an iron rich mica is readily deduced from the optical properties, and the modal quantity of mica in a given rock type is closely related to its composition.

The biotite melteigite contains large quantites of very poikilitic phlogopite, enclosing euhedra of perovskite and apatite. An analysis by Currie (page 17) shows it to be very rich im MgO (21.2%, with FeO = 8.66%). In conjunction with the trend of iron enrichment evidenced by the crystallization of hedenbergite, the more differentiated middle ijolites contain an iron rich mica (table 7). The total quantity of biotite decreases with differentiation, so that the urtites contain only secondary biotite after pyroxene. A reaction rim of biotite is commonly developed between pyroxene and basic mineral segregations. Titanium contents also decrease with differentiation; the phlogopites in biotite melteigite are so Ti rich (Currie gives 3.45%) that the normally pale mica has a strong reddish absorption. Phlogopite present in mica lamprophyres and as reaction rims around diopside nodules are virtually colourless.

Only iron rich biotites with strong bronze-green or brown pleochroism and high birefringence are present in the syenitic rocks, and they are subordinate in quantity to kaersutite. Iron rich biotite is also present in the silicocarbonatite, associated with the aluminous serpentine berthierine (analysis table 12). The berthierine was the principal component of a silicate melt which separated from the carbonatite by liquid immiscibility, and is present now as discrete globules, flow-banded streams, and interstitial material.

Pyroxene

Pyroxene is present in all igneous rock types. In both suites, it follows the trend titanaugite - hedenbergite - acmite, showing strong iron enrichment and only becoming sodium rich in highly differentiated rocks (figures 40,41; analyses in table 8). It is the principal mafic mineral in all silicate rock types, occasionally joined by subequal amounts of phlogopite or kaersutite; the pyroxenites are about 90% titanaugite by volume. Completely euhedral pyroxene crystals are not common on other rocks, due to interference by other pyroxenes and peculiar chemical gradients during growth (vida infra).

The titanaugites are typically poikilitic, with euhedral apatite the most common type of inclusion, although magnetite and perovskite or sphene may also be in this position. Opaque, symmetry controlled exsolution lamellae of ilmenite are prominent in jacupirangite pyroxenes. The edges of these and most other pyroxenes are ragged due to partial replacement by aegirine and biotite. Weak patchy zoning and normal zoning from purplish cores to greenish rims is common.

Hedenbergitic pyroxenes are less homogeneous than titanaugites, often showing strong normal zoning from purplish cores to pale green-yellow rims. Hedenbergites in the ultramafics are almost always surrounded by a rim of melanite, and often display peculiar growth patterns such as slightly curving edges and the acicular textures described earlier. A pale green-yellow to medium green pyroxene is by far the most common type in both suites. An optically acmitic variety is typical of the urtites, but is still hedenbergitic in composition (Currie, page 26). The progression in optical properties is well represented by examples from the ultramafic rocks:

Titanaugite (81-IR-6): optically positive; dispersion r>>v; birefringence =

.025; $2V_z$ = 70 degrees; Z = pale yellow brown, X=Y = purplish brown

Hedenbergite (82-IR-17): optically positive; dispersion r>v; birefringence = .03; $2V_z$ = 64 degrees; Z = pale yellow-green, X=Y = pale pistachio green

Acmite (81-IR-9): optically negative; dispersion r>v and weak; birefringence = .02? (strongly coloured); $2V_x$ = 68 degrees; Z = greenish brown, Y = dark green, X = medium green

Small quantities of euhedral diopside are present in biotite melteigite as inclusions in titanaugite (figure 17) and as nodules 0.5-3 cm wide, coated with fine grained phlogopite; these nodules are also present in some syenite and lamprophyre dikes. These would seem to be xenocrysts from an earlier phase of crystallization, probably at a higher pressure than the presently exposed rocks. Diopside also occurs with melanite as part of the iron rich residue assemblage, but only in the most primitive phlogopitic rocks.

Aegirine is a common mineral, usually associated with other alkaline phases (alkali feldspar, zeolites, and sodalite). In the ultramafic rocks, it is restricted to the alkaline residua association, where it occurs as colourless, acicular crystals, and as green to yellow pleochroic secondary mats around magnetite and titanaugite. It is widely dispersed in the nepheline syenites and in sodium metasomatized country rocks (natrolite-aegirine rocks and feldspar pegmatites). In the sodalite syenite, it forms thin wisps and bands up to 1 cm wide, but is restricted to small tufts of acicular crystals in other syenites. It is very common in the silicocarbonatite as corroded phenocrysts and swarms of fine needles in calcite.

## Amphibole

A primary amphibole is absent from all samples of ultramafic rock collected, although a pargasitic amphibole was noted as secondary after titanaugite in biotite melteigite and jacupirangite. Kaersutite or barkevikite (analyses in table 10) is a characteristic mineral of the syenite suite, forming large, idiomorphic crystals in foyaites and about 40% by volume of the amphibole jacupirangite. Twinning on (100) is very common; pleochroism is in shades of brown and orange-brown (kaersutite) or greenish brown (barkevikite) and absorptions are frequently so intense that the other optical properties are impossible to determine.

Normal zoning from orange cores to greenish rims is common, and the cores of titaniferous pyroxenes, particularly those with rims of hedenbergite, are very often replaced by kaersutite. A very poikilitic kaersutite is present in amphibole melteigite (81-IR-16) and is texturally equivalent to the phlogopite of the biotite melteigite.

## Nepheline

Nepheline is the principal felsic mineral of the complex, occurring in all rock types except carbonatite and very sodalite rich syenites. Analyses are given in table 11, and the nephelines are non-stoichiometric, containing variable amounts of the kaliophyllite molecule and excess quartz, which is present in greatest amounts in nephelines from syenites. Anomalously large amounts of calcium are present in the nepheline from the pyroxenite of Buttress Peak, which may result from its being a phase intercumulate to very calcium rich minerals (pyroxene, apatite, sphene, and perovskite).

Most nephelines in melanocratic rocks are crowded with inclusions, including apatite, aegirine, and rosenbuschite (Allen, page 162). Curved bubble trains, now crystallized, are common in nephelines from tabular ijolite bodies, and larger globules of alkaline residua are also present.

Nearly all grains of nepheline are replaced to some extent by cancrinite or vishnevite. Calcite, when included in nepheline, is invariably surrounded by a rim of highly birefringent cancrinite. In most syenites and in sphene bearing ijolites, sodalite also replaces nepheline, forming lobate embayments originating in interstices.

## Feldspar

Alkali feldspar is the dominant phase of the nepheline syenites, where it forms an interlocking network of platy crystals. In such rocks, it forms complex perthitic textures of several varieties (string, rod and interlocking, as described by Deer et al 1977, page 313). Microcline is very rare; only one occurrence of plagioclase feldspar was noted, in the amphibole foyaite (81-IR-12) where it is rare, and normally zoned from An37 to An25 (determined optically).

No microprobe analyses of feldspar are reported here, but Currie (page 41) notes that the host phase of the perthites is potassium rich. This is consistent with the composition of the rare interstitial, homogeneous alkali feldspar found in sphene bearing ijolites, which has the optical properties of orthoclase, as reported by Deer et al (1977, page 285).

Most grains of feldspar are more or less clouded by a very fine grained, pale brown material, especially those of the contact feldspar pegmatites (82-MC-1A). Although this material is too fine grained to identify optically, its association with natrolite in the upper contact rocks (81-IR-15) and in zeolite - feldspar carbonatite (Currie, page 45) suggests it is principally natrolite.

Carbonates

Carbonate minerals are ubiquitous in the ultramafic suite, occurring as deuteric phases in all silicate rocks and as the prinipal component of the carbonatites. Microprobe analyses reveal that calcite in the silicate rocks is virtually pure, but varies from pure calcite in the buff carbonatite to manganese rich and ankeritic types (table 12; see also Rapson, 1964). Large numbers of siderite phenocrysts occur in the silicocarbonatite; they are concentrated as 1 mm crystals in flow bands in the centre of the dike sample (83-IR-3) and also as 1 cm, slightly rounded crystals dispersed between the centre and the carbon bearing base. No analyses of carbonates from the syenitic carbonatite were made, but one specimen collected (83-IR-6) contains patches of pink and green carbonate; these may be rhodochrosite and smithsonite.

Calcite is rather rare in the silicate syenitic rocks, but is very commonly associated with both melanitic and zeolitic segregations in the ultramafic rocks. It is a common phase in the urtites, forming irregular grains which are always surrounded by a reaction zone of highly birefringent cancrinite(figure 23).

## Zeolites and Related Minerals

Zeolites and related minerals are observed in four associations; in alkalic residua in ultramafic rocks (natrolite, pectolite, and cancrinite), in carbonatites (natrolite and edingtonite), in metasomatized country rocks (natrolite), and as secondary minerals after nepheline and alkali feldspar (natrolite, cancrinite - vishnevite, and sodalite). A single pectolite analysis is given in table 12; analyzed natrolites from alkaline residua are stoichiometric. An unusual tetragonal natrolite is associated with carbon in the silicocarbonatite; this mineral has been reported from the Ilimaussaq intrusion in Greenland (Andersen et al, 1969). The barium zeolite edingtonite in the silicocarbonatite is also stoichiometric, with only trace quantities of Ca, Na, and K present.

Sodalite is widespread in sphene and alkali feldspar bearing ijolites and in foyaites and syenites. Most commonly, it occurs as irregular interstitial growths with curved rather than angular edges, due to replacement of nepheline. Euhedral dodecahedral crystals are present in the rare pyrochlore - fluorite syenite, which lacks nepheline; in all cases, it is spotted and viened with a weakly birefringent vishnevite. A beautiful deep blue variety is dispersed in many syenites, and colourless and pale green or blue types are common. The most intensely coloured material is present as discrete bands in syenite associated with streams of green aegirine; these bands frequently display brecciation textures, and may be related to the synmetamorphic sodalite - albite - cancrinite - calcite dikes developed regionally (Balkwill, 1969).

Primary cancrinite is only present in primitive ultramafic rocks. A more weakly birefringent variety (corresponding to the sulfatian variety vishnevite) is widespread as a secondary mineral in nepheline syenite.

## Miscellaneous Minerals

A complete list of miscellaneous minerals from this complex would be prohibitively long, and only a few important ones will be mentioned here. Apatite is widespread in all silicate rocks, particularly the melanocratic varieties, but is inexplicably absent from the carbonatites. A hydroxy apatite forms spherical, radiating aggregates 10 cm across in urtitic rocks (83-IR-17) poikilitically enclosed by pegmatitic pyroxene. Vesuvianite with an identical habit was found in a pure perthite syenite.

Zircon is present in some syenites, but is not particularly common. The isostructural mineral xenotime is present in the red carbonatite. Rinkite is present in a very curious nepheline-free syenite dike; two samples of this material were found 500 vertical feet apart at Aquila Ridge (samples 82-IR-6 and 13) with the lower one intimately associated with dark lamprophyric rocks and containing diopside nodules. A partial rinkite analysis is given in table 12; energy dispersive spectrometry reveals the only element missing from the analysis is zirconium.

Fluorite is invariably associated with sodalite, and is usually identifiable in hand specimen by its purple colour. As noted previously, this colour is especially intense in rocks bearing uraniferous pyrochlore.

# PETROLOGY

## I Intensive Variables During Crystallization

The lack of mineral assemblages which can be used to calculate temperatures and pressures from calibrated mineral equilibria places constraints on the precision with which these variables can be known. For example, ilmenite is absent as a primary phase from all silicate rocks so that the geothermometer of Buddington and Lindsley (1964) cannot be used. The potential for alkali feldspar-nepheline geothermometry is present, but the results of such calculations are erratic: the strongly perthitic nature of most feldspars precludes accurate analysis, and all rocks crystallized with high volatile content, so that subsolidus re-equilibration must be expected.

From estimates of the thickness of the overlying sediments at the time of intrusion, Currie estimated the total pressure to have been 2.5 to 3.0 kilobars; the presence of a homogeneous magnetite solid solution suggests a lower temperature limit of 975 degrees ~~Currie,~~ and of phlogopite at water pressures on the order of 1.0 kilobars gives a maximum temperature of 1050 degrees (Currie, page

60). These estimates must be considered very tentative, but constitute reasonable values for a temperature slightly below the liquidus of the ultramafic rocks.

The absence of pyrite in the biotite melteigite sets an upper limit on the fugacity of S2. Using the pyrrhotite geothermometer of Toulmin and Barton (1964) and the composition of the pyrrhotite in sample 81-IR-6 (Fe/S = 0.97) this limit is log[f(S2)] = -2.71 at 975 degrees. This permits an evaluation of the upper limit on the fugacity of oxygen, by the equation:

$$(1)\ Fe_3O_4 + 3/2\ S_2 = 3FeS + 2O_2$$

Using the composition of the core of the magnetite in 81-IR-6 with the pyrrhotite solution model of Froese (1976) and thermodynamic data from Helgeson et al (1978) this limit is log[f(O2)] = -12.4 at 975 degrees. This is well below that corresponding to the stability field of ilmenite, which is log[f(O2)] = -10.6, according to Spencer and Lindsley (1981).

The presence of deep red melanite indicates large quantities of ferrous ion and very low oxygen fugacities (Huggins et al, 1981), probably below the iron-wustite buffer (Virgo and Huggins, 1977). At 975 degrees and one bar solid pressure this corresponds to log[f(O2)] = -15.46 (Darken and Gurney, 1945). According to the study by

Huggins et al the increasing opacity of melanite, a distinct trend in the ijolites of Aquila Ridge, corresponds to decreasing values of oxygen fugacity. This trend is the reverse of cooling in more "ordinary" mafic liquids. The mobility of $H_2$ over that of $O_2$ is about 1000 times in silicate liquids (Carmichael et al, 1974, page 328). This produces oxidizing conditions by favouring the right side of the equilibrium:

$$(2)\ H_2O = H_2 + 1/2\ O_2$$

The decreasing oxygen fugacities in the ijolites indicates they became progressively dehydrated as they crystallized. A steady reduction in the content of volatile bearing phases is a noteworthy feature of the petrography of the ultramafic rocks: biotite steadily decreases in quantity, despite the net iron enrichment during cooling, and zeolitic minerals (natrolite and pectolite) are rare or absent in the urtites. It may be assumed that $H_2O$ as well as $CO_2$ was continually "siphoned off" due to the continuing presence of the carbonatite - silicate melt solvus, with $H_2O$ being further fractionated into the carbonate melt.

The appearance of wollastonite in the urtites is anomalous, since wollastonite lies well off the trend in pyroxene compositions with continuing differentiation (cf.

figures 40,41). Its growth is probably due to the increase of silica activity in the presence of excess deuteric calcite near the solidus:

$$(3)\ CaCO_3 + SiO_2 = CaSiO_3 + CO_2$$

Since relatively pure wollastonite occurs in the urtite, a knowledge of $a(SiO_2)$ should permit an estimate of $f(CO_2)$ at this point. Using standard thermodynamic data from Helgeson et al (1978) at a constant pressure of 2.5 kilobars, the following equation may be derived by least squares:

$$(4)\ \log[a(woll)f(CO_2)/a(SiO_2)a(cc)] = 3696/T - 7.29$$

Since alkali feldspar is present in small amounts with nepheline, the value of $a(SiO_2)$ must be near the nepheline - alkali feldspar buffer (Nicholls et al, 1971). At T=900 degrees and P=2.5 kilobars, this is $\log[a(SiO_2)] = -0.72$. Assuming unit activity of calcite and an activity of wollastonite equal to its mole fraction in the solid solution yields $\log[f(CO_2)] = -4.78$. This is likely to have been relatively constant throughout crystallization of the ultramafic rocks, since calcite is present in most ijolites, and those rocks with lower $a(SiO_2)$ (feldspar and/or sphene absent) contain pyroxene poorer in the $CaSiO_3$ component. The carbonatite would also exert a buffering effect on f(CO2) throughout crystallization.

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## II Differentiation and Production of the Syenite Suite

From the field and petrographic evidence, one can only conclude that the ultramafic and syenitic suites represent two separate differentiation series. The ultramafic rocks constitute a complete variation from pyroxenite to urtite, and the most mafic syenitic rocks, containing abundant kaersutite, could not have been derived from the magnesium and titanium depleted residual liquids of the ijolites. The syenites clearly intruded later than the ultramafics, and also at different locations. Therefore, the simplistic approach of Allen and Campbell must be rejected, ie., that all igneous rocks exposed were derived from a homogeneous magma.

There are also difficulties inherent in Currie's hypothesis of liquid immiscibility between the magmas giving rise to each suite. Definitive field evidence for such a process, such as exsolution textures, is lacking, and the differentiation trends of each suite do not display the features inherent in such systems. In general, for established cases of immiscibility, strongly divergent trends are immediately apparent, eg., sulfide-silicate liquids (Roedder, 1979), carbonatite-ijolite (Nash, 1972, and this paper), and siliceous-ferrous glasses in lunar rocks (Roedder and Weiblen, 1971). It is well known that silicate-silicate immiscibility in natural compositions is almost universally a subliquidus phenomenon, and is frequently metastably sub-solidus (Carstens, 1979). In order for immiscibility to be a viable mechanism for differentiation on such a large scale as the Ice River Complex, it must occur near the liquidus, with both liquids being in equilibrium with a mutual set of solid phases at the time of separation. However, the ijolites (perovskite-no feldspar) began crystallization at much lower silica activities than the mafic syenites (sphene +/- alkali feldspar) and the two liquids could therefore not have been in equilibrium at the liquidus. Textures strongly indicative of liquid immiscibility are widespread in the ultramafic rocks, but such separation always occurred near the solidus, and there is evidence that it was not an equilibrium process (vida infra).

A closer examination of the two suites reveals remarkable parallelism in their chemical evolutions, especially in pyroxene composition. Although the trend in the syenitic rocks follows a slightly more titanium poor path, it is virtually identical to that of the pyroxenes of the ultramafic rocks (figures 40,41). Both major intrusions were accompanied by simultaneous emplacement of a carbonatite, with that coexisting with the syenites displaying the same characteristics as the silicate rocks, with respect to their ultramafic counterparts: a net enrichment in Al, Na, and K over Mg, Ti, and Fe. The depletion in Si of the syenitic carbonatite is simply a result of increasing compositional divergence along the carbonate-silicate solvus with decreasing temperatures. Remarkably, both carbonatites contain the very rare barium zeolite edingtonite. Lastly, feldspar and sodalite, two essential minerals of the late syenites, appear late in the crystallization history of the ijolites.

The only prominent differences between the two suites are: (1) a higher silica activity at the liquidus for the syenites, as described, and (2) predominance of kaersutite in the syenites, versus phlogopite in the ultramafics as the magnesium bearing hydrated mineral present. The latter is consistent with a lower value of water fugacity in the syenites relative to the ultramafics, as is the abundance of pectolite and natrolite in the latter. This recalls the unusual depletion of water in the ultramafics with crystallization.

The simplest and therefore most attractive differentiation scheme which can account for these observations is one of partial differentiation of an alkaline ultramafic (ijolitic) magma in a hypothetical magma chamber at depth, with a polyphase type intrusion of increasingly felsic syenitic liquids occurring sporadically after initial injection of the primitive ijolitic magma. The removal of liquidus phases from the magma must then result in higher silica activities and lower volatile contents, as well as partial depletion in ferromagnesian components. Removal of a silico-carbonatite (the black carbonatite) and minor amounts of perovskite, magnetite, and titanaugite would accomplish this; these are of course the very earliest phases which separated from the ultramafic liquid.

More definitive evidence for this mechanism could be established if the compositions of the magmas parental to both suites were known, but the coarse grained and extremely differentiated nature of most exposed rocks precludes this possibility. However, analogous trends are observed in other alkaline complexes, eg., Nash (1972) has postulated a differentiation mechanism for the Iron Hill alkaline and carbonatite complex very similiar to that just described. The results of differentiation identifiable at more than one occurrence of these complicated rocks strongly implies that a reproducible, equilibrium process is responsible. The ad hoc hypotheses required by Currie, such as the necessity for the denser ultramafic liquid to be injected up and over the conjugate syenitic liquid after separation, are inconsistent with this. This author concludes that more familiar and better documented processes of magmatic differentiation are not only adequate to account for the observed features of the Ice River Complex but are conceptually preferable.

## III Evidence for Non Equilibrium Processes: Igneous Layering and Late Stage Immiscibility in the Ultramafic Rocks

Historically, considerable effort has been made to account for the textural and mineralogical features of igneous rocks by the application of equilibrium thermodynamics and hydrodynamics. While this approach is largely successful for a wide range of rocks, it is observed that some systems have difficulty readjusting to changing physicochemical parameters; prominent examples include oscillatory zoning in plagioclase feldspars in intermediate magmas and pronounced supercooling (formation of glass) in siliceous magmas. Great difficulty may be experienced in accounting for or quantitatively describing such features: there is only one true equilibrium state for a given set of intensive variables, but a large (theoretically infinite) number of metastable or unstable states may be possible. A prejudice toward application of simple or familiar models has also led to an explanation of primary igneous layering in basic intrusions as resulting from gravitative or convective deposition of crystals from the melt; this constituted Currie's description of layering in the ultramafic rocks of the Ice River Complex. While the former action of such processes can be identified at the contacts with the country rocks, this author recognized none of the sedimentary features Currie reported (such as cross bedding and channel scours), though they may exist in areas not studied.

An excellent critique of this topic was presented by McBirney and Noyes (1979) with specific reference to the Skaergaard intrusion. The problems inherent in interpreting layering in this body - including density inversions which could not have formed under gravitative control, and yield strength too great to permit crystal settling - are directly applicable to the Aquila Ridge ultramafics. Three types of layering these authors described are present: cyclic layering, with alternating bands of mafic rich and mafic poor material (the layered dikes); crescumulate layering, with acicular crystals oriented normal to the direction of layering; and intermittent layering, with equigranular and homogeneous bodies alternating with those showing one or more types of other forms of layering (the tabular ijolite bodies). The prevalence of isotropic, ooikilitic textures in basal biotite melteigite and biotite ijolite strongly suggests to this author that crystal settling was not a prominent process, even in those rocks crystallizing near the liquidus (ie., rich in liquidus phases such as perovskite and magnetite), which should have begun consolidation at relatively low viscosities.

The formation of these various layerings is best described as a non - equilibrium process, caused by the supercooling generally required to induce crystallization in silicate magmas. This is an especially attractive hypothesis for the symmetrically cyclically layered dikes. As the dike cools from the margins inward, a temperature front at Tn (the temperature of nucleation, lower than the equilibrium liquidus temperature) induces crystallization of pyroxene. This results in a local gradient in the corresponding components, and a drop in the liquidus temperature of pyroxene such that precipitation of nepheline occurs before more mafic components are able to diffuse toward the pyroxene band (so called "double diffusion"). When the Tn front reaches mafic liquid again, a second burst of nucleation is initiated, resulting in cyclic layering. The preferred orientation of pyroxene crystals perpendicular to the direction of layering results from the stronger negative gradient in the proper components parallel to the layering, since many individual pyroxenes nucleate simultaneously; thus, the grains become elongated in the direction of "fresher" melt with a higher liquidus temperature. This effect is carried to an extreme in the crescumulate layering, with the length:width ratio approaching 40:1. Rocks with crescumulate textures contain less modal pyroxene than cyclically layered rocks, and it is presumed the enhanced effect is due to lower concentrations of pyroxene forming components.

The irregular pegmatitic layerings can be explained as due to local concentrations of volatile components, or in the case of nepheline pegmatites, to dilatory expansion of the crystal mush near the liquidus. Statistical fluctuations in a large volume of melt are to be expected, and unusual processes need not be invoked to explain these features.

The more enigmatic horizontal, tabular bodies of homogeneous ijolite may possibly be explained as a result of gravitative stratification, as described by McBirney and Noyes (page 541). The mechanism they propose involves convection in tabular bodies, resulting from gradients in temperature and density, and release of latent heat of crystallization to overlying magma. In the present case, exothermic unmixing of ijolitic liquid may contribute to the energy budget of such a process, and it is of importance that globules of alkaline liquid, interpreted to have resulted from dynamic disturbances in the melt, are found in such bodies (cf. figure 22).

The fine scale zeolitic - melanitic layering does not possess an analogy in the Skaergaard intrusion, and other means must be used to account for it. Textural and mineralogical evidence for late stage immiscibility between the liquids crystallizing to yield these layers has been presented; such late stage immiscibility is observed in other systems, such as some lunar basalts (Roedder and Weiblen, 1971). An important feature of this immiscibility is that it does not occur in urtitic rocks, or result in larger bodies such as the granitoid schlieren in the Skaergaard, which separated from the ferrogabbro late in its crystallization (A.R. McBirney, personal communication). This argues against it being a natural equilibrium process in the differentiation of the ijolites, as is exsolution of solid phases with progressively decreasing liquidus temperatures.

A second feature of this immiscibility is the occurrence of oscillatorily zoned melanite. Oscillatory zoning in (for example) plagioclase feldspar of intermediate magmas can be explained on the basis of magma mixing or fluctuations in P-T regimes as the diapir ascends, but such mechanisms are not available in this case. Such zoning could be accounted for by differential rates of thermal and chemical diffusion, similiar to the process invoked to account for the macroscopic cyclic layering. However, oscillatory zoning does not occur in contiguous minerals, as might be expected, and much of the colour of the melanite must be ascribed to varying quantities of reduced iron and titanium and therefore oxygen fugacity (as discussed earlier), which should be capable of rapid re-equilibration, unless temporal oscillations in melt structure are occurring.

The non - equilibrium textures so far discussed are oscillations resulting from spatial periodicities, in contrast to temporal ones, as described by Nicolis and Portnow (1973). Interesting examples of the latter are the familiar redox oscillations revealed by cerium indicators in halogen and oxy-halogen ion bearing systems, which can also produce dissipative (spatial) fluctuations (eg., Epstein et al, 1983). These oscillations cannot occur around an equilibrium state (Prigogine and Glansdorff, 1971).

Noting that melanite invariably occurs as rims on mafic substrates, I propose that the late stage immiscibility is a non - equilibrium separation induced by nucleation of iron rich liquid on such minerals, with local equilibrium enforcing the formation of the alkaline conjugate liquid. This conjugate liquid would then be free to form the observed vug-filling growths, or free- floating globules. The repetitions of melanite-zeolite horizons can then be explained as resulting from temporal oscillations, wherein components are exchanged between the two liquids, or the inherently unstable immiscibility periodically "relaxes" back into an unsplit ijolitic liquid. Fluctuations in melt structure (degree of polymerization) and therefore oxygen fugacity would form a necessary part of this process.

This contrasts with the equilibrium immiscibility between ijolite and carbonatite, which is a matter of experimental record as well as decades of compelling field evidence. Continuous carbonate - silicate immiscibility is very prominent in the black silicocarbonatite, with iron rich berthierine globules and streams being common. Only (relatively) minor amounts of calcite appear in the ijolites, it being much more common in urtitic rocks. This is a strong indication that, at least for the ijolite - carbonatite system, the solvus is highly asymmetrical, with the consolute point being much nearer to the silicate side of the system. Thus, the solvus limb which the silicate liquid traces would be nearly vertical, and little separation would occur after the initial exsolution, but the limb followed by the carbonate liquid would have a slope of considerably less magnitude, and continuous exsolution would result.

## Emplacement

The irregular outcrop pattern of the Ice River Complex must be considered as anomalous and due to the incompetent nature of the country rocks. Intrusions of closely related composition tend to form concentric, circular or elliptical outcrop patterns, with a core of carbonatite surrounded by ijolites, nepheline syenites, and metasomatized country rocks (usually granitic basement gneisses), eg., Jacupiranga (Odman, 1952) and Fen (Brogger, 1921). Some tendency to a radially symmetric form is exhibited by the carbonatite plug in the ijolites of Aquila Ridge, and by small, isolated occurrences of syenitic rocks at country rock - ultramafic rock contacts at Garnet Mountain and Sharp Mountain.

Folded dikes of nepheline syenite and pyroxenite which predate regional deformation are found to the northwest, in the core of the Porcupine Creek Anticlinorium, and post or synmetamorphic viens of sodalite - cancrinite- albite -

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calcite may be found in axial planar fractures up to 60 kilometres away from the complex in the same direction (Balkwill, 1969). As noted by Currie, this implies the presence of other, unexposed bodies of alkaline igneous rock, and remobilization of easily melted (or hydrothermally transported) material during metamorphism. Thus, the hypothesis that the spatially separated ultramafic rocks of the Ice River Complex are also temporally separated and chemically distinct must be given credence, particularly since more than one intrusive centre over a much larger and hidden rock body can be identified.

In this context, it would appear that the ultramafic rocks at Buttress Peak are less primitive than those at Aquila Ridge, which was suggested earlier and rationalized by the relative iron enrichment and overall higher silica activities of the Buttress Peak ultramafics. One of the bodies of jacupirangite included in the syenite breccia at the head of Sodalite Creek and described by Currie as part of a former link between the Aquila Ridge and Sharp Mountain ultramafics, proved on close examination to be the fine grained amphibole jacupirangite of the syenite suite. The total volume of true ultramafic rock in this area seems far too small to have formed a bridge between these two major occurrences of ijolitic rocks. The syenites have demonstrably intruded in three pulses, and a polyphase intrusion of ultramafic rock seems likely.

The issue could be decided by determining the subsurface structure below and around the complex; Dr. F. Cook had planned seismic surveys of the complex for July of this year (1983), but recent policy changes regarding scientific study in Yoho National Park resulted in his permit not being approved. The relationship of the exposed rock to any underlying system of feeder pipes has probably been obliterated, since the complex lies within a fold and thrust zone with total displacements to the northeast on the order of 100 kilometres (P.S. Simony, personal communication).

## Summary and Conclusions

The Ice River Complex represents a polyphase intrusion of magmas aperiodically withdrawn from a larger, unexposed body of alkaline ultramafic liquid which was continuously differentiating by a combination of precipitation of solid phases (presumed to be perovskite, magnetite, and titanaugite) and exsolution of an immiscible carbonatite. Two major intrusive events are recognized, characterized by the simultaneous emplacement of silicate and carbonate liquids: the parental magma, corresponding to the exposed ultramafic rocks, and a differentiate of this magma, corresponding to the syenites. Emplacement of the syenitic rocks occurred in three pulses, producing a highly characteristic breccia of successively less mafic dikes in formerly emplaced material.

Both suites followed parallel differentiation trends, with the syenitic suite (sphene +/- alkali feldspar) having an initial silica activity at the liquidus greater than the ultramafic suite (perovskite). In addition, the syenites contain a titanium - magnesium amphibole (kaersutite or barkevikite) in contrast to phlogopite in the ultramafics; this is interpreted as a result of the "dehydrating" effect due to continued immiscibility in the ultramafic silicate liquid - carbonate liquid system.

Unusual layered textures in the ultramafic rocks are analogous to those found in other basic intrusions, particularly the Skaergaard intrusion, and have been interpreted as the result of the formation of chemical, thermal, and density gradients resulting from non - equilibrium crystallization processes. Textures which can be ascribed to gravitative or convective accumulation are restricted to rocks occurring immediately above the floor of the complex.

A late stage (near-solidus) liquid immiscibility between an iron and titanium rich liquid and a basic or alkaline liquid has been described, and evidence presented for its being a non - equilibrium process. Oscillatory zoning in melanite and alternating bands of the two liquids indicate it may be a natural example of a chemical oscillator.

Fundamental petrographic differences between spatially separated occurrences of ultramafic rock, the presence of pre-metamorphic intrusion of syenite and pyroxenite dikes along the axis of the Porcupine Creek Anticlinorium, and regional synmetamorphic sodalite - cancrinite viening indicate that the Ice River Complex is a single example of a number of alkaline intrusions, none other of which are exposed. The relationship of the Ice River Complex to its source is likely to remain enigmatic, since it must be rootless, situated as it is in a region of major thrust faulting with displacements on the order of 100 kilometres.

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