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Subduction-related Mafic to Intermediate Plutonism in the Northwestern Wilson Terrane, North Victoria Land and Oates Coast, Antarctica

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Abstract: The largest three mafic intrusive complexes of the northwestern Wilson Terrane were investigated with respect to geological position, petrography, and geochemical composition.

In terms of age relationships, the mafic intrusives are younger than Ross metamorphism and orogenic tectonism, but older than the emplacement of the Granite Harbour granitoid intrusions, and thus represent an early member of the Granite Harbour intrusive complex.

In the Kavrayskiy Hills, an orthopyroxene-clinopyroxene-hornblende-plagioclase gabbro at Schubert Hill and a diorite with additional biotite, K-feldspar and quartz occur. Both gabbro and diorite were subjected to intensive secondary alteration. The rocks are sheared and mylonitised along narrow shear zones parallel to the Rennick Glacier as a result of young rift-forming tectonism along the Rennick.

Hornblende Bluffs are a differentiated and possibly layered complex of clinopyroxene-olivine gabbro to monzonite, biotite-hornblende-clinopyroxene gabbro to diorite, anorthosite to syenite and mafic microdiorite dikes and veins. A biotite granite with feldspar porphyry dikes and veins intrudes the pyroxene gabbro-monzonite.

The southeasternmost outcrops of the Archangel Nunataks consist of an unaltered clinopyroxene-hornblende-biotite-plagioclase gabbro containing schlieren of hornblende-rich cumulate.

Geochemically, the three mafic intrusive complexes cannot be derived from exactly the same parent magma because they form separate scatter groups in nearly all discrimination diagrams. The gabbro and diorite of the Kavrayskiy Hills are the most primitive ones, having a subalkaline to calc-alkaline composition. The samples from Hornblende Bluffs have an alkaline composition, tending slightly towards calc-alkaline. The gabbros from Archangel Nunataks are intermediate in composition between the other two mafic complexes. An active continental margin milieu becomes evident for all three occurrences when their MORB-normalized trace-element patterns are compared with those of mafic rocks from other geotectonic settings. Thereby, an increase in alkalinity is observed from Kavrayskiy Hills to Archangel Nunataks to Hornblende Bluffs. This supports the plate-tectonic model for the evolution of the Ross orogeny (KLEINSCHMIDT & TESSENSOHN 1987) with the Wilson Terrane in an active continental margin position.

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[Subduktionsbezogener basischer bis intermediärer Plutonismus im nordwestlichen Wilson Terrane, Nord-Victoria-Land und Oates Coast, Antarktis]

Kurzfassung: Die drei größten der basischen Intrusionen im nordwestlichen Wilson Terrane wurden auf ihre geologische Position, ihre petrographische Zusammensetzung und ihren geochemischen Charakter hin untersucht.

Hinsichtlich der Altersbeziehungen sind die basischen Intrusionen jünger als die Ross-Metamorphose und die gebirgsbildende Tektonik, aber älter als die Intrusion der Granite-Harbour-Granitoide. Sie stellen offenbar die Frühphase des gesamten Granite-Harbour-Intrusionskomplexes dar.

In den Kavrayskiy Hills treten ein Orthopyroxen-Klinopyroxen-Hornblende-Plagioklas-Gabbro am Schubert Hill und ein Diorit mit zusätzlich Biotit, Kalifeldspat und Quarz am White Point auf. Gabbro und Diorit unterlagen einer starken sekundären Alteration. Eine Scherung und Mylonitisierung der Gesteine verläuft parallel zum Rennick-Gletscher und wird als Folge junger, riftbildender Tektonik entlang des Rennick gedeutet.

Hornblende-Bluffs sind gebildet von einem deutlich differenzierten und möglicherweise lagig aufgebauten Komplex von Klinopyroxen-Olivin-Gabbro bis Monzonit, Biotit-Hornblende-Klinopyroxen-Gabbro bis Diorit, Anorthosit bis Syenit, und von basischen mikrodioritischen Gängen. Ein Biotitgranit mit Feldspat-porphyrischen Gängen intrudiert den Pyroxen-Gabbro-Monzonit.

Die zwei südöstlichsten Aufschlüsse der Archangel-Nunataks bestehen aus frischem Klinopyroxen-Hornblende-Biotit-Plagioklas-Gabbro mit Hornblende-reichen Kumulatschlieren.

Geochemische Untersuchungen zeigen, daß die drei Intrusivkomplexe nicht von dem selben Stamm-Magma abgeleitet werden können, da sie in nahezu allen Diskriminationsdiagrammen separate Streugruppen bilden. Gabbro und Diorit der Kavrayskiy Hills besitzen die primitivste Zusammensetzung der drei Komplexe, mit subalkalischem bis kalkalkalischem Charakter. Die Proben von Hornblende-Bluffs zeigen eine alkalibetonte Zusammensetzung, ein leicht kalkalkalischer Trend ist jedoch erkennbar. Die Gabbros der Archangel-Nunataks liegen mit ihrer Zusammensetzung zwischen den beiden anderen basischen Komplexen. Ein Vergleich MORB-normierter Spurenelement-Muster mit Mustern basischer Gesteine aus unterschiedlichen geotektonischen Positionen beweist, daß die Intrusion aller drei Komplexe im Bereich eines aktiven Kontinentalrandes stattfand. Dabei steigt die Alkalinität von den Kavrayskiy Hills über die Archangel-Nunataks zu den Hornblende-Bluffs. Dieses Ergebnis unterstützt das plattentektonische Modell für die Entwicklung des Ross-Orogens von KLEINSCHMIDT & TESSENSOHN (1987), mit dem Wilson Terrane in der Rolle eines aktiven Kontinentalrandes.

[Связанный с субдукцией плутонизм от основного до промежуточного состава в северо-западной части террейна Уилсона, северная часть Земли Виктории и Берег Отса (Антарктида)]

Резюме: Три самые крупные интрузии основного состава в северо-западной части террейна Уилсона были исследованы на их геологическое положение, петрографический состав и геохимический характер.

Интрузии основного состава в отношении возраста моложе, чем метаморфизм Росса и орогенная тектоника, но древнее, чем интрузия гранитоидов типа гранита Харбор. Они представляют собой очевидно раннюю фазу всего интрузивного комплекса гранита Харбор. В пределах Хиллс Каврайский встречаются ортопироксен — клинопироксен — роговая обманка — плагиоклазовый габбро на холме шуберт, и диорит с дополнительными биотитом, калиевым полевым шпатом и кварцем — на Уайт Пойнт. Габбро и диорит подверглись сильному вторичному изменению. Скол и милонитизация пород протекают параллельно леднику Ренник и интерпретируются как следствие молодых рифтообразующих тектонических процессов вдоль этого ледника.

Рогообманковые блаффы сложены отчетливо дифференцированным и, возможно, слоистым комплексом, состав которого варьирует от клинопироксена — оливина — габбро до монцонита — биотита — роговой обманки — клинопироксена — габбро до диорита, анортозита, сиенита, и до микродиоритовых жил основного состава. Биотитовый гранит с полевошпатово-порфировыми жилами проникает пироксен — габбро — монцонит.

Два расположенные на самом юго-востоке выхода нунатаков Архангель состоят из свежих клинопироксена — роговой обманки — биотита — плагиоклаза — габбро с высокорогообманковыми шлирами кумулятивных пород.

Геохимические исследования показывают, что это три интрузивные комплекса не могут происходить из той же материнской магмы, так как они образуют сепаратные группы разброса почти на всех дискриминационных диаграммах. Габбро и диорит в Хиллс Каврайский обладают самым примитивным среди трех комплексов составом, имея субщелочной до известково-щелочной характер. Пробы рогообманковых блаффов показывают преимущественно щелочной состав, однако с проявлением слабо известково-щелочного тренда. Состав габбро нунатаков Архангель занимает промежуточное положение между двумя другими комплексами основного состава. Сопоставление микроэлементов по стандарту MORB (базальты средне-океанического хребта) с рисунками пород основного состава из различных геотектонических обстановок доказывает, что интрузич всех трех комплексов произошла в пределах активной краевой зоны континента. При этом возрастает щелочность от Хиллс Каврайский через нунатаки Архангель до рогообманковых блаффов. Этот результат подтверждает модель тектоники плит, предложенную Клейншмидтом и Тессенсоном (KLEINSCHMIDT & TESSENSOHN, 1987) для эволюции орогена Росса, в которой террейн Уилсона играет роль активной краевой зоны континента.

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1 Introduction

The basement of North Victoria Land and Oates Coast is subdivided into three different NW-SE-trending lithotectonic units: the Robertson Bay, Bowers, and Wilson terranes, which, according to some authors (e.g. KLEINSCHMIDT & TESSENSOHN 1987), reflect a converging plate boundary situation during early Paleozoic times. Following KLEINSCHMIDT & TESSENSOHN (1987), westward subduction of oceanic crust under the East Antarctic craton during the Cambrian and Lower Ordovician led to the formation of an oceanic island arc and a trench-related flysch sedimentary basin, today represented by the Bowers and Robertson Bay terranes, respectively. The Wilson Terrane played the role of an active continental margin. These units were welded together during the Ross Orogeny about 500 to 480 Ma ago.

The Wilson Terrane, as the westernmost belt of the Pacific end of the Ross Orogen forms part of a Precambrian platform area of the Antarctic craton (ROLAND 1991). In North Victoria Land and along the Oates Coast, it is build up of originally rather monotonous pelitic to psammitic sedimentary sequences with subordinate calcareous intercalations, which were then transformed to metasedimentary rocks, e.g. gneisses, biotite schists, calc-silicate rocks, and migmatites, by medium- to high-grade regional metamorphism. A subdivision into a medium-pressure belt along the eastern border of the Wilson Terrane and a low-pressure belt more to the southwest has been suggested and was interpreted as a paired metamorphic belt (GREW et al. 1984; KLEINSCHMIDT & TESSENSOHN 1987). In the west and southwest, sediments which were metamorphosed under low- to medium-grade conditions (Berg Group, Priestley Formation) are in proven or possible tectonic contact with the high-grade Wilson Terrane basement (SKINNER 1989, 1991; FLÖTTMANN & KLEINSCHMIDT 1991). The entire Wilson Terrane was extensively intruded by the syn- to post-tectonic Granite Harbour Intrusives granitoids, with I-type compositions regionally confined to the metamorphic medium-pressure belt and with S-types confined largely to the metamorphic low-pressure belt (VETTER & TESSENSOHN 1987).

During their 1963/64 traverse through the Wilson Hills and the USARP Mountains of North Victoria Land and Oates Coast, STURM & CARRYER (1970) noted the presence of a small number of mafic rock types within the granitoid sequence, e.g. foliated hornblende granodiorites at and north of the Exile Nunataks, a basaltic dike at Mt. Gorton, a hornblende gabbro dike north of Mt. Harrison, and most importantly, a gabbroic intrusion forming the "Hornblende Bluffs" on the Suvarov Glacier. MCLEOD & GREGORY (1967) described a two-pyroxene basalt dike at Cook Ridge.

During GANOVEX V, other basic dikes were detected near the Oates Coast on Stanwix Ridge, Arthurson Ridge and Drake Head; and basic plutonic intrusions were discovered in the Kavrayskiy Hills, at Mt. Blowaway, and at the two southeasternmost outcrops of the Archangel Nunataks. Samples were collected from these new occurrences and from Hornblende Bluffs.

As not much time was available, no properly detailed observations on the Mt. Blowaway biotite-augite granodiorite intrusion and its relationship to the gneissic and migmatitic country rocks could be carried out. The other basic intrusives at Kavrayskiy Hills, the Archangel Nunataks and Hornblende Bluffs, which are subject of this paper, show clear similarities. They are obviously differentiated with ultramafic to basic and even intermediate compositional ranges, in some places with cumulate schlieren or indefinite transitions (Archangel Nunataks, Kavrayskiy Hills) and with definite layering at Hornblende Bluffs. Deformation is usually absent or only slight, and regional metamorphic overprints were not observed. This indicates a post-metamorphic and late- to post-tectonic stage of the Ross Orogeny for the time of intrusion. An even younger shearing deformation is probably associated with hydrothermal alteration and minor sulphide veining at White Point and Schubert Hill.

2 Geological Setting and Petrography

2.1 Kavrayskiy Hills

The Kavrayskiy Hills (70°25'S,161°E), at the western side of the lower Rennick Glacier and east of the Wilson Hills and the Kooperatsiya Ice Piedmont, form a small, N-S-trending block about 30 km long and up to 15 km wide; they were first visited for geological studies during GANOVEX III (1982/83) and belong to the metamorphic basement of the northwestern Wilson Terrane. However, their geological position is still unclear: Their geology cannot be directly compared with the rock series of the neighbouring medium- to high-grade areas (Daniels Range, Wilson Hills), and a terrane position analogous to the Lanterman Range's position relative to the Bowers Mountains is still in discussion (TESSENSOHN, pers. com.). From first field studies (SCHUBERT et al. 1984), the main rock units are paragneisses, orthogneisses, minor ortho-amphibolites, and felsic intrusives. Estimated PT conditions for the peak of metamorphism range between 4.5—5 kbar and 600—650 °C with absence of anatectic melting. As only a few outcrops of the Kavrayskiy Hills, especially the Pacific Terrace area with its predominantly metasedimentary rocks, was visited during GANOVEX III, new reconnaissance flights with landings on all the outcrops at the eastern side of the mountain chain between Thompson Point and Schubert Hill, except for those of McGovarin Hill, where carried out during GANOVEX V.

2.1.1 Thompson Point

The flat exposures at Thompson Point consist of a granite that has undergone severe shearing and stretching. The main cleavage trends NNW-SSE parallel to Thompson Point (and the Rennick Glacier) with steep to vertical dips. This is crossed by extensive jointing or second cleavage trending NW-SE, also with steep dips. Diorite-like inclusions up to 2 m in diameter are common. South of Blohm Hill and ENE of the Pacific Terrace, the rock is far less gneissic and is recognizably a deformed granite.

2.1.2 White Point

The earlier reconnaissance mapping carried out during GANOVEX III has to be revised south of the end of Serrat Glacier: The steep cliffs and high outcrops at White Point are not metasediments. The massive rock is a partly hydrothermally altered diorite complex that is dislocated by a pervasive and prominent shearing at 155°, dipping 50° SW, and including cm-thick blastomylonite veins. Dislocated lensoid quartz-pyrite veins (max. 15 cm thick) show a right-lateral shear component of up to 50 cm. These veins have a persistent local trend of 235° to 255° and southerly dips of 55° to 65°, and lie in a crush zone about 1 m thick of closely spaced shears and/or joints. Minor blue-green staining suggests that some copper sulphides could also have been present in the quartz veins, as well as disseminated in the diorite envelope of the veins. A younger set of shears (115°/48° NE) with a thrust component crosses the quartz veins. Calcite lines the shear planes and fills sigmoidal tension gashes between the planes. Although there seems to be an age difference between the quartz and the calcite shears, their trends and sense of movement also suggest that they form a conjugate set about a principal horizontal stress vector directed about 25°/205°. The most persistant shear direction is that at 155°, again parallel to the Rennick Glacier trend.

At White Point, almost no unaltered diorite samples (Plate 1a) could be collected. In some cases, however, the primary igneous mineral assemblage is still preserved:

clinopyroxene + hornblende + biotite + plagioclase + quartz
+ orthoclase + orthopyroxene

The predominant mafic mineral is brown, hypidiomorphic to xenomorphic biotite. The xenomorphic, greyish-green hornblende is subordinate. Colourless clinopyroxene may form the core of magmatic hornblende. Plagioclase, sometimes with beautiful oscillatory zoning, is hypidiomorphic. All these minerals occur in a coarse, ophitic texture, with xenomorphic quartz filling the interstices. Accessories are apatite, opaques and few zircons.

The whole assemblage is more or less strongly altered. Most of the clinopyroxene is mantled by secondary, pale-green to colourless actinolitic amphibole or has been converted with the orthopyroxene to two different chlorites of the clinochlorite and the pennine types. Magmatic hornblende has also been altered to pale-green amphibole. Plagioclase is often sericitized and partly converted to saussuritic assemblages. Biotite has been substantially replaced by pale-green and brown-green chlorite with muscovite interlayers. Secondary Fe-rich epidote grows at plagioclase-chlorite grain boundaries and, with sphene, in cleavage cracks of the altered biotite. Secondary K-feldspar and aggregates of polycrystalline-strained quartz have formed in considerable amounts. Calcite, albite and dark-green tourmaline are secondary constituents, along with disseminated pyrite.

2.1.3 Schubert Hill

Schubert Hill, with flat outcrops near the top and a steep cliff down to the margin of the Rennick Glacier (not visited by the GANOVEX III field party), is formed by a gabbroic intrusion. In some parts, the gabbro has suffered more or less intensive shearing and is crossed by cm-thick mylonite zones and fine-grained sheared dikes up to 1 m wide. The rock breaks easily into a blocky scree along a younger set of closely spaced (10—30 cm) sheared joints. At the highest outcrops, the gabbro is bordered by a granite similar to that which occurs in the outcrops between Serrat Glacier and Thompson Point (Fig. 1). The gabbro is intruded by cm-wide marginal dikes of this granite, whereas the granite contains basic xenoliths close to its contact to the gabbro. This is evidence for the gabbro intrusion being earlier than the granite intrusion.

At Schubert Hill, only a few unaltered samples, especially from the top region, could be collected. However, the primary igneous mineral assemblage is more or less relict in the altered rocks. The primary paragenesis is

orthopyroxene + clinopyroxene + hornblende + biotite + plagioclase ± quartz

Accessories are apatite in considerable amounts with dispersed rutile or sphene, and opaques. The colourless pyroxenes occur as hypidiomorphic to xenomorphic, prismatic to sphaeric grains, with orthopyroxene subordinate to clinopyroxene. In the lower rocks, magmatic hornblende usually forms large, hypidiomorphic to xenomorphic grains, coloured from pale-yellow (X) to pale-brown (Y = Z), whereas in the upper gabbro, the hornblende, often containing inclusions of biotite and pyroxene, is distributed as an intergranular to ophitic last crystallisation phase (Plate 1b). At lower outcrop levels the rocks appear to have contained considerably more primary brown hornblende as well as clinopyroxene. Only part of the samples show large, brown, hypidiomorphic biotite flakes, which are intensively intergrown with the hornblende. Plagioclase is hypidiomorphic with An_{72-75} in the top outcrops and from An_{60-68} to An_{80} in the cliffs below. The igneous paragenesis forms a typical coarse ophitic, gabbroic texture with minor quartz filling the interstices between the other minerals.

Most of the samples have been more or less strongly altered. Pyroxenes are replaced by pale-green to colourless amphibole at the rims (uralite), more often they are decomposed to very fine-grained aggregates of various sheet-silicates (e.g. talc, sericite). The originally brown hornblende has been altered both around the edges and in the center of the crystals to pale-green or colourless amphibole (actinolite). In addition, clearly secondary, ragged actinolite has also grown from the matrix and as coronas to the original brown hornblende. Both actinolites are themselves corroded by radial acicular growth coronas of orthoamphibole (anthophyllite), muscovite, and chlorite. In some samples, large grains of the brown hornblende have been decomposed to finergrained aggregates of secondary, usually long, prismatic, pale-green to colourless amphibole, pseudomorphically contouring the older magmatic grains. Biotite is partly or completely replaced by very pale-green chlorite. Plagioclase is patchily altered to sericite, but extensively replaced by the secondary amphibole and chlorite. Veinlets and pools of secondary quartz and chlorite vary from minor to abundant. The degree of alteration and the amount of secondary amphibole is very variable and accounts for the observed lithological variability of the rocks in the field.

Some of the samples exhibit a degree of shearing and stretching into augen-like polycrystalline clumps with large biotite growth or formation of flaser-like chlorite along the shear planes. There is associated granulation and sericite alteration of the plagioclase, and the biotite itself has been mortared against plagioclase and amphibole. In smaller shear zones, magmatic amphiboles have suffered cataclasis, and kinking of the magmatic biotite and plagioclase twins is obvious. Minor clinozoisite and Fe-rich epidote have crystallised between plagioclase and chlorite, and a great deal of polycrystalline strained quartz has formed.

A sample taken from a structure appearing in the field to be a fine-grained dike is a blastomylonite with remnant sericitized plagioclase and quartz grains surrounded by growth shadows of quartz and actinolite, and biotite flakes growing from the shear planes but altered to chlorite with sparse, tiny, yellowish epidote.

2.2 Hornblende Bluffs

Hornblende Bluffs (69°54.4'S,159°43.4'E) is by far the largest and most complex of the basic intrusions in the NW Wilson Terrane. It is at the eastern margin of the Wilson Hills, northwest of the Kooperatsiya Ice Piedmont, forming an ENE-WSW-trending isolated mountain block in the middle of the Suvarov Glacier, about 4 km long and up to 2 km wide. Hornblende Bluffs rises as a narrow, steep, serrate ridge from about 600 m at its western end to a summit of 1050 m in the central part, with rocks exposed only along the narrow crest and the very steep southern face. The central and widest part of the ridge is covered by ice extending over the face of the bluff, except for a narrow area of rock exposed for about 500 m at the eastern end of the central part of the ridge. From a NW-SE-trending rocky ridge, the NE face drops steeply to the glacier below. At the eastern end of the ridge, at about 500 m above m.s.l., there is a small, almost detached, exposed islet. The physiography is essentially controlled by changes in rock type or by dikes.

The geology of the Hornblende Bluffs massif — a layered basic intrusion — stands out within the rather monotonous gneissic metasediments, migmatites, anatexites and granites of the Wilson Hills. Judging from their survey and field notes, the northeastern end of Hornblende Bluffs was visited by STURM & CARRYER (1970). They describe the rocks as "composed of medium-grained hornblende gabbro containing bytownite, brown hornblende, and biotite, with minor altered olivine, augite, iron ore, and apatite".

During GANOVEX V, four reconnaissence landings were made by helicopter — one on the jagged lower western end of the ridge, two on the high, central part of the ridge, and one on the lowest eastern outcrops just above the Suvarov Glacier. Although inclement weather conditions only allowed short stays, there was opportunity for a quick traverse across the ridge in the central, highest part of the massif over about 500 m of a variable rock succession. Fly-pasts under varying light conditions along the south-facing cliffs of the Hornblende Bluffs massif revealed that the geology is more complex than suggested by the traverse.

Broadly, Hornblende Bluffs is part of a layered complex of anorthosite and gabbronorite at the western end, passing up through gabbros into diorites in the central part. The eastern part and NE face are pyroxene gabbro to monzonite, passing up into hornblende gabbro and diorite. The small islet at the extreme eastern end is a coarse-grained granite.

At the western end of the central part of the ridge, the foliation strikes 170°, dipping west at 50°. At the western end of the massif, parallel layering and foliation in the cumulates at the anorthosite-gabbro boundary strike 135° and dip to the NE at 25°. Hence, a basin-like structure is apparently present.

2.2.1 Western end of Hornblende Bluffs

The lowest platform at the western end marks the junction of a light gray, planar jointed, sparsely foliated anorthosite below a dark brown, coarse olivine-pyroxene-hornblende gabbronorite. The transition between the two is a 20-cm-thick sequence of alternating 1-to-3-cm bands of anorthosite and rocks which are more enriched in mafic minerals. About 20 m above this transition, the gabbronorite progressively passes up into biotite-pyroxene gabbro and diorite. Thin composite mafic sills and dikes up to 20 cm wide intrude the anorthosite, and dikes of anorthosite up to 50 cm wide intrude gabbronorite, gabbro, and diorite. Higher on the ridge and along the south-facing rock wall, another thick, light-coloured band — presumably anorthosite — could be seen, but not sampled.

The anorthosite is coarsely intergranular with 80 % to 90 % consisting of randomly orientated idiomorphic bytownite with An-contents around 77 mol % and commonly with a narrow, less calcic outer zone. The intergranular spaces are occupied predominantly by anhedral clinopyroxene, opaque oxides and apatite. The clinopyroxene is commonly rimmed and partly replaced by subordinate, late crystallising, brown hornblende. Sparse olivine phenocrysts have been completely serpentinized, but their idiomorphic shape and symplectitic intergrowth with adjacent opaque oxides are preserved (Plate 1c). Considerable deuteric and argillic/propylitic hydrothermal alteration has caused illite/sericite to partly replace plagioclase, and uralite and chlorite with minor calcite, biotite and rutile have formed from the clinopyroxene.

The felsic layers of the anorthosite/gabbronorite contact are entirely similar to the underlying anorthosite, but a much clearer cumulate texture and prefered orientation of the plagioclase is apparent. The merger with the more mafic layers is accompanied by a considerable increase in intergranular brown hornblende and opaque oxides, and a depletion of clinopyroxene, in response to greater replacement by the amphibole. Serpentinized olivine remains a sparse constituent but is associated with severely altered orthopyroxene. Perhaps the most significant difference is the growth of coarse, intergranular biotite, certainly at the expense of plagioclase and clinopyroxene, but, to a lesser extent, also the amphibole. Again, there has been the same deuteric and hydrothermal alteration as in the underlying anorthosite, including chloritisation of biotite.

The overlying gabbronorite is a dark-brown, phaneritic rock consisting of 45 % random to sub-oriented, granular plagioclase (An_{87-90}), clinopyroxene (22 %), olivine (8 %), and euhedral apatite (2 %), with considerable intergranular brown amphibole (10 %) and opaque oxide (13 %). There is an indistinct layering of more olivine-rich/pyroxene-rich laminae with minor orthopyroxene adjacent to some olivine crystals. The olivine and pyroxene are both partially replaced by amphibole although there is no reaction corona. The pyroxene commonly includes a considerable amount of opaque oxide, plagioclase, and biotite grains, and biotite has formed between plagioclase grains adjacent to the intergranular amphibole. Later hydrothermal alteration is relatively minor, producing illite from plagioclase, chlorite from pyroxene, serpentinite from olivine, and uralite from the small amount of orthopyroxene. The gabbro-norite passes up with complete loss of amphibole and olivine and an increase in plagioclase (60—70 %) into biotite gabbro to diorite. These are hypidiomorphic to allotriomorphic rocks with clumps of opaque oxide (10 %), and clinopyroxene (10 %) partly replaced by coarse, brown biotite (20 %), with large euhedral apatites and subhedral skeletal zircons as prominent accessories. The plagioclase shows complex twinning and is coarsely zoned, commonly with sectoral, oscillatory, and reverse zoning to a more calcic rim, although zoning to a more sodic, poorly twinned outer rim also occurs. The final intergranular material to crystallise was a small amount of quartz. The crystals of both plagioclase and biotite are bent as if they were deformed by post-crystalisation stresses.

2.2.2 Central part of the ridge above Hornblende Bluffs

At the western end of the central part of the ridge above Hornblende Bluffs, the outcrops are dark brown, well-foliated biotite-hornblende-pyroxene diorite. Further east, the diorite is less foliated and includes bands and stringers of coarse biotite-hornblende pegmatoid, the hornblende crystals reaching 3 cm in length. In addition, the diorite surrounds very large (up to tens of meters) rafts of very coarse hornblende gabbro, and is rimmed by fine-grained mafic biotite-hornblende monzonite-syenite dikes (up to

30 cm wide) and red aplitic syenite stringers and veins (2 to 5 cm wide). The pegmatoid bands and stringers and the mafic dikes follow the general foliation in the diorite, i.e. they dip 30° to 50° to the west.

The diorite varies little in the high area of the central part of the ridge, the main differences being the degree of crystal alignment and the relative preservation of the clinopyroxene with respect to biotite. The rocks are medium- to coarse-grained phaneritic, idiomorphic to hypidiomorphic diorite with about 50 % preferentially to randomly oriented (and in places, bent) plagioclase (An_{42-55}, commonly zoned with a low-anorthite rim), 20 % euhedral brown hornblende, 20 % ragged and bent, brown biotite, and up to 10 % granular clinopyroxene. There is a clear reaction series from pyroxene to biotite to hornblende, but close to the pegmatoid veins and stringers, a second biotite preferentially replaces the hornblende along its cleavages. The biotite and hornblende include a considerable number of euhedral apatite crystals and are clumped together with a significant amount of opaque oxide and large irregular sphene. There is minor hydrothermal alteration of plagioclase to sericite (illite) with sparse interstitial calcite and chlorite.

The pegmatoid phases are very coarse-grained phaneritic rocks with individual crystals up to 50 mm, averaging 5—10 mm in length. The mineralogy is similar to the enclosing diorites but is relatively depleted in clinopyroxene and opaque oxide and enriched in sphene and zircon, particularly in association with increased biotite that has formed partly as a preferential replacement of the hornblende along its cleavages. Apatite is still a significant accessory. Deuteric and hydrothermal alteration is severe in patches although mostly of minor bulk significance. Uralite has formed from pyroxene, illite/sericite from plagioclase, and chlorite from biotite; mm-wide calcite veinlets are locally extensive.

The gabbro at the eastern end of the central part of the ridge represents a further stage in the differentiation sequence. This rock is a medium- to very coarse-grained phaneritic, hypidiomorphic rock that is particularly enriched in sphene and apatite and is completely lacking in pyroxene. It contains only about 35 % plagioclase (An_{44} zoned outwards to oligoclase-andesine), the bulk of the rock being large, brown amphibole surrounded by subordinate biotite and the sphene, and including a large amount of opaque oxide and apatite, some of which reach 2 mm in length. Alteration is fairly strong, with the formation of sericite-chlorite-calcite and secondary albite in the plagioclase.

The associated pegmatoid phase is similar but coarser grained and includes a considerable amount of secondary calcite that has disrupted the amphibole along the cleavages, and calcite together with chlorite disrupted the biotite in the same way. Secondary muscovite has also formed along the biotite cleavages, and a second biotite has overgrown earlier formed biotite. There are two distinct differences between the gabbro and its pegmatoid. The plagioclase of the former is labradorite, whereas in the pegmatoid it is more calcic labradorite (An_{62}) zoned via andesine to calcic oligoclase (An_{27}). In addition, the pegmatoid contains pseudohexagonal, colourless spinel crystals, >0.5 mm in diameter, and very clear zircons of similar size.

2.2.3 Eastern end of Hornblende Bluffs

The easternmost outcrop at glacier level is the little islet at the foot of the SE end of Hornblende Bluffs. This is a coarsely porphyritic biotite granite with minor muscovite, apatite and sphene, strained quartz and orange-pink perthitic K-feldspar. The granite is cut by cm-wide, red porphyry dikes. A contact could be seen in the nearby cliffs which appeared to show the granite intruding the mafic rocks, however, it could not be reached in the time available. Similarly, mafic rock in place could not be reached, but large blocks of gabbro were collected that had fallen from the cliffs above. These are olivine-biotite-pyroxene gabbro to monzonite with stringers of felsic biotite-pyroxene-hornblende gabbro, monzodiorite, and monzonite.

Most of these easternmost outcrops at glacier level are clinopyroxene monzogabbro or monzodiorite to monzonite (depending on the proportions of plagioclase to K-feldspar and the plagioclase composition), consisting predominantly of about 10 % maximum olivine, 64 % clinopyroxene and 26 % feldspar. The rock is phaneritic and hypidiomorphic granular and porphyritic, the phenocrysts being olivine and clinopyroxene up to 7 mm across in a 0.15—2 mm feldspathic matrix.

Olivine includes plagioclase fragments (An_{57}) and has reaction coronas progressively outwards from the olivine, of orthopyroxene (partially converted to uralite) and minor clinopyroxene, brown amphibole and opaque oxide grains, and biotite. Adjacent to clinopyroxene, the olivine has a symplectic intergrowth with the opaques (Plate 1d).

The clinopyroxenes are commonly twinned, very spongy, sieve-textured phenocrysts, full of irregular plagioclase fragments and opaque oxide grains, and rimmed with opaques near and outside of the crystal margins. There is a reaction rim against matrix plagioclase and biotite with the formation of dark brown amphibole. The clinopyroxenes are commonly zoned and include small rounded olivine cores. Smaller clinopyroxene grains are irregularly dispersed through the matrix. Very fine dark needles, perhaps an amphibole, commonly lie on the (110) rhombic crystal cleavages of the clinopyroxenes, and very faint exsolution laminae at about 30 ° from the longitudinal cleavage are a sparse occurrence. Small biotite flakes are plentifully dispersed throughout the rock matrix, but amphibole is seldom seen away from its growth position adjacent to the olivine and orthopyroxene except in more granular, less porphyritic parts of the rock and remains a minor constituent.

Few of the plagioclase are euhedral, most being stubby, randomly oriented, well zoned anhedra, the larger ones with cores of An_{57} and the smaller ones An_{48} zoned outwards to An_{43}. The outer rim has commonly intergrown and reacted with K-feldspar to form symplectic intergrowths. Perthitic K-feldspar also forms a few individual crystals, but it mainly occurs as intergranular matrix along with minor quartz. Although it is always considerably subordinate to plagioclase, and with quartz forms the last mineral phases to crystallise, K-feldspar is sufficiently variably distributed throughout the rock for the rock composition to trend towards monzonite.

Apart from the opaque oxide grains, accessory minerals are minor sphene and apatite. There is almost no hydrothermal alteration.

In contrast, there are irregular stringers up to 50 mm wide of more felsic material interfingering with the main part of the rock. These contain large (10 mm) brown hornblende crystals surrounding plagioclase and clinopyroxene, and include olivine crystals, some with lamella twinning, separated from the hornblende by an opaque reaction rim. Large biotite flakes are intergrown with, but subordinate to the hornblende, and the spongy clinopyroxene, now also subordinate to the hornblende, contains aligned hornblende inclusions as well as the usual plagioclase and opaques. The biotite has replaced pyroxene and with plagioclase forms symplectic intergrowths with opaques. Plagioclase is larger than in the main part of the rock and is irregularly twinned and zoned, although the zones have similar compositions (An_{42}) and the more albitic rims are in contact with each other. K-feldspar and quartz are very minor and opaques are the only accessory minerals. Hydrothermal chlorite and sericite have developed from the biotite and plagioclase.

2.3 Archangel Nunataks

The Archangel Nunataks, first visited for geological investigation during GANOVEX V, are amongst the westernmost outcrops of Oates Coast. Situated west of the high-grade metamorphic rocks of the Wilson Hills and Lazarev Mountains in the Matusevich Glacier area and SE of the Berg Mountains, they form a NW-SE-trending chain of separate nunataks bordering the Polar Plateau. The largest and central outcrop is the Outrider Nunatak, which along with the surrounding smaller nunataks, consists of a massive, rather homogenious granite complex, intruding and thermally metamorphosing remnant Berg Group metasediments. Berg Group also forms the northwesternmost nunatak, where pelitic to psammitic siliciclastites have been affected by low-grade regional metamorphism before the more intensive contact metamorphism caused by the intrusion of the Outrider granite massif.

At the two southeasternmost nunataks (69°38'S,156°45'E), gabbroic intrusives similar to the Schubert Hill gabbro are exposed in very flat outcrops. The southern of the two is a somewhat lighter coloured gabbro, whereas darker gabbros with ultramafic cumulate-schlieren predominate at the northern one. The gabbros are cut by small mafic dikes that possibly represent a final stage of mafic intrusion. In contrast to the Kavrayskiy Hills, the gabbroic complex has not been obviously affected by tectonic movement.

Blue ice covers the contact with the neighbouring Outrider granite. However, the granitic nunatak closest to the basic intrusion contains xenoliths of basic material. This situation is similar to that at both Kavrayskiy Hills and Hornblende Bluffs, where an earlier gabbroic intrusion and a younger granitic intrusion also occur.

The igneous mineral paragenesis of the gabbros is

clinopyroxene + hornblende + plagioclase + biotite + epidote + chlorite

Considerable amounts of accessory sphene, apatite, and opaques, are present.

The igneous mineral assemblage is extremely variable from sample to sample, ranging between nearly monomineralic hornblendites (cumulates), plagioclase-pyroxene-biotite gabbros with only accessory hornblende, and plagioclase-pyroxene-hornblende gabbros without biotite. Pale-green clinopyroxene occurs with hypidiomorphic to xenomorphic, sphaeric to prismatic grains. Hornblende is xenomorphic with colours ranging from pale-green (X) to bright olive-green or olive-brown (Y = Z), with slight zonation indicated by browner cores and greener rims. It often contains inclusions of clinopyroxene, plagioclase, and sometimes biotite. Biotite forms hypidiomorphic to xenomorphic, dark-brown flakes. Epidote occurs sporadically, filling interstices between the coarse gabbroic minerals, and pale-green chlorite is occasionally included in hornblendes of the hornblendites. The high amount of large, idiomorphic sphene and apatite is remarkable. In contrast to the Kavrayskiy Hills, secondary alteration plays a subordinate role with minor sericitisation of plagioclase and replacement of hornblende by epidote at the grain boundaries.

3 Mineral Chemistry

Chemical composition of rock-forming minerals was determined from samples from the Kavrayskiy Hills and the Archangel Nunataks:

Clinopyroxenes from both occurrences are all diopside (IMA nomenclature compiled by MORIMOTO 1988), with those from the Archangel Nunataks containing somewhat more Fe than those from the Kavrayskiy Hills (Fig. 2).

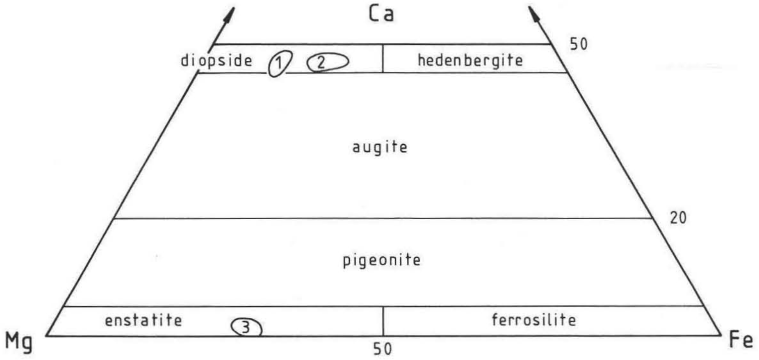

Fig. 2: Chemical composition of pyroxenes (for nomenclature, see MORIMOTO 1988): Clinopyroxene and orthopyroxene from the Kavrayskiy Hills intrusives (1 and 3) and clinopyroxene from the Archangel Nunataks gabbro (2).

Orthopyroxenes from gabbros (Schubert Hill) and diorites (White Point) of the Kavrayskiy Hills are enstatites with 30 % ferrosilite component, i.e. hyperstene using the nomenclature of POLDERVAART & HESS (1951).

Amphiboles from the Archangel Nunataks gabbros are magnesian hastingsitic hornblendes and magnesian hastingsites (IMA nomenclature compiled by LEAKE 1978). Amphiboles from the Kavrayskiy Hills samples are magnesiohornblendes, however, with Si values around 6.5 per formula unit (p.f.u.) for the Schubert Hill gabbros and around 7.2 p.f.u. for the White Point diorite (Fig. 3).

Biotites in gabbros from the Archangel Nunataks and in the diorite from the Kavrayskiy Hills are meroxene/lepidomelane and meroxene, respectively.

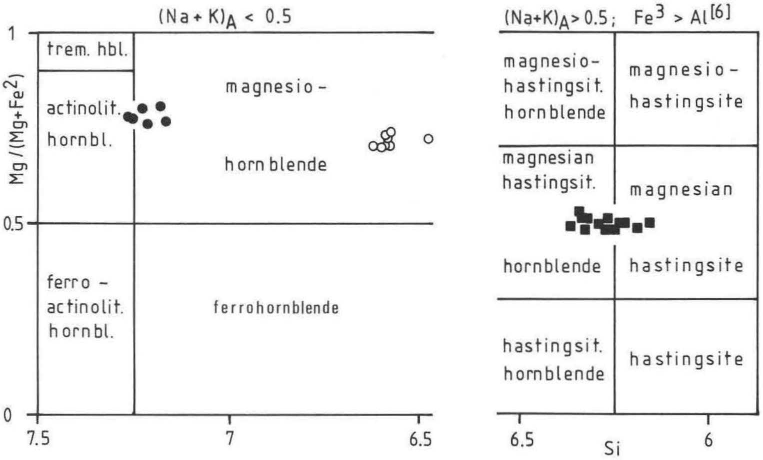

Fig. 3: Chemical composition of amphiboles (for nomenclature, see LEAKE 1978): Magnesian hastingsitic hornblende/magnesian hastingsite from the Archangel Nunataks gabbro (squares), magnesiohornblende from the Kavrayskiy Hills gabbro (open circles), and magnesiohornblende/actinolitic hornblende from the Kavrayskiy Hills diorite (filled circles).

4 Chemical Composition of the Gabbroic Intrusives

4.1 Analytical work

Geochemical analyses were carried out on 21 whole-rock samples from the Kavrayskiy Hills, 19 of which are gabbroic rocks from Schubert Hill and 2 are dioritic rocks from White Point. Six samples were analysed from the Archangel Nunataks basites and 9 basic to intermediate/acid samples from the Hornblende Bluff intrusion.

Major and trace elements were determined by XRF analysis at the laboratory of the Federal Institute for Geosciences and Natural Recources, Hannover, F.R.G. The analytical results are listed in Table 1. The As, Bi, Hf, Mo, Pb, Sn, Ta, Th, and U values were at or close to the detection limits for nearly all samples. These values are therefore not listed in Table 1.

4.2 Analytical Results

In most of the variation diagrams used, the different geochemical characteristics of the three intrusive complexes are clearly demonstrated by distinctly separated scatter groups. In the SiO_2 versus $Na_2O + K_2O$ diagram (Fig. 4), the Kavrayskiy Hills basites follow a clear subalkaline differentiation trend. SiO_2 contents vary between 47.9 and 55.9 % (average 51.2 %, excluding sample US-296) for the Schubert Hill gabbros and make up about 62 % for the White Point intermediate rocks. The gabbroic rocks from the Archangel Nunataks show a more alkaline trend. SiO_2 contents range from 40.1 to 52.2 %, average 47.6 %. The basic to acid samples from the Hornblende Bluffs intrusion

Table 1: Whole-rock analysis of samples from Schubert Hill and White Point in the Kavrayskiy Hills, from Archangel Nunataks, and from Hornblende Bluffs.

	NR 2507 Schubert Hill	US-288 Schubert Hill	US-289 Schubert Hill	NR 2509 Schubert Hill	NR 2510 Schubert Hill	NR 2511 Schubert Hill	NR 2512 Schubert Hill	NR 2513 Schubert Hill	NR 2514 Schubert Hill	NR 2515 Schubert Hill	NR 2516 Schubert Hill	US-339 Schubert Hill
SiO_2	53.01	55.18	54.51	50.60	51.23	53.72	51.13	47.88	49.07	59.16	48.17	50.14
TiO_2	0.45	0.44	0.30	0.62	0.48	0.41	0.62	0.46	0.64	0.68	0.74	0.29
Al_2O_3	14.67	14.18	14.73	8.94	14.36	14.03	12.85	13.45	9.30	16.48	13.02	11.35
Fe_2O_3	8.64	8.08	8.24	11.65	9.49	8.64	10.02	10.76	12.05	6.88	11.46	11.18
MnO	0.15	0.14	0.14	0.19	0.16	0.15	0.18	0.18	0.20	0.11	0.19	0.20
MgO	9.43	8.49	9.21	15.96	10.43	9.31	11.84	12.87	16.09	3.66	12.80	13.19
CaO	8.13	7.80	8.20	8.05	8.54	8.05	8.51	9.24	7.96	6.17	9.55	9.38
Na_2O	2.23	2.06	1.77	0.79	2.25	1.79	1.10	1.12	0.68	3.07	0.93	0.88
K_2O	0.77	1.07	0.77	0.56	0.72	0.98	0.86	0.76	0.57	1.11	0.59	0.63
P_2O_5	0.15	0.14	0.14	0.09	0.13	0.18	0.12	0.17	0.07	0.18	0.18	0.03
L.O.I.	1.85	1.90	1.48	1.95	1.69	2.21	2.22	2.48	2.76	1.98	1.79	2.20
TOTAL	99.48	99.48	99.49	99.40	99.48	99.47	99.45	99.37	99.39	99.48	99.42	99.47
V	170	165	152	242	199	165	229	221	234	171	253	219
Cr	626	582	612	1508	712	636	899	955	1540	90	936	920
Ni	222	200	223	460	252	218	317	323	525	54	315	317
Cu	42	22	51	<10	16	52	36	204	38	53	77	<10
Zn	77	78	84	102	93	84	69	92	115	69	100	100
Rb	30	40	29	16	29	40	26	20	20	40	15	30
Sr	303	285	280	104	292	287	239	234	93	381	233	183
Y	10	15	13	20	13	13	20	16	28	16	26	20
Zr	61	76	47	46	88	54	52	38	44	135	52	26
Nb	8	12	6	11	9	10	8	8	10	13	13	<5
Ba	166	261	125	<50	171	256	155	60	110	395	94	85
Ce	<35	58	<35	44	36	59	48	<35	<35	60	70	<35
[Mg]	0.72	0.71	0.72	0.76	0.72	0.72	0.73	0.74	0.76	0.55	0.72	0.73

Table 1 continuing:

	US-340 Schubert Hill	US-341 Schubert Hill	US-342 Schubert Hill	US-363 Schubert Hill	US-364 Schubert Hill	US-365 Schubert Hill	US-366 Schubert Hill	US-368 White Point	US-369 White Point	US-394 Archang. Nunataks	US-395 Archang. Nunataks	US-396 Archang. Nunataks
SiO_2	50.60	51.12	48.27	49.63	55.90	52.10	49.19	61.49	62.13	52.24	51.36	49.62
TiO_2	0.36	0.48	0.43	0.63	0.40	0.47	0.59	0.52	0.53	1.05	1.11	1.21
Al_2O_3	13.77	14.08	13.46	9.63	13.87	12.48	13.01	13.75	13.42	17.40	17.35	17.19
Fe_2O_3	9.74	10.11	9.30	11.02	7.73	9.49	10.55	5.90	5.61	9.36	9.72	10.73
MnO	0.17	0.17	0.15	0.18	0.13	0.16	0.18	0.10	0.09	0.20	0.21	0.23
MgO	11.07	11.32	11.44	16.63	8.45	11.88	12.51	5.89	5.57	2.81	2.95	3.32
CaO	9.29	9.49	8.95	8.22	7.14	8.58	9.51	5.20	5.01	8.82	9.11	10.04
Na_2O	1.47	1.41	1.34	0.62	2	0.92	1.11	2.44	2.13	3.97	3.95	4.09
K_2O	0.34	0.18	2.05	0.62	1.32	0.95	0.55	2.54	2.59	2.32	2.29	1.71
P_2O_5	0.12	0.13	0.13	0.07	0.11	0.12	0.12	0.12	0.10	0.42	0.44	0.48
L.O.I.	2.55	0.98	3.93	2.15	2.40	2.31	2.10	1.50	2.25	0.77	0.89	0.78
TOTAL	99.48	99.47	99.45	99.40	99.45	99.46	99.42	99.45	99.43	99.36	99.38	99.40
V	202	209	197	221	155	193	239	130	134	231	228	274
Cr	748	742	796	1668	572	934	934	447	463	17	21	17
Ni	267	261	264	472	204	323	331	148	141	<7	<7	14
Cu	19	11	23	21	40	67	60	82	82	149	107	110
Zn	88	97	65	98	73	81	98	57	52	97	102	115
Rb	9	<5	79	18	61	35	12	119	123	78	79	55
Sr	278	307	260	130	267	224	243	219	219	1038	1075	1068
Y	18	12	12	23	15	13	18	13	12	21	20	27
Zr	26	29	25	39	92	52	44	144	133	104	91	78
Nb	7	<5	6	8	11	9	<5	12	15	12	10	8
Ba	60	103	251	<50	274	140	108	556	437	927	1037	649
Ce	41	<35	38	<35	49	<35	56	44	75	85	58	53
[Mg]	0.73	0.72	0.74	0.78	0.72	0.74	0.73	0.70	0.70	0.41	0.41	0.42

Table 1 continuing:

	US-397 Archang. Nunataks	US-339 Archang. Nunataks	US-400 Archang. Nunataks	NR 2025 Hornbl. Bluffs	NR 2026 Hornbl. Bluffs	NR 2027 Hornbl. Bluffs	NR 2028 Hornbl. Bluffs	NR 2550 Hornbl. Bluffs	NR 2551 Hornbl. Bluffs	NR 2552 Hornbl. Bluffs	NR 2553 Hornbl. Bluffs	NR 2554 Hornbl. Bluffs
SiO_2	47.16	40.05	45.29	71.64	49.95	70.65	45.54	45.90	38.05	38.86	48.81	59.68
TiO_2	1.39	2.27	1.31	0.42	1.99	0.42	2.61	2.58	4.42	3.82	2.01	0.53
Al_2O_3	18.52	12.26	21.91	13.25	10.82	13.90	17.87	18.03	14.32	16.22	17.59	18.31
Fe_2O_3	11.28	19.52	10.67	2.93	12.97	2.70	11.35	11.15	16	15.86	10.03	4.80
MnO	0.20	0.35	0.18	0.05	0.21	0.08	0.21	0.21	0.21	0.20	0.19	0.19
MgO	3.90	8.01	2.70	0.45	8.16	0.56	4.17	4.26	7.50	5.64	3.47	0.69
CaO	10.70	12.28	11.71	1.64	10.94	1.32	9.39	9.35	11.34	10.89	7.75	2.04
Na_2O	3.71	1.50	3.25	3.10	1.90	2.98	3.75	3.94	2.65	2.62	4.28	6.14
K_2O	1.03	1.37	0.63	4.33	1.58	5.11	1.94	1.87	1.53	1.71	2.63	5.21
P_2O_5	0.42	0.66	0.55	0.16	0.27	0.14	1.33	1.17	1.76	2.10	0.95	0.18
L.O.I.	1.11	1.23	1.22	1.51	0.65	1.54	0.97	0.81	1.32	1.22	1.40	1.47
TOTAL	99.42	99.50	99.42	99.48	99.43	99.40	99.13	99.27	99.10	99.14	99.11	99.24
V	249	477	170	30	362	31	127	127	324	319	158	<10
Cr	43	33	11	<7	169	11	11	<7	12	<7	<7	<7
Ni	25	36	<7	<7	39	<7	8	<7	8	<7	<7	<7
Cu	127	14	264	<10	18	<10	<10	<10	<10	<10	12	11
Zn	113	196	108	60	110	39	98	87	102	96	94	98
Rb	22	19	8	271	70	293	61	55	35	44	82	159
Sr	1052	230	1133	125	384	129	1643	1700	1059	1330	1160	448
Y	29	52	42	35	22	30	37	39	38	36	29	20
Zr	84	93	209	288	216	263	267	267	161	164	349	709
Nb	12	19	17	21	15	22	45	41	35	29	41	64
Ba	304	142	135	492	599	515	1253	1246	785	856	1182	1899
Ce	97	73	61	164	103	99	277	232	169	189	207	238
[Mg]	0.45	0.49	0.37	0.26	0.59	0.33	0.46	0.47	0.52	0.45	0.45	0.25

can be split into a clear alkaline trend (6 samples) and a more subalkaline one, documented by one basic (NR 2026) and two more acidic (NR 2025, 2027) samples. These two different trends for the Hornblende Bluffs also appear in most of the other variation diagrams, including several Harker diagrams, e.g. Al_2O_3, MgO, CaO, Na_2O and K_2O versus SiO_2. SiO_2 contents for the basic samples from Hornblende Bluffs range between 38.1 and 50.0 %, average 44.5 %.

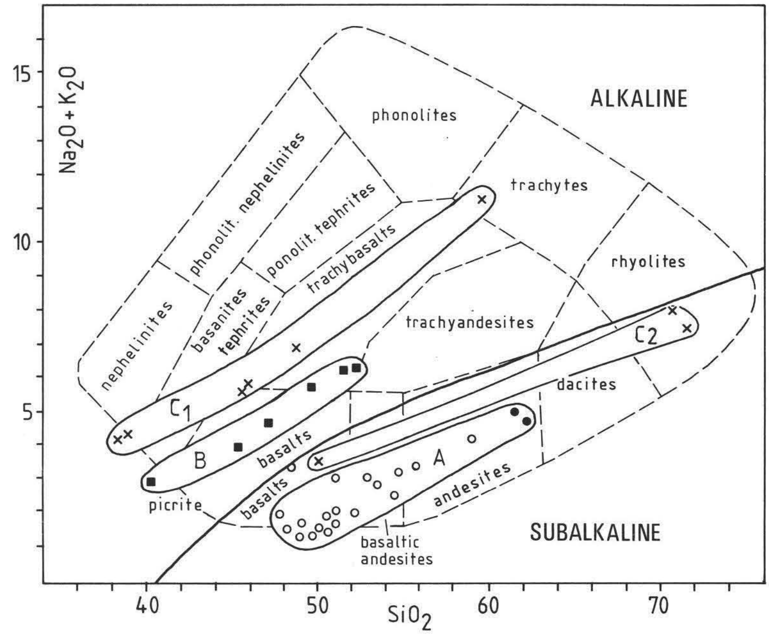

Fig. 4: $Na_2O + K_2O$ vs. SiO_2 diagram for subdivision of subalkaline-alkaline trends (after COX et al. 1979); Kavrayskiy Hills intrusives: Schubert Hill gabbro (open circles) and White Point diorite (filled circles); Archangel Nunataks gabbro (squares); Hornblende Bluffs intrusives (crosses).

The Zr/TiO_2 versus Nb/Y diagram (Fig. 5; FLOYD & WINCHESTER 1978) shows no clear distinction between the samples from the Kavrayskiy Hills and those from the Archangel Nunataks. In contrast to Figure 4, the gabbros from Archangel Nunataks plot in the subalkaline field, whereas the gabbros from Schubert Hill (Kavrayskiy Hills) are subalkaline for the more basic members and somewhat alkaline in character for the more acid members. Like in Figure 4, the samples from Hornblende Bluffs again are divided into the same two differentiation trends, the more subalkaline (3 samples) and the more alkaline one (6 samples).

In the JENSEN (1976) "cation" plot (Fig. 6), the Kavrayskiy Hills samples form a separate scatter group, whereas, in this case, the samples from Hornblende Bluffs and the Archangel Nunataks cannot be subdivided. The diagram reflects the degree of differentiation for the analysed rocks in each of the intrusive complexes. The differentiation trend within the respective intrusions is nearly the same in all three complexes, beginning with relatively Mg + Fe-rich, Al-poor compositions (hornblende-olivine-

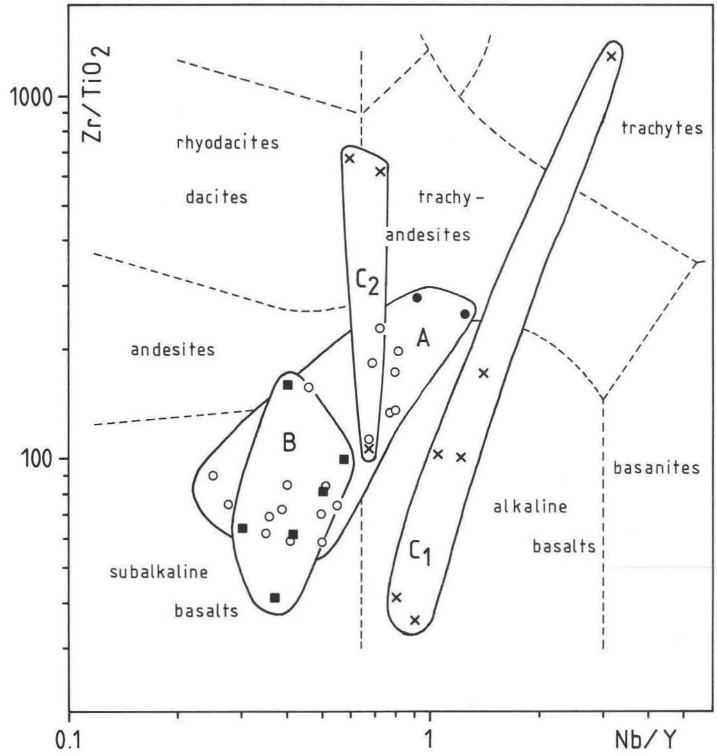

Fig. 5: Subalkaline-alkaline discrimination plot (after FLOYD & WINCHESTER 1978); for symbols, see Fig. 4.

pyroxene gabbros, occasionally with cumulate character) and ending with relatively Mg + Fe-impoverished, Al-enriched, intermediate to acid members. With respect to the Mg/Fe ratio, however, the Kavrayskiy Hill basites show clearly higher Mg contents than the other two intrusions, reflecting a more primitive magma type. This is also expressed by [Mg] values for the respective groups (see Table 1; $[Mg] = Mg/(Mg + Fe^{2+})$ with Fe^{3+}/Fe^{2+} assumed to be 0.15, after DUPUY & DOSTAL 1984). Except for one sample, [Mg] values for the Kavrayskiy Hills intrusives (Schubert Hill and White Point) are between 0.70 and 0.78 (average 0.73), typical for primitive basaltic magmas (DUPUY & DOSTAL 1984). In contrast, the [Mg] values for the basic samples from Hornblende Bluffs and the Archangel Nunataks respectively scatter from 0.45 to 0.59 (average 0.49) and 0.37 to 0.49 (average 0.43). These values indicate clearly higher differentiated magma types. The intermediate to acid end-members of the Hornblende Bluffs magma have [Mg] values ranging from 0.25 to 0.33.

The Ti versus Zr diagram (Fig. 7) again demonstrates the differences between the three intrusion complexes. There is separation of the Kavrayskiy Hills basites (with low Ti and Zr contents) from the Archangel Nunataks basites (with medium values) and the

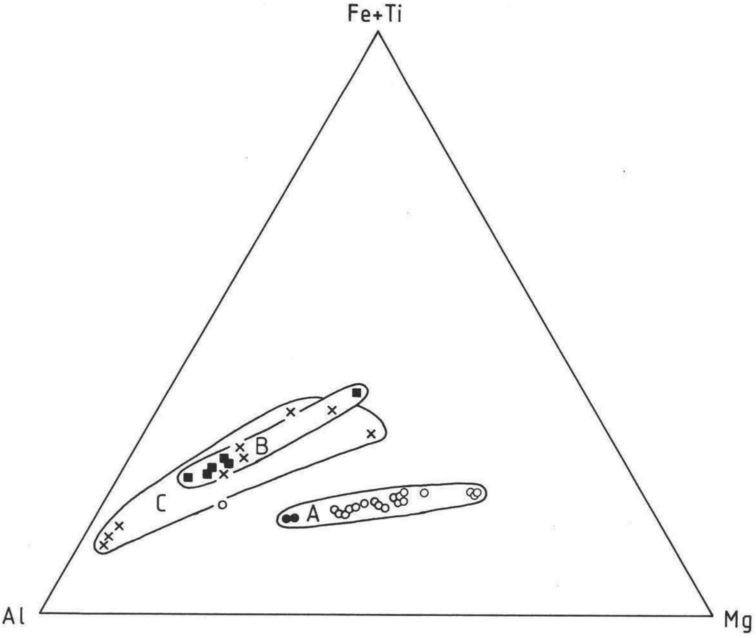

Fig. 6: Fe + Ti/Al/Mg plot (after JENSEN 1976); for symbols, see Fig. 4.

Hornblende Bluffs intrusives (with higher Ti and Zr values). In terms of geotectonic settings for modern basaltic magmas (after PEARCE 1982), the Kavrayskiy Hills samples show affinities to island arc magmas, whereas the Hornblende Bluffs intrusives seem to indicate a within-plate situation (however, again with two different trends). The Archangel Nunatak samples are of intermediate composition. The same holds true for the TiO_2-MnO-P_2O_5 triangle (Fig. 8; MULLEN 1983). The Kavrayskiy Hills intrusives plot in the fields of island arc and calc-alkaline basalts, whereas the samples from Archangel Nunataks and Hornblende Bluffs (basic samples only) follow a trend from island arc affinities to alkaline-igneous compositions (one basic sample of Hornblende Bluffs that belongs to the second, subalkaline trend known from the other diagrams plots in the MORB field). A similar development is observed in several other diagrams not presented here, e.g. the Cr versus Y diagram (PEARCE 1982).

Trace element patterns normalized with respect to normal-MORB composition (Fig. 9) demonstrate a more complicated geochemical situation, as they do not reflect one of the simple, widespread magma types. The patterns of all three complexes are rather similar in shape. Compared with the normal-MORB composition, they are enriched in elements with low ionic potentials (e.g. Sr, K, Rb, Ba), typical for alkaline magmas, but also for tholeiitic and calc-alkaline subduction-related magmas. A variable concentration of incompatible elements with higher ionic potentials leads to a general, more or less steep negative slope of the plots from Ba to Y. This is usually characteristic of magma with alkaline tendencies. The negative anomalies for Nb and Zr are frequently observed features of tholeiitic and calc-alkaline subduction-related magmas. Thus,

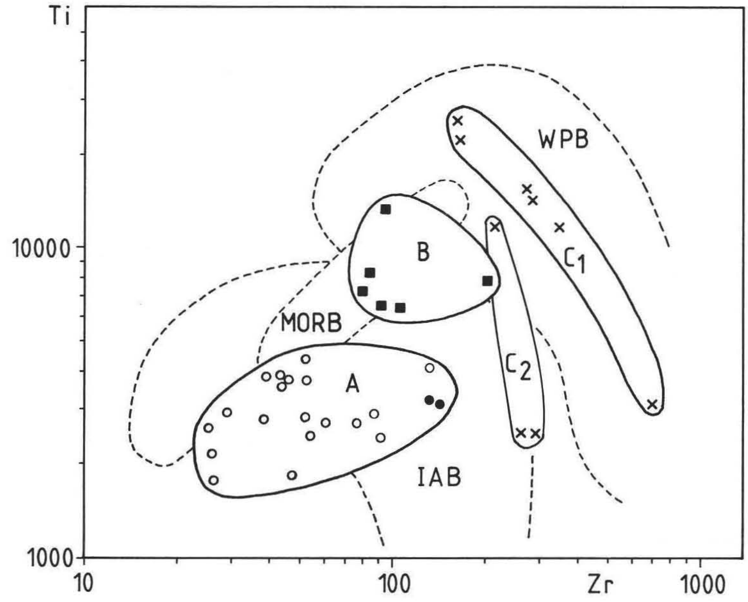

Fig. 7: Ti-Zr diagram for comparison of the investigated mafic complexes with modern magmas from different geotectonic settings (after PEARCE 1982); IA: island-arc basalts, M: mid-oceanic ridge basalts, WPB: within-plate basalts; for symbols, see Fig. 4.

the samples from all three complexes exhibit tholeiitic to calc-alkaline components, but also alkaline ones, a different proportion of each, however. The plots for the Kavrayskiy Hills samples (Fig. 9A) show only slight enrichment (Nb, Ce) or even depletion (Zr, Ti, Y) of incompatible elements with higher ionic potentials. Pronounced Nb and Zr anomalies can be seen. This again points out the subalkaline character with calc-alkaline tendency seen in several of the variation diagrams (e.g. Figs. 4 & 5). However, the steep slope from Ba to Y indicates a slight alkaline character. In contrast to the Kavrayskiy Hills, the Hornblende Bluffs intrusives (Fig. 9C) are clearly more highly enriched in all incompatible elements. This underscores the alkaline character of these samples as indicated by the other diagrams. Nevertheless, the negative Nb anomaly does not fit this alkaline pattern and points to some calc-alkaline influence. As in most of the variation diagrams, the samples from the Archangel Nunataks (Fig. 9B) have intermediate patterns between the other two compositions.

With respect to Cr content, the Kavrayskiy Hills samples with Cr contents up to 1600 ppm (average 907 ppm) are very different from the Archangel Nunataks basites with Cr between 11 and 43 ppm and the Hornblende Bluffs intrusives with Cr below the detection limit of 7 ppm in most samples (see Table 1). The same feature is seen for Ni: with contents up to 525 ppm (average 305 ppm) for the Kavrayskiy Hill gabbros and values close to the detection limit of 7 ppm for the other two complexes.

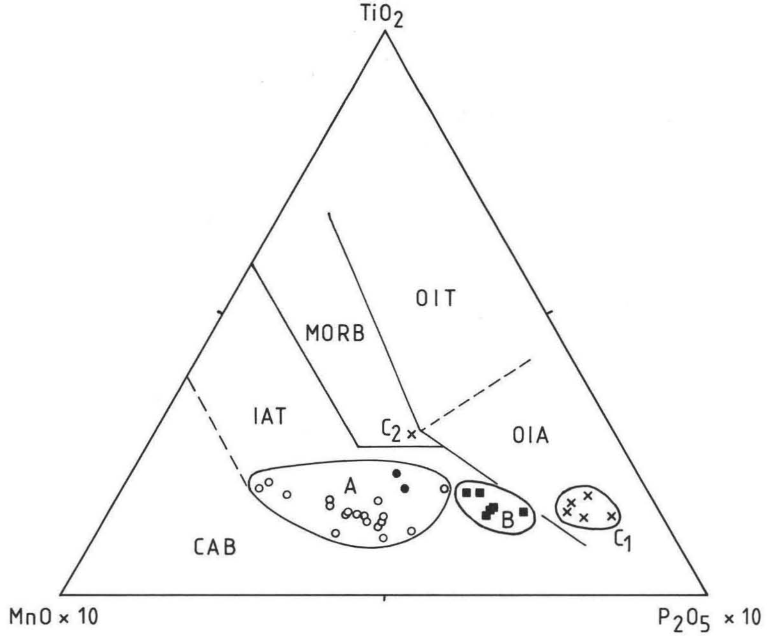

Fig. 8: $TiO_2/MnO/P_2O_5$ triangle for distinguishing between magmas from different geotectonic settings (after MULLEN 1983); MORB: mid-oceanic ridge basalts, IAT: island-arc tholeiites, CAB: calc-alkaline basalts, OIT: ocean-island tholeiites, OIA: ocean-island alkaline basalts; for symbols, see Fig. 4

4.3 Discussion

The magmas of the three basic intrusive complexes cannot have originated from exactly the same magma source. This is clearly demonstrated by the different scatter groups for the three complexes in various discrimination diagrams and also by Harker diagrams for all major elements, where the samples show clearly separated trends for each complex. On the other hand, there are striking geochemical similarities between the complexes, as shown by trace element patterns, which indicate magma genesis in a similar environment.

A simple oceanic environment like a mid-oceanic ridge or ocean island situation can be ruled out. The geochemical characteristics of the intrusives rather clearly indicate a subduction-related situation for the magma-producing processes. This is corroborated by the K_2O versus SiO_2 diagram (Fig. 10) and the factor analysis of PEARCE (1976), which underscore compositional similarities between the investigated rock series and subduction-related igneous series. On the basis of a comparison of the trace element patterns with typical island-arc tholeiites and oceanic calc-alkaline basalts, however, an oceanic island-arc environment can be excluded (data for comparison from PEARCE 1983). Geochemically, the studied intrusives compare best with magmas from active continental margins which contain both calc-alkaline (subduction-related) and alkaline

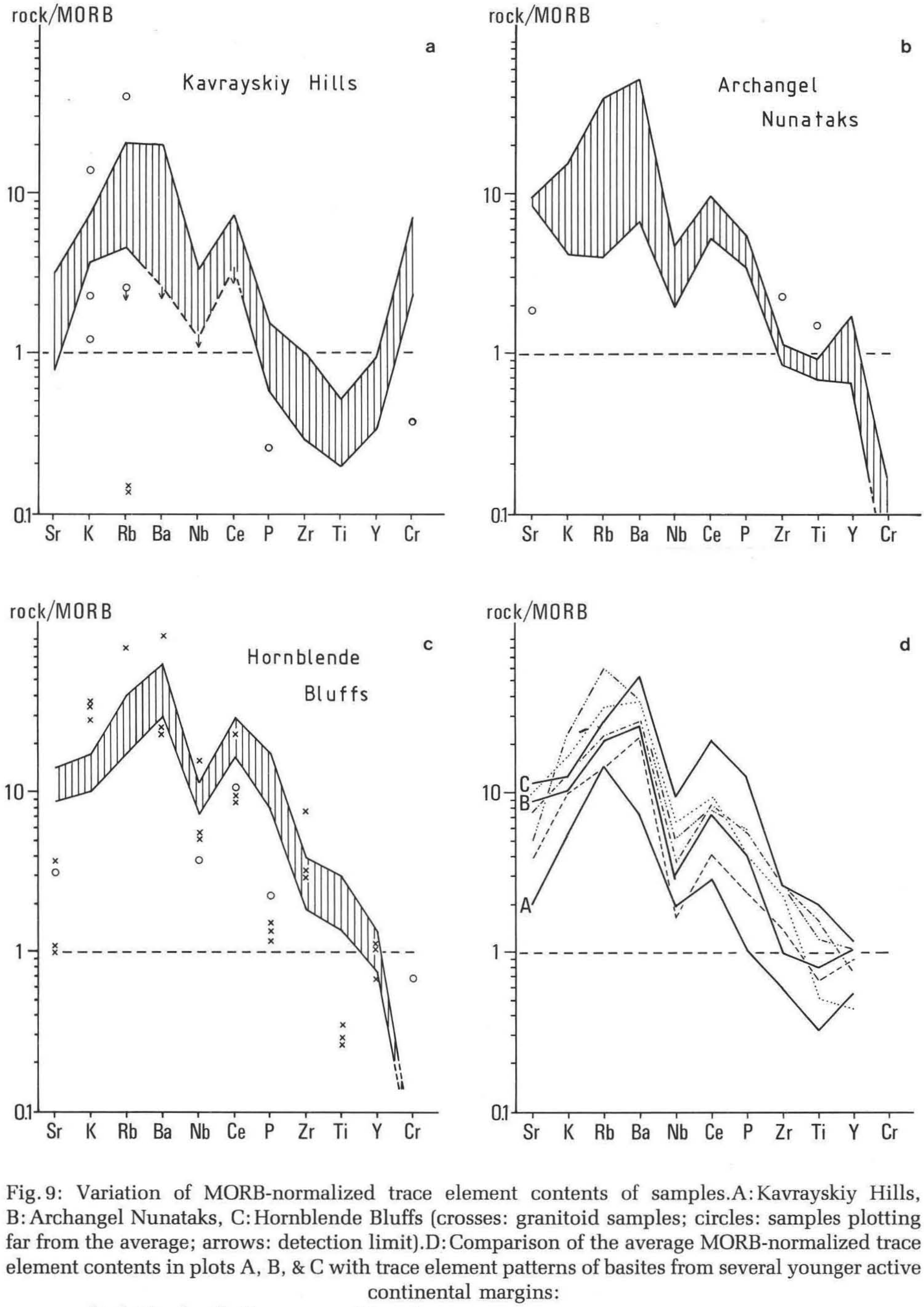

Fig. 9: Variation of MORB-normalized trace element contents of samples. A: Kavrayskiy Hills, B: Archangel Nunataks, C: Hornblende Bluffs (crosses: granitoid samples; circles: samples plotting far from the average; arrows: detection limit). D: Comparison of the average MORB-normalized trace element contents in plots A, B, & C with trace element patterns of basites from several younger active continental margins:

. . . . . = high-K calc-alkaline composition, Iran;
. - . - . = high-K calc-alkaline composition, western USA;
— — = calc-alkaline composition, central Chile;
-...-...- = shoshonite composition, central Chile(data for comparison from Pearce 1983).

(within-plate-related) components. This is clearly demonstrated by a comparison of average trace element patterns of basites from the Kavrayskiy Hills, Hornblende Bluffs and Archangel Nunataks with patterns of basites from several younger active continental margins (Fig. 9D). According to our results, the magma compositions for the gabbroic to intermediate intrusions of the study area are due to partial melting in a source region situated in the heated and fluid-rich wedge above a subducted slab and below a continental crust, and thus contain subduction-related components from the slab, components from the mantle wedge, and components from a presumably enriched, subcontinental lithosphere (PEARCE 1983). This "original" magma may have been affected by crustal contamination as it ascended. As crustal contamination may cause enrichment of incompatible elements, especially those with a low ionic potential, and a negative Nb anomaly, contamination may intensify the typical features, especially those of basic magmas from active continental margins (see PEARCE 1983).

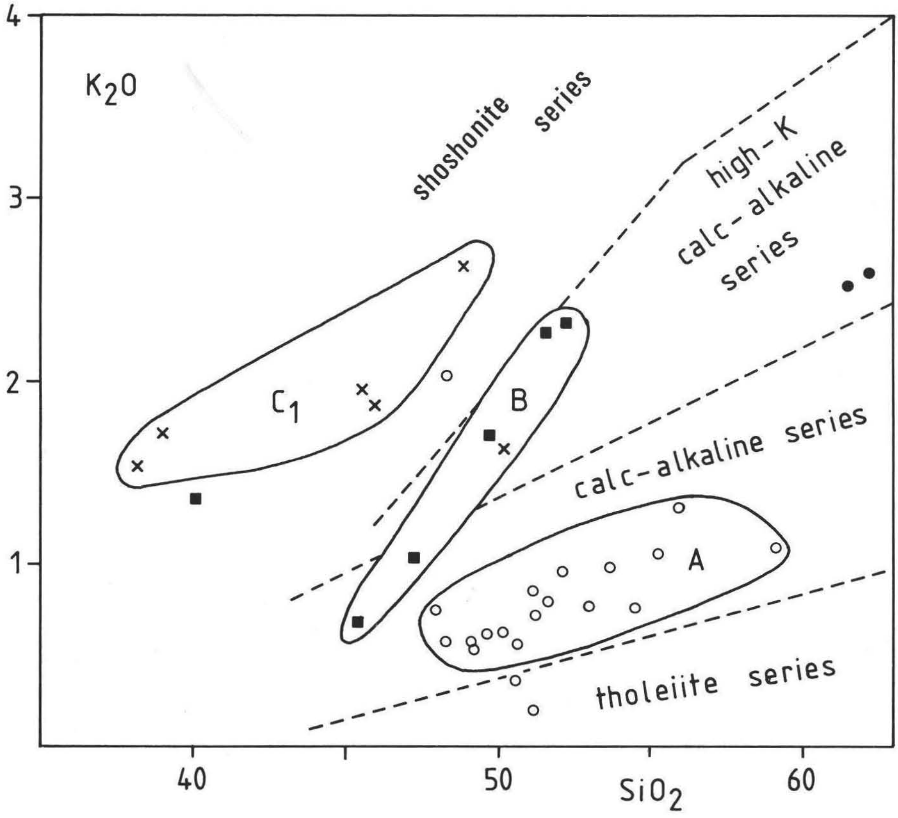

Fig. 10: K_2O vs. SiO_2 diagramm for classification of mafic series produced along destructive plate boundaries (after PECCERILLO & TAYLOR 1976); for symbols, see Fig. 4.

A certain degree of crustal contamination of the intrusive complexes in the study area must be taken into account. However, it is hardly possible to estimate the degree of contamination only on the basis of major and trace element chemical composition.

According to PEARCE (1983), a large degree of crustal contamination for basalts is unlikely because contamination should noticeably raise the SiO_2 content to more intermediate concentrations. As the gabbroic rocks from the intrusive complexes are apparently not enriched in SiO_2, crustal contamination does not seem to be significant and it is probable that the investigated rocks will reflect the approximate composition of their primary magmas.

5 Conclusions

From their geochemical composition, the Schubert Hill gabbro and the White Point diorite (Kavrayskiy Hills) show striking similarities and thus may originate from the same parent magma.

The Hornblende Bluffs complex seems to be somewhat more heterogeneous than the other basite intrusions. In several variation diagrams, it seems possible to split the sample plots into a more alkaline trend and a more subalkaline trend (Fig. 5). There are not enough analyzed samples, however, to really verify the subalkaline trend. In any case, the more subalkaline and the more alkaline samples from Hornblende Bluffs, as well as the basic and acid ones, are derived from familiar magma types, as shown by the trace element patterns (Fig. 9C) and by the differentiation trends (Figs. 4 & 5).

The geochemical analyses have led to a clear classification of the basic to intermediate intrusive complexes in terms of paleogeotectonic setting at an active continental margin. A plate-tectonic reconstruction of the early Paleozoic evolution of North Victoria Land was proposed by KLEINSCHMIDT & TESSENSOHN (1987): They suggested that pre-Ross to main-Ross (i.e. 550—500 Ma), two-stage, westward subduction of oceanic crust under the Antarctic craton, with a trench region east of the Wilson Terrane, led to the formation of paired metamorphic and igneous belts with medium-pressure metamorphism and I-type granitoids in the eastern part and low-pressure metamorphism and S-type granitoids in the western part of the northern Wilson Terrane (GREW et al. 1984; VETTER & TESSENSOHN 1987).

On the basis of their geochemistry, the investigated gabbroic intrusives confirm the role of the Wilson Terrane as an active continental margin at that time. As is typical for subduction zones, the Kavrayskiy Hills gabbro, situated closest to the trench, is characterized by the most primitive and most calc-alkaline composition, whereas the Hornblende Bluffs intrusives and the Archangel Nunataks gabbro, situated at a greater distance from the trench, are of more alkaline composition. The fact, however, that Hornblende Bluffs, presumably not as far from the trench as Archangel Nunataks, have a much more pronounced alkaline composition than the Archangel Nunataks gabbro seems to be somewhat contradictory to the commonly observed continuous increase in alkalinity with increasing distance from a trench.

It should be noted that the investigated gabbroic to intermediate intrusives in the northwestern part of the Wilson Terrane are quite similar to gabbroic intrusives from the southeastern part of the Wilson Terrane. With respect to age relationship, the gabbros there are also younger than the Ross orogeny, but older than the main intrusion of the Granite Harbour acid intrusives. This is excellently demonstrated, for example, by gabbroic outcrops in the Gerlache Inlet/Terra Nova Bay, where the gabbros are intruded by a large number of granitic apophyses, and the granites themselves contain a large number of gabbroic xenoliths of different sizes. Moreover, the chemical composition of the gabbros in the southeastern Wilson Terrane is similar to that of the gabbros in the northwestern Wilson Terrane (geochemical analyses on gabbros from the southeastern part were carried out by C. GHEZZO, pers. comm., and by RUPPRECHT 1992). The evidence indicates that gabbroic magma of the same compositional type — active continental margin type — intruded throughout the Wilson Terrane at the same time.

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Plate 1:

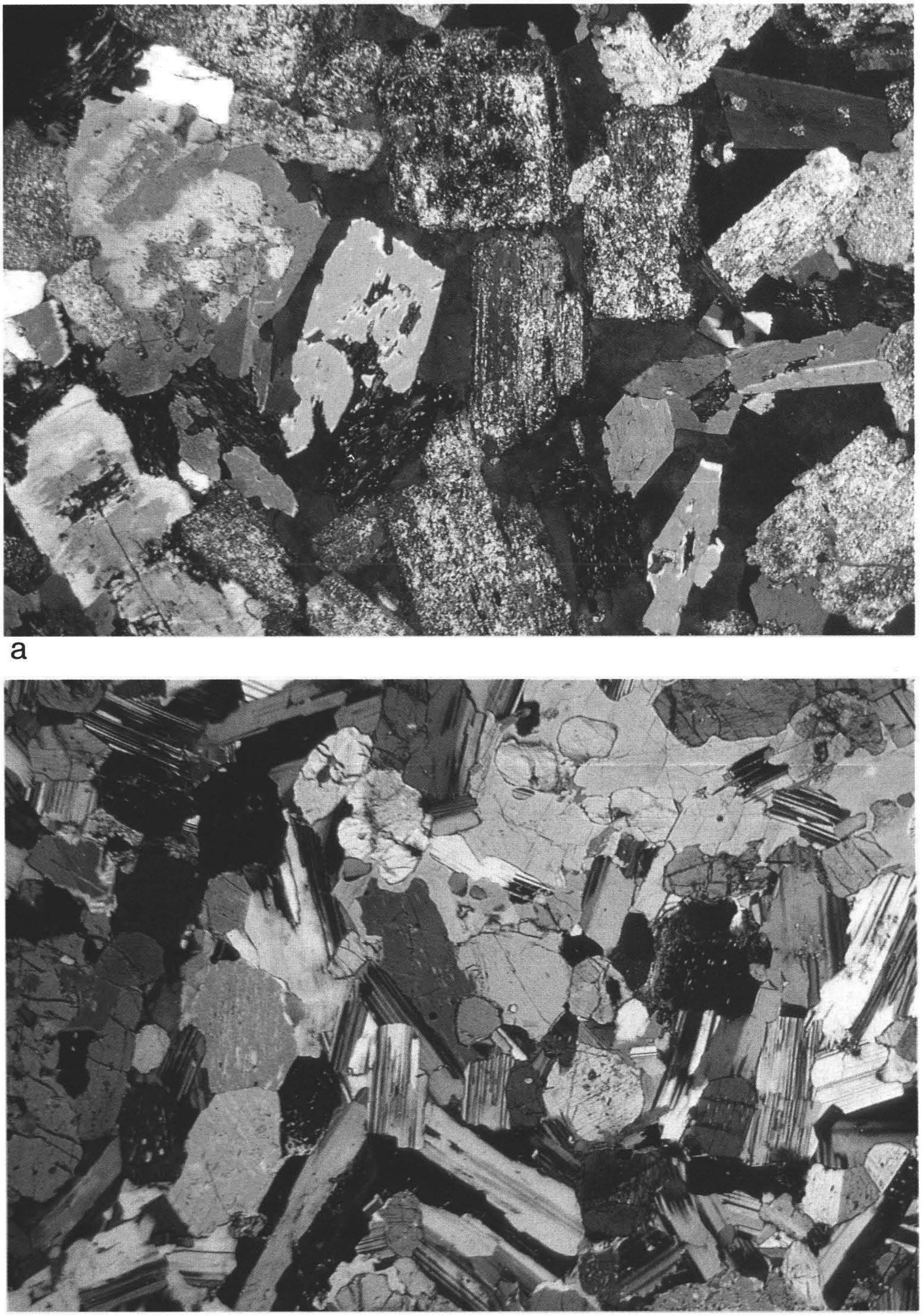
Thin sections (X nicols) of basic rocks from White Point, Schubert Hill, and Hornblende Bluffs; length of photos: 4.3 mm.

a: Strongly altered diorite of White Point; euhedral actinolite, and saussuritised plagioclase; actinolite rimming relict clinopyroxene.

b: Gabbro of upper part of Schubert Hill, containing clinopyroxene and orthopyroxene, hornblende, plagioclase, and minor opaques; hornblende partly filling the interstices.

c: Altered anorthosite from west ridge of Hornblende Bluffs; hornblende replacing clinopyroxene and interstitial to plagioclase; serpentinized olivine (criss-cross pattern); center: orthopyroxene core surrounded by clinopyroxene.

d: Gabbromonzonite from Hornblende Bluffs; olivine with reaction rim, surrounded by orthopyroxene, biotite, and opaques.


a
b

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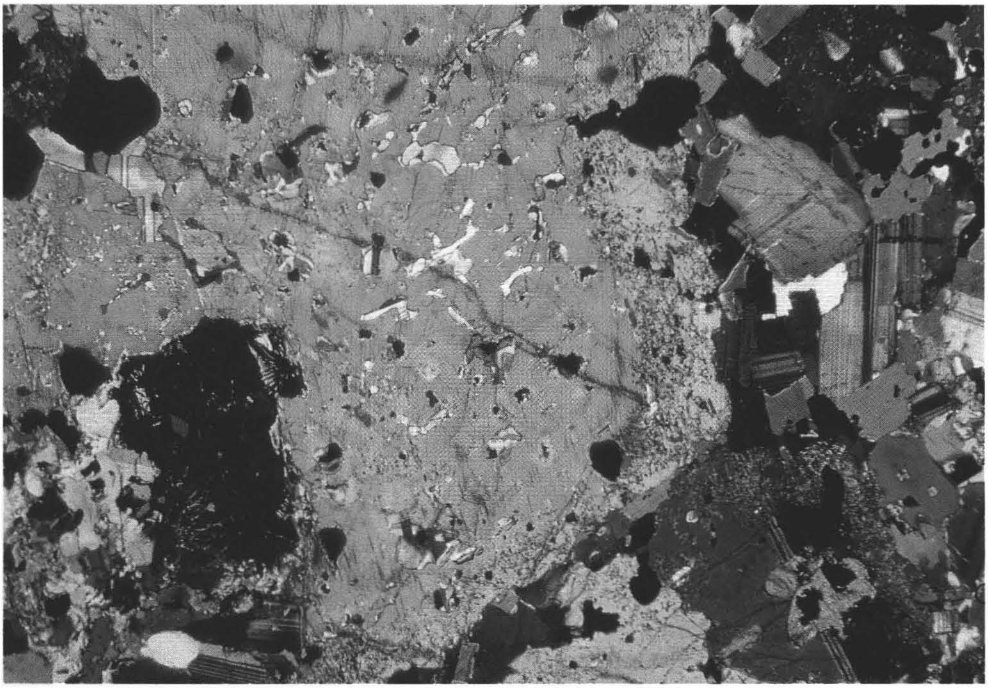

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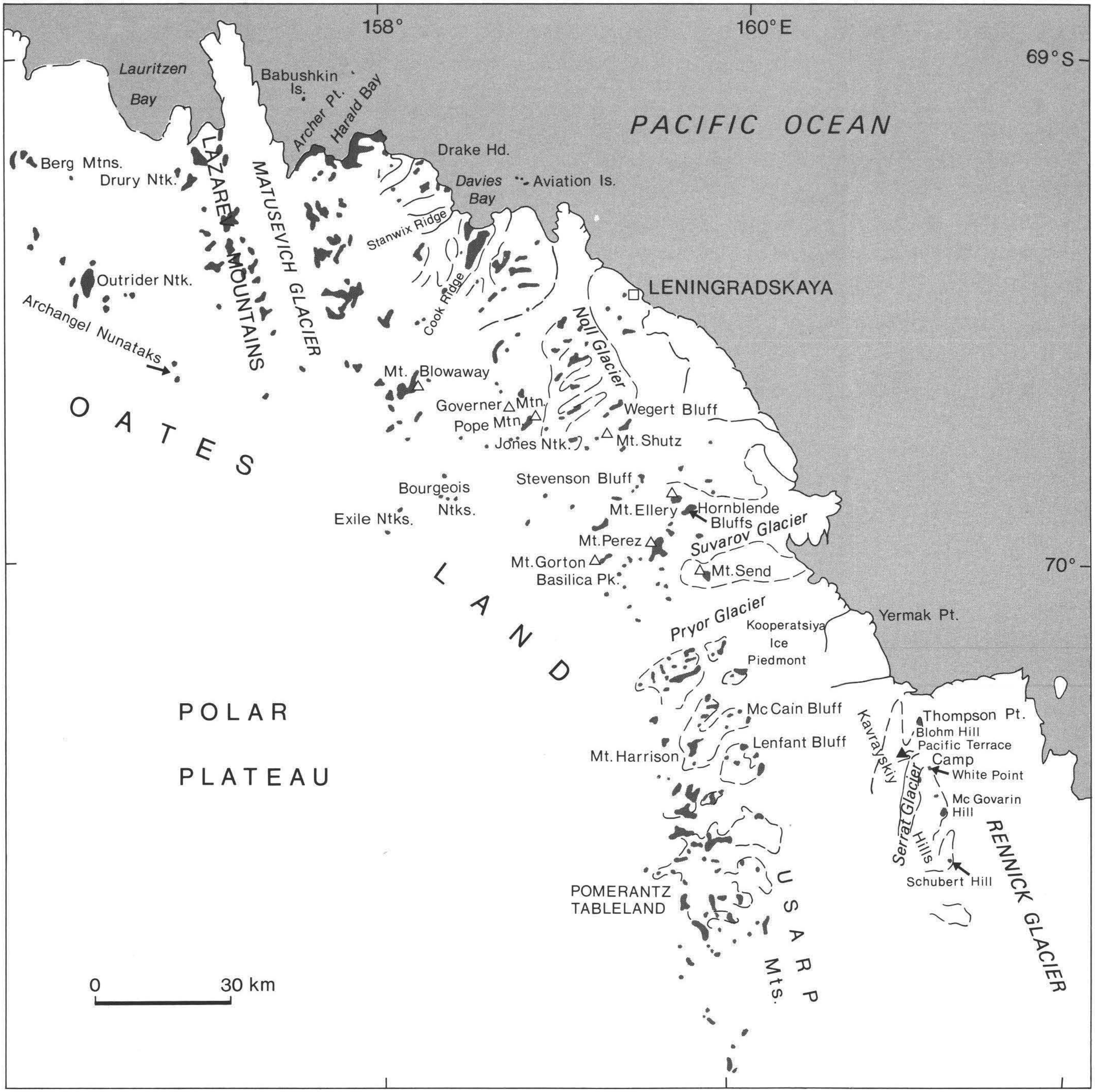

Fig. 1: Oates Coast in the northwestern part of the Wilson Terrane: locations of the mafic intrusive complexes shown by arrows. Black: outcrop area; white: ice-covered area; dotted: southern Pacific Ocean.