Leif Johansson

EXAMENSARBETE I GEOLOGI VID LUNDS UNIVERSITET

Mineralogi och petrologi

A Petrographic and Geochemical Study of the Early Proterozoic, Bangenhuk Granitoid Rocks of Ny Friesland, Svalbard

Patric Carlsson

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Geologiska Institutionen, Lunds Universitet

ERRATA

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12	27	..virtually undeformed..	**..relatively undeformed (lineated)..**
13	18	Reddish grey,..	**Grey to reddish,..**
14	9	Reddish, fine to medi-um-grained aplites or aplitic granites	**Reddish, medium-grained granites or fine-grained aplitic granites**
15	J91006/Al_2O_3	12,78	12.78
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15	L9013/Nb/Ta	13.05	**11.66**
16	PC9214/Mo	1.68	**0.88**
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Appendix	PC9225	..granite (90071)	..granite **(L9013)**
Appendix	PC9225		79 46'29"N/15 49'30"E.
Appendix	PC9230		79 50'05"N/16 07'41"E.

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Abstract

Old Red Sandstones and younger strata overlie a variety of deformed and metamorphosed Early Paleozoic and Precambrian rocks on Svalbard, referred to as the Hecla Hoek Complex. At least three different terranes are recognized, occurring in eastern, northwestern and southwestern areas. The Eastern Terrane is exposed in the northeastern parts of the Svalbard archipelago in Nordaustlandet and Ny Friesland. In the latter area, c. 1750 Ma old granites and gneissic granites, mostly from the Bangenhuk Formation in the lower part of the Hecla Hoek, have been studied. Petrographical and geochemical data indicate that the rocks can be classified as granites and granodiorites and plot as A-type granites in tectonic discrimination diagrams. They are characterized by high alkali contents, high K_2O/Na_2O- and $Fe_2O_3^*/(Fe_2O_3^*+MgO)$ ratios and high contents of Zr, Zn, Y, Nb, Ga and REE (except Eu). The geochemical coherence of the rocks suggests that they represent related magmatic events. Deformation and metamorphism have not influenced the element distribution significantly.

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Contents

1. Introduction

Svalbard is the geographical name of a group of islands (including Spitsbergen and the smaller islands Kvitøya, Kong Karls Land, Hopen and Bjørnøya) situated in the northwestern corner of the Barents Sea Shelf, between latitudes 74°N and 81°N, and longitudes 10°E and 35°E. Spitsbergen comprises Vestspitsbergen (39500 sq. km), Nordaustlandet (15000 sq. km), Edgeøya (5151 sq. km), Barentsøya (1300 sq. km) and Prins Karls Forland (650 sq. km), making a total area of 61600 sq. km. This study is located in Ny Friesland, in the northeastern part of Vestspitsbergen.

Old Red Sandstones and younger strata overlie a variety of deformed and metamorphosed Early Paleozoic and Precambrian rocks on Svalbard, referred to as the Hecla Hoek Complex. The latter is separated into different provinces by major high-angle N-trending faults. As the nature of the pre-Devonian rocks differs greatly across some of these faults, Harland (1972 & 1985) and Harland & Wright (1979) concluded that they separate terranes with independent tectonic histories. These are referred to here as the Eastern, Northwestern and Southwestern terranes (Fig. 1). Caledonian elements can also be found to the south of Spitsbergen on Bjørnøya, Svalbard's southernmost island.

A correlation has been drawn between the Eastern Terrane and the Caledonides of east Greenland (Harland, 1972; Harland & Wright, 1979; Harland et al., 1992; Swett, 1981; Hambrey, 1982); furthermore, there are similarities between the Southwestern Terrane and Ellesmere Island (Harland, 1985; Ohta et al., 1989). The dissimilarities in the stratigraphies and tectonothermal histories of the Svalbard terranes have been explained by hypotheses that involve variable amounts of transcurrent motion on the faults seperating the terranes

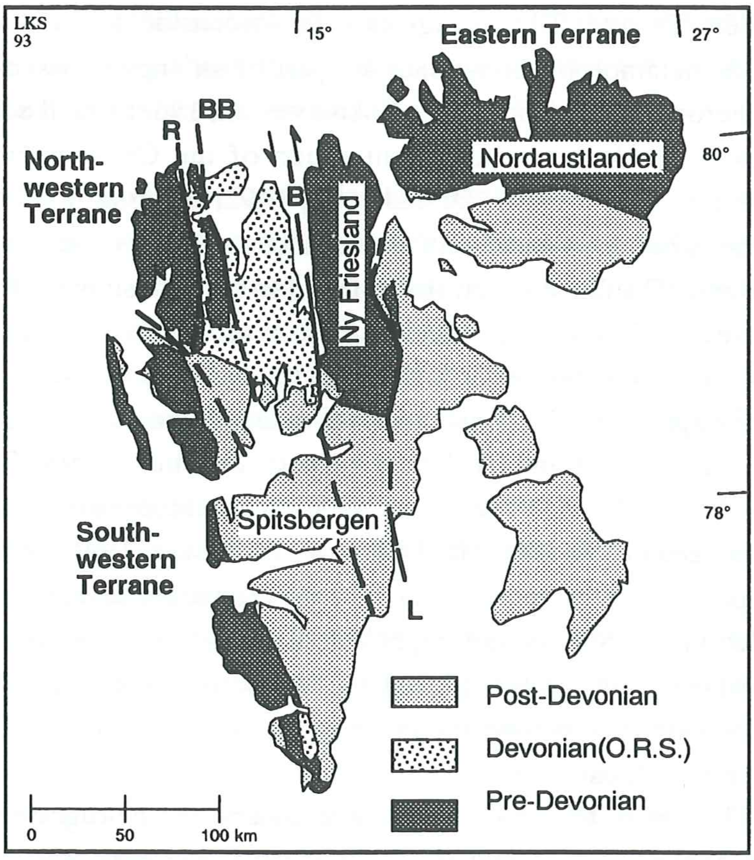

FIGURE 1. Regional geology of Svalbard. From Gee et al. (in press a).

(Harland & Wright, 1979; Harland, 1985; Birkenmayer, 1981; Gee, 1986).

The Eastern Terrane is exposed in the northeastern parts of the Svalbard archipelago in Nordaustlandet and Ny Friesland (Vestpitsbergen). The pioneering studies in this area were undertaken by Nordenskiöld (1863), Blomstrand (1864), De Geer (1909), Nathorst (1910), Tyrell (1922), Odell (1927), Kulling (1934), Fairbairn (1933), Fleming & Edmonds (1941) and Harland (1941).

The term Hecla Hoek was originally used by Nordenskiöld (1863) for sedimentary sequences found in the vicinity of Mount Hecla (now Heclahuken) in northern Ny Friesland. Nordenskiöld (1863) considered these sequences to be separated from the more highly metamorphosed "Urgebirge" or basement occurring in western Ny Friesland, which he interpreted to be "Archaean" in age. Furthermore, Blomstrand (1864) noticed the conspiciuous regional conformity of the structures in the rocks as they pass westwards and downwards with increasing metamorphic grade from well preserved sedimentary strata, now known to be of Late Proterozoic and Early Paleozoic age, into metasedimentary and metaigneous rocks of controversial origin and age. Later, all rocks of pre-Devonian age in Svalbard, with the exception of possible (but not demonstrated) basement, have been called Hecla Hoek (Harland, 1959).

Two main hypotheses have dominated the literature on the metamorphic complex of the Eastern Terrane. The one agrees with Nordenskiöld's early suggestions that the amphibolite facies metamorphic complexes are part of an ancient basement to the Late Proterozoic and Phanerozoic successions (*e.g.* Sokolov et al., 1968; Krasil'schikov, 1979). The second postulates the rocks to be an essential part of the Caledonian "geosynclinal" succession (*e.g.* Harland, 1959 &1985; Harland et al., 1992; Gayer & Wallis, 1966; Manby, 1990). This hypothesis has been based on the structural conformity and metamorphic transition between the "basement" and the cover, first referred to by Blomstrand (1864).

New U/Pb age-determinations (Gee et al., 1992) give unambiguous evidence that there are basement elements in the lower structural levels of western Ny Friesland. So far, nine U/Pb zircon age-determinations have been made on granites and granitic gneisses in the lowermost units in Ny Friesland (Å. Johansson pers. commun., 1993). They indicate ages of approximately 1700-1800 Ma. These ages are similar to recent data obtained from the basement in East Greenland (1650-1800 Ma, Dallmeyer & Tucker, 1991). Whereas the new U/Pb zircon data support the interpretation that Early Proterozoic basement is present in the Ny Friesland Caledonides, they do not imply that the entire assemblage of amphibolite facies rocks in Ny Friesland is of this age. Indeed, Gee et al. (in press a) have argued that this metamorphosed succession is a tectonostratigraphic pile, the various formations being seperated by at least two major thrusts.

The aim of this study has been to undertake a petrographic and geochemical characterization of the c. 1700-1800 Ma old granites and granitic gneisses in Ny Friesland, mostly from the Bangenhuk Formation in the lower part of the Hecla Hoek (see Table 1). Fifteen new and seven previously published analyses (Manby, 1990) are considered here.

2. Svalbard's Eastern Terrane: Regional Geology of Ny Friesland

The Eastern Terrane contains a major synclinorium, with N-trending axis through Hinlopenstretet, flanked to east and west by major antiforms (Fig. 2 & 3). The rock units in Ny Friesland generally strike N-S and dip eastwards. In western areas, the foliations flatten over the hinge of a major fold, the Atomfjella Antiform (Harland, 1959), and then dip westwards along the Wijdefjorden coast. Early isoclinal folds are refolded homoaxially by this structure (Gayer, 1969; Manby, 1990). A major fracture, the Billefjorden Fault Zone is situated in Wijdefjorden and delimits the Eastern Terrane from the Northwestern Terrane further to the west.

The Hecla Hoek stratigraphy has been described by Harland & Wilson (1956), Harland et al. (1966), Harland (1985) and Harland et al. (1992). It is divided into three major units (Table 1);

- Hinlopenstretet Supergroup (Upper Hecla Hoek).
- Lomfjorden Supergroup (Middle Hecla Hoek).
- Stubendorffbreen Supergroup (Lower Hecla Hoek).

The Hinlopenstretet Supergroup is estimated to be c. 1800 meters thick. In the lower part it comprises shales that contains two tillite horizons, correlated with the Tillite Group in Central East Greenland (Hambrey, 1982). Following above these Vendian rocks there are Cambro-Ordovician sandstones, dolomites and limestones and the succession reaches into the Llanvirn (Fortey & Bruton 1973; Fortey, 1980).

The underlying Lomfjorden Supergroup comprises nearly 6000 meters of siliciclastic and carbonate sediments. These are suggested to have been deposited in a subsiding, intracratonic, extensional basin (Knoll & Swett, 1990). The succession has similarities with parts of the Eleonore Bay Group of Central East Greenland (Harland et al., 1992).

The Hinlopenstretet and Lomfjorden Supergroups are very weakly metamorphosed and the lower strata contain excellently preserved Late Proterozoic acritarchs (Knoll & Swett, 1985; Knoll et al., 1986).

The underlying Stubendorffbreen Supergroup contains the most intensely tectonized and metamorphosed rocks of the Ny Friesland succession. It is divided, from top downwards, into the Planetfjella, Harkerbreen, and Finnlandsveggen Groups.

The Planetfjella Group, described in detail by Wallis (1969), is the highest of the three units. It occurs conformably below the sandstones of Lomfjorden Supergroup and is estimated to be c. 4000 meters thick. The group is dominated by metasediments and is reported to contain minor amounts of acid pyroclastics. There are no recorded mafic rocks in this unit. Metamorphic grade increases downwards from low greenschist facies at the top to high amphibolite facies at the base. The transition from the Planetfjella Group to the overlying Lomfjorden Supergroup, has been postulated to be a normal stratigraphic transition by Harland et al. (1966) and Wallis (1969). However, Nathorst (1910) and, recently, Manby (1990), Manby & Lyberis (1991) and Lyberis & Manby (1993) have suggested that the "tran-

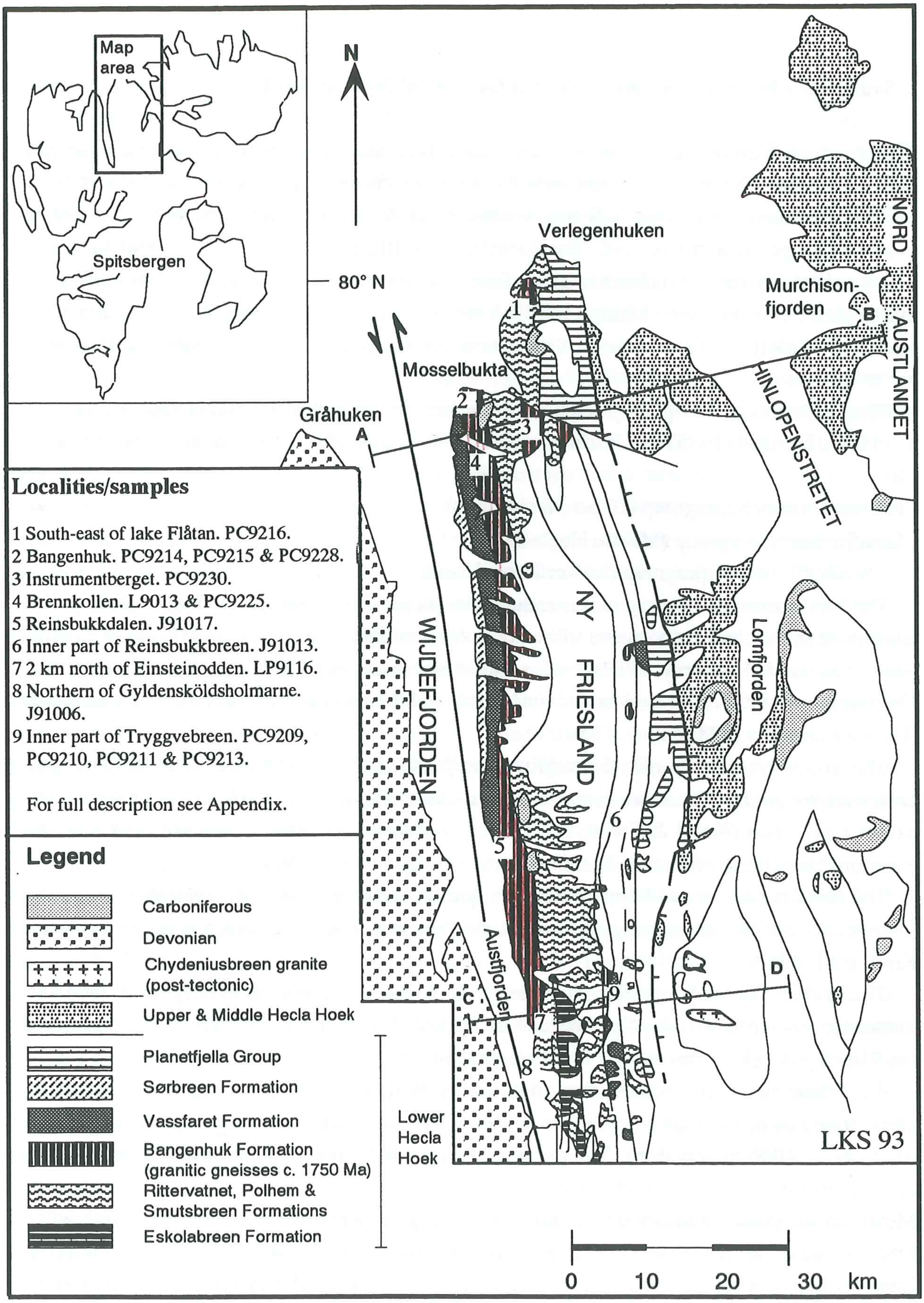

FIGURE 2. Regional geology of Ny Friesland. Based on Gee et al. (in press a).

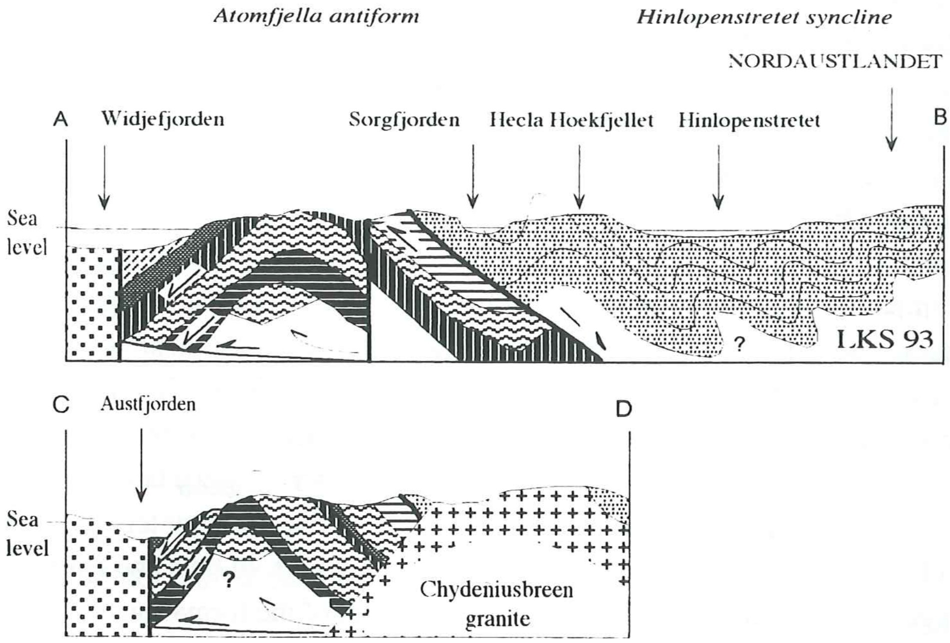

FIGURE 3. Schematic profiles through northern (A-B) and southern (C-D) Ny Friesland (location and legend on Fig. 2). From Gee et al. (in press a).

Hinlopenstretet Supergroup (Upper Hecla Hoek)

Oslobreen Group (1.2 km)
Valhallfonna Fm (limestone) Llanvirn
Kirtonryggen Fm (limestone and dolomite) Canadian
Tokommane Fm (dolomite and sandstone) Early Cambrian

Polarisbreen Group (0.8 km) Vendian
Drakoisen Fm (shale) Ediacara
Wilsonbreen Fm (tillite and carbonate) Late Varanger
Elbobreen Fm (shale, carbonate and tillites) Early Varanger

Lomfjorden Supergroup (Middle Hecla Hoek)

Akademikerbreen Group (2km) Late Riphean
Backlundtoppen Fm (dolomite and shale)
Draken Conglomerate Fm
Svanbergfjellet Fm (limestone and dolomite)
Grusdievbreen Fm (limestone and dolomite)

Veteranen Group (3.8 km) Late Riphean
Oxfordbreen Fm (shales)
Glasgowbreen Fm (greywacke and quartzite)
Kingbreen Fm (quartzite and limestone)
Kortbreen Fm (quartzite and limestone)

Stubendorffbreen Supergroup (Lower Hecla Hoek)

Planetfjella Group (4.7 km)
Vildalen Fm (semipelite, psammite and quartzite)
Flåen Fm (semipelite, psammite and quartzite with acid pyroclatics)

Harkerbreen Group (3.5-4.0 km)
Sørbreen Fm (quartzite and amphibolite)
Vassfaret Fm (semipelite, psammite and amphibolite)
Bangenhuk Fm (feldspathite, psammite and amphibolite)
Rittervatnet Fm (psammite, semipelite, marble, conglomerate and amphibolite)
Polhem Fm (quartzite and amphibolite)

Finnlandsveggen Group (2.7 km)
Smutsbreen Fm (semipelite and marble)
Eskolabreen Fm (feldspathite, semipelite and ampibolite)

TABLE 1. Stratigraphy of Hecla Hoek. Based on Harland et al. (1992).

sition zone" between the Lomfjorden Supergroup and the Stubendorffbreen Supergroup is a major tectonic contact, referred to as the Eolussletta Shear Zone by Manby (1990) & Manby & Lyberis (1991), or the Sorgfjorden Shear Zone by Lyberis & Manby (1993). These later authors postulated that the fault has the same importance as the BFZ. This could have important implications for explaining the differences between Ny Friesland and Nordaustlandet (Gee et al., in press b).

The underlying Harkerbreen Group is estimated to be about 4000 m thick (Gayer & Wallis, 1966). It is composed of a variety of metasedimentary rocks and intercalated granitic and feldspathic gneisses. The contact to the Planetfjella schists is apparently conformable, but tectonic (Gayer, 1969; Gee et al., in press a). It is within the Harkerbreen Group that the granitic gneisses, analysed herein occur, mainly but not exclusively in the Bangenhuk Formation.

The Harkerbreen Group is in turn underlain by the Finnlandsveggen Group, which is also characterized by feldspathic gneisses and metasediments about 4000 meters in thickness, including a thick sequence of schists and marbles in the upper part. In both the Harkerbreen and Finnlandsveggen Groups, amphibolites are frequent in most of the formations.

The characteristic concordance between Lower Hecla Hoek lithologies, has persuaded most authors to interpret the feldspathic gneisses (*i.e.* in the Bangenhuk Formation) to be acid metavolcanites extruded in a Caledonian "geosyncline" (Harland, 1959; Harland et al., 1966; Harland et al., 1992; Gayer & Wallis, 1966; Krasil'shcikov, 1979). Manby (1990) provided geochemical evidence, suggesting that the acid gneisses "were derived from rhyodacitic and rhyolitic magmas in an attenuated Within-Plate setting". Gee et al. (in press a) prefer the interpretation that the gneisses are mainly of plutonic origin, locally showing intrusive reliationships (Gayer, 1969) to adjacent metasediments (*e.g.* Vassfaret Formation). These authors infer that the concordance between the formations is largely the result of penetrative shearing; Caledonian thrusting is thought to account for much of the intercalation of these gneisses (both in the Harkerbreen and Finnlandsveggen Group) with the metasediments (*e.g.* Rittervatnet, Polhem, Smutsbreen Formations).

Most of the granitic gneisses studied in this paper were collected in the Bangenhuk Formation, outcropping in both the eastern and western limbs of the Atomfjella Antiform (Harland et el., 1992). The two samples PC9216 and PC9230 (No 1 & 3 on Fig. 2) occur at lower levels in the tectonostratigraphy (D.G. Gee pers. commun., 1993).

3. Bangenhuk Formation

The Bangenhuk Formation, c. 2000 m thick, was described in detail by Gayer & Wallis (1966). These authors divided the formation into two units; the Femmilsjøen member (1250 m), dominated by poorly foliated, lineated feldspathites and amphibolites and the underlying Flatøyrdalen member (735 m), a composite unit of foliated feldspathites, psammites and amphibolites. As mentioned above, most previous authors have interpreted the feldspathites and the amphibolites to be acid and basic pyroclastics. The subordinate intercalated sediments were explained by deposition of the pyroclastics in shallow water. Bayly (1957) however, interpreted some of the gneisses from the lower Hecla Hoek to have a granitic origin and Gayer (1969) reported intrusive relationships near Femmilsjøen.

The typical lithology of the Bangenhuk Formation is a felsic gneiss. During the fieldwork many observations indicated that these gneisses were derived from granites by deformation. The gneisses vary from reddish, fine-grained (aplitic) granites to grey-reddish, medium- to coarse-grained varieties. Primary relationships are often obscured by the strong deformation and augen gneisses occurs.

A number of localities, where well-preserved granitic rocks occur, were visited in the 1992 field-season; these are described briefly below.

Brennkollen (western limb of the Atomfjella Antiform)

The Brennkollen locality, south of Femmilsjøen, first described by Gayer (1969) and discussed by Gee et al. (in press a), is one of the most instructive. A more or less undeformed grey to slighty pinkish, coarse-grained granite occurs (sample L9013), containing many randomly orientated xenoliths of metaigneous rocks (Fig. 4), and cross-cutting aplites (sample PC9225, Fig. 5), and a felsic composite dyke. There is a gradual transition between this unstrained body and a gneissic granite, within which flattened xenoliths (Fig. 6) and concordant aplites are frequent. This gneissic granite is very similar in appearance to other gneissic grantites found in many places in Ny Friesland, *e.g.* at Bangenhuk and in the nunataks of eastern Tryggvebreen (described below). The gneissic granite has a tectonic contact to the foliated margin of Gayer's (1969) intrusive porphyritic "granodiorite". The latter contains large xeno-

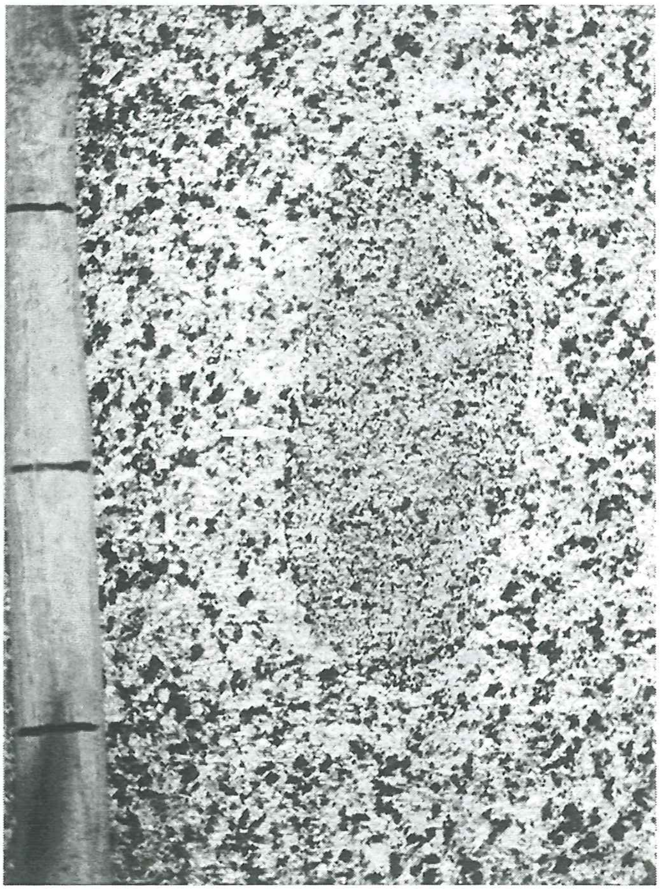

FIGURE 4. Brennkollen granite with undeformed xenolith. Interval on scale: 1 dm.

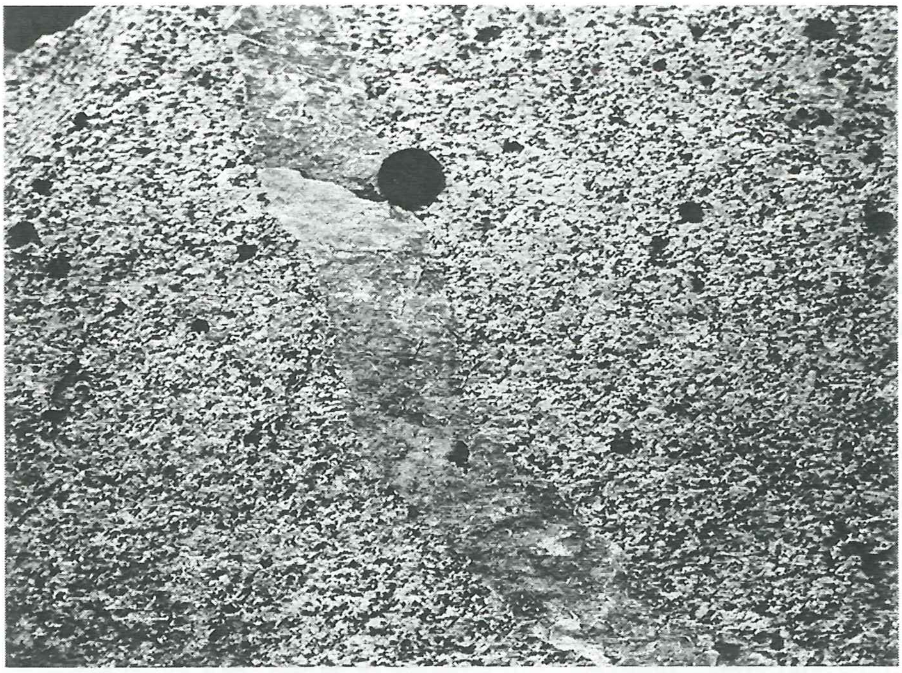

FIGURE 5 Brennkollen granite with cross-cutting aplite.
Scale on lens cap: c. 0.5 dm.

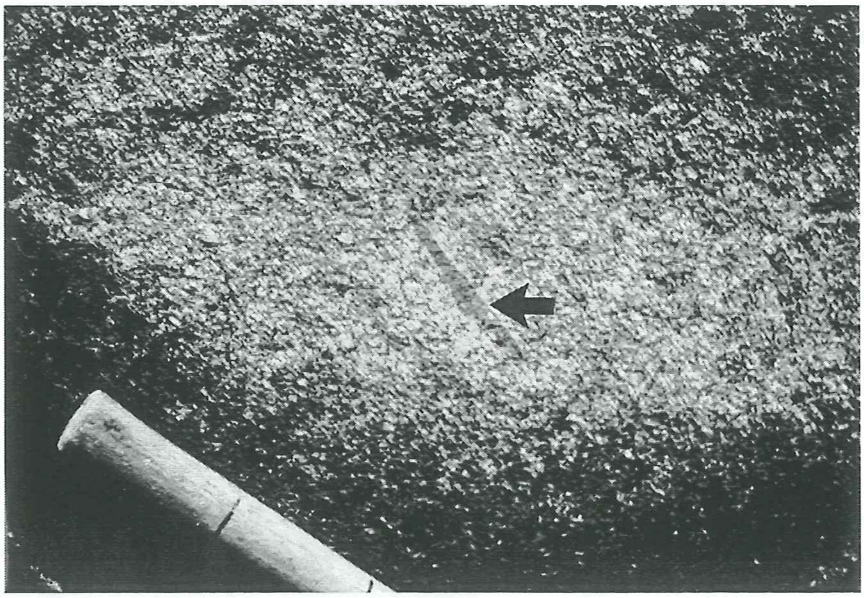

FIGURE 6. Deformed Brennkollen granite with flattened xenolith.
Interval on scale: 1 dm.

liths of psammites and other metasediments.

Bangenhuk (western limb of the Atomfjella Antiform)

At the Bangenhuk locality, relatively well-preserved psammites and semipelites of the Vassfaret Formation, with cross-bedding and other primary sedimentary structures (*e.g.* load casts Fig. 7) occur in a low-strain zone. These sediments are intruded by a number of aplitic dykes. At one locality, a grey-reddish, gneissic granite (sample PC9215), similar to the deformed "Brennkollen granite", intrudes the metasediments (Fig. 8). This granite is in turn intruded by a c. 10 m thick, foliated aplitic granite dyke (sample PC9214, Fig.9). Xenoliths are found in both types of granites (Fig. 10).

FIGURE 7. Load cast structure in Vassfaret Formation at Bangenhuk.
Scale on knife edge: c. 1 dm.

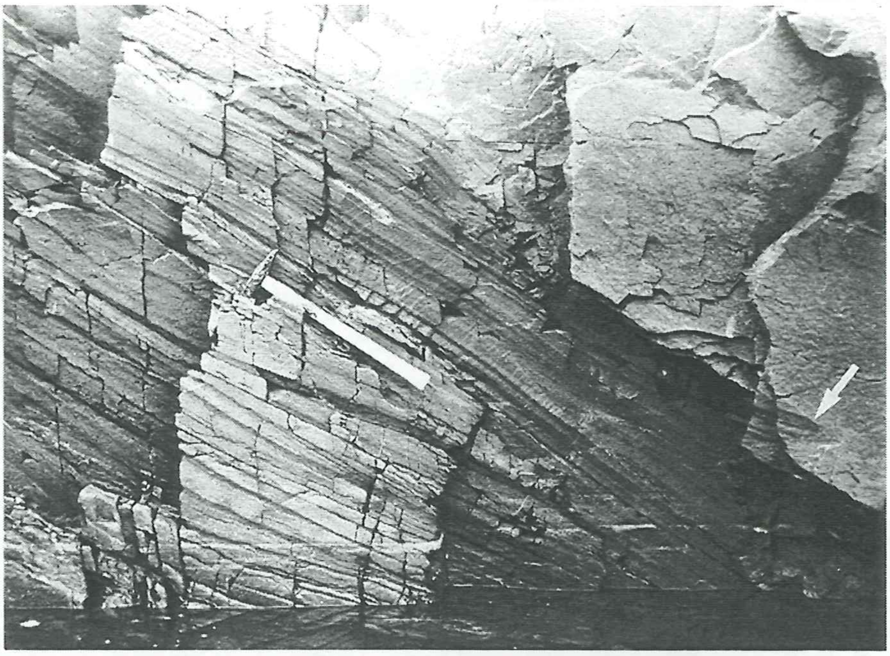

FIGURE 8. Grey -reddish, gneissic granite intrudes metasediments at Bangenhuk. The hammer is c. 6 dm long.

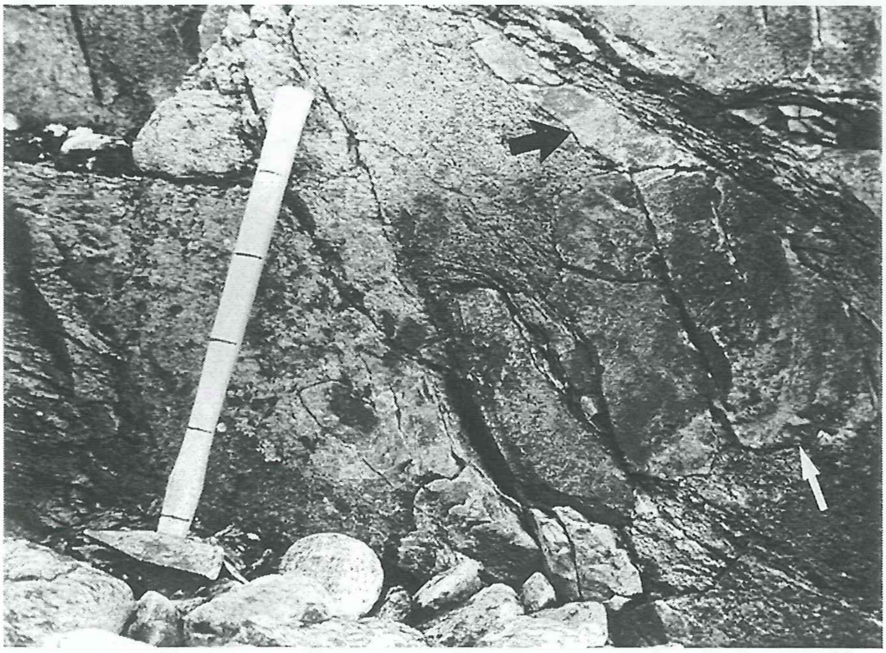

FIGURE 9. Aplitic granite intrudes a grey-reddish, gneissic granite at Bangenhuk (the same granite as shown in Fig. 8). Interval on scale: 1 dm.

FIGURE 10. Xenolith in grey-reddish, gneissic granite at Bangenhuk (the same granite as shown in Fig. 8 & 9). Scale on lens cap: c. 0.5 dm.

Nunataks of eastern Tryggvebreen (eastern limb of the Atomfjella Antiform)

The nunataks of eastern Tryggvebreen are dominated by grey-reddish, gnessic granites (samples PC9209 & PC9210) of the same type as the deformed "Brennkollen granite". No intrusive relationships with adjacent metasedimentary formations were observed for these granites, but xenoliths occur. At the southern spur of Perriertoppen, a medium-grained, foliated reddish granite (sample PC9213) occurs, intruding a grey-reddish, gneissic granite.

Verlegenhuksflya and Istrumentberget

Reddish gneissic granites (Blomstrand, 1864) occur in northernmost Ny Friesland in the hinge of a major antiform (S.A. Abakumov, unpublished map). These rocks (PC9216) and those occuring south of Mosseldalen on Insrumentberget (PC9230) occur at a lower level in the Harkerbreen Group than the Bangenhuk Formation (D.G. Gee, pers. commun., 1993).

A number of well-preserved intrusive granites were also found in the northern Ny Friesland in the 1993 field-season (P. Nilsson, pers. commun., 1993). These observations support the interpretation that the gneisses in the Harkerbreen Group are mainly of granitic origin. Nevertheless these observations do not eliminate the possibility that metavolcanic rocks also occur.

4. Age-determinations of the Bangenhuk and related granites

The first isotopic age-determination studies (Krasil'scikov et al., 1964; Gayer et al., 1966) of Svalbard rocks provided some evidence for the hypothesis that basement elements are present in the orogen. However, the majority of these ages were obtained by the K/Ar method on micas and a few hornblendes and could be variously interpreted. Recently, with regard to Ny Friesland, Gee et al. (1992) published U/Pb-zircon data from an intrusive granite on Brennkollen, south of Femmilsjöen (sample 89141), and a gneissic granite near lake Flåtan on Verlegenhuksflya (sample 89142). These yielded ages of 1809±165/122 Ma and 1778±53/43 Ma respectively, and were interpreted as intrusion ages. A common regression line for these granites defines an age of 1778±30 Ma. Geochemical analyses of Manby's (1990) sample 322 (Brennkollen) and PC9216 (Flåtan) are from approximately the same localities as the samples that were dated (Gee et al., 1992).

Seven new age-determinations of granites from the Bangenhuk formation have been undertaken by Å. Johansson (pers. commun., 1993). The same samples have moreover been analysed geochemically (except J92010), and the results are included here. For full details of analysed samples, their localities and descriptions see Appendix.

Sample L9013 is from Brennkollen (the same locality as sample 89141), but is less deformed. It gives an U/Pb zircon intrusion-age of 1759±19/14 Ma.

Sample LP 9116 is a granodiorite from c. 2 km north of Einsteinodden. An age of 1748±8 Ma was obtained from zircons by the U/Pb method.

Sample J91006 is a foliated and lineated granite from the northern of the Gyldensköldsholmarne islands in Austfjorden. It gives an age of 1728±21/18 Ma. Sample 370 (Manby, 1990) is also from this locality.

Sample J91013 is a virtually undeformed granite from the inner part of Reinsbukkbreen (eastern limb of the Atomfjella Antiform). It gives an age of 1766±43/35 Ma.

Sample J91017 is a red lineated granite from Reinsbukkdalen (western limb of the Atomfjella Antiform). It yields an age of 1724±14 Ma.

Sample J92010 is a red gneissic granite from Instrumentberget south of Mosseldalen (from a structural level below the Bangenhuk Formation, D.G. Gee, pers. commun., 1993). It gives an age of 1737±46/41.

Sample J92011 (collected together with PC9214) is an intrusive aplitic granite from Bangenhuk. This aplitic granite intrudes a gneissic granite (PC9215) of the "normal" Bangenhuk type and yields an age of 1739±49/43 Ma.

These ages are interpreted as magmatic crystallization ages, indicating formation of the Bangenhuk granitoids at around 1750 Ma. The age of the strongly sheared and lineated granites, especially the sample taken within the Billefjorden fault zone, may have been slightly lowered due to deformation (Å. Johansson, pers. commun., 1993).

No contact relationships have been observed for the samples LP9116, J91006, J91013, J91017 and J92010.

Rb-Sr whole rock dating of six granitoid samples, L9013, LP9116, J91006, J91013, J91017 and J92011 (PC9214), gives an ill-defined "errorchron" age of c. 1650 Ma, with initial Sr^{87}/Sr^{86} of 0.703, suggesting some disturbance of the Rb-Sr system (Å. Johansson, pers. commun., 1993).

In addition to these ages on the Bangenhuk granitic rocks, Manby & Lyberis (1991) referred to a preliminary Sm/Nd model age of 1757±90 Ma on Harkerbreen amphibolites. These mafic rocks were reported to cut early schistosites in the host rocks. However, neither the location of the dated samples nor the analytical data were presented.

5. Petrographic description of the Bangenhuk and relatedgranitic rocks

Described below are the fifteen samples selected for geochemical analysis. The rocks can be divided into two groups;

1) Reddish grey, medium to coarse-grained granites (J91006, LP9116, L9013, PC9209, PC9210, PC9215). With the exception of the largely undeformed "Brennkollen granite" (L9013), they are all foliated and/or lineated rocks. Sample L9013 is a coarse-grained granite consisting of quartz, potash-feldspar (often microcline twinned), plagioclase of oligoclase composition (sometimes albite twinned) and mafic aggregates composed of dark green hornblende, brownish biotite, epidote, opaques, zircon and sphene. The sphene often occurs as rims around the opaque grains. In the other samples, original igneous feldspars now form porphyroclasts around which the matrix has been deformed and has undergone metamorphic recrystallization. In the strongly deformed rocks, the porphyroclasts sometimes show patchy extinction and fracturing. Commonly these rocks are foliated, with segregation into quartz and feldspar-rich domains and hornblende and biotite-rich domains. The major felsic minerals are quartz and feldspars. Large deformed quartz grains display strained extinction and sutured grain boundaries. These grains and "augen" of feldspars are set in a matrix of finer-grained recrystallized quartz and feldspars that normally approaches a granoblastic polygonal texture. Potash feldspar (normally perthitic), is sometimes microcline-twinned. In plane polarized light, the potash feldspar is slightly brownish, due to alteration. Granophyric intergrowths with quartz have been seen in some of the samples. Plagioclase (oligoclase to andesine) grains are commonly albite-twinned and sericitized to greater or less degree. Large plagioclase

grains are especially sericitized in their cores. Antiperthite occurs sporadically and myrmekitic intergrowths have been observed. The major dark minerals are light green to dark blue-green hornblende and brownish biotite, with the former normally dominating over the latter. Relics of a phase that probably is clinopyroxene can be seen in sample LP9106. Amongst the accessories, sphene, epidote, zoisite, allanite, apatite, garnet, zircon and opaque phases have been identified. Point-counting with 500 points in each sample (432 points in sample PC9215) and subsequent plotting according to Streckeisen (1976) indicates that these rocks are mainly monzogranites, but include granodiorites (LP9116).

2) Reddish, fine to medium-grained aplites or aplitic granites (J91013, J91017, PC9211, PC9213, PC9214, PC9216, PC9225, PC9228, PC9230). They are normally even-grained; moreover all are totally recrystallized. They are foliated and/or lineated rocks. Biotite and rarely muscovite (sample PC9213) define the foliation. The major felsic minerals are quartz and feldspars. Potash feldspar is sometimes perthitic and show often well-developed cross-hatched twinning. Similar to group (1), the potash feldspar is brownish in plane polarized light. Plagioclase (albite to oligoclase) grains are often albite-twinned and moderately sericitized. Brownish biotite is the dominating dark mineral, but hornblende occurs in lesser amounts in most samples; both phases are less frequent than in the first group. The most common accessories are epidote, zoisite, allanite, apatite, zircon and opaque phases. Garnets occurs in samples J91013, J91017, PC9211 and PC9213. Point-counting with 500 points in each sample (468 points in sample PC9225) and subsequent plotting according to Streckeisen (1976) indicates that these rocks are syenogranites (PC9211) to monzogranites.

6. Geochemistry

Major and trace element analyses of the Bangenhuk granites are displayed in Table 2 and in Manby (1990) and Rare-Earth-Element (REE) data are displayed in Table 3 and in Manby (1990). The precision of Manby's data (1990) can be somewhat lower as the major elements do not sum up to 100 %, and in some trace element plots (especially the REE-diagrams) there is significant scatter. Despite this, they follow the same pattern as the new data in most plots. In Tables 2 and 3 is also included a standard granite from the analytical laboratory of the Geological Institute, University of Lund (marked SGUL and SG(CNRS)). Full details of sample locations and rock descriptions are given in the Appendix.

Of the 15 new analyses, J91006, J91013, J91017, LP9116 and L9013 were crushed and powdered at the Museum of Natural History, Stockholm. The sample-sizes of these varied between 20 and 30 kg as U-Pb-zircon age-determination also was to be undertaken. They were crushed in steel jaws and the rock chips were powdered in a steel alloy shatterbox. The high contents of Cr in these samples (Table 2) are explained by contamination from the shat-

Samples	J91006	J91013	J91017	LP9116	L9013	PC9209	PC9210	PC9211	PC9213
SiO_2	70.39	73.93	73.81	62.70	67.99	72.90	69.50	75.46	74.68
Al_2O_3	12,78	12.53	12.46	12.86	13.23	12.30	12.30	11.94	12.60
Fe_2O_3*	4.69	2.79	2.72	9.49	5.83	3.79	6.19	2.42	2.08
MnO	0.07	0.04	0.03	0.16	0.08	0.05	0.11	0.02	0.03
MgO	0.88	0.32	0.30	1.76	0.70	0.34	0.53	0.06	0.11
CaO	1.52	0.69	1.00	3.50	2.54	1.29	2.12	0.75	0.93
Na_2O	3.66	3.32	3.20	3.45	3.59	3.16	3.29	3.50	3.70
K_2O	4.08	4.91	5.44	3.20	4.16	4.87	4.30	4.91	4.94
TiO_2	0.72	0.34	0.38	1.41	0.81	0.40	0.68	0.17	0.16
P_2O_5	0.15	0.13	0.06	0.40	0.20	0.08	0.15	0.02	0.03
LOI	0.61	0.48	0.32	0.73	0.46	0.38	0.37	0.48	0.66
Total	99.55	99.48	99.72	99.66	99.59	99.56	99.54	99.73	99.92
K_2O/Na_2O	1.11	1.48	1.70	0.93	1.16	1.54	1.31	1.40	1.34
Fe_2O_3*/ (Fe_2O_3*+MgO)	0.84	0.90	0.90	0.84	0.89	0.92	0.92	0.98	0.95
ASI	0.97	1.04	0.96	0.83	0.88	0.96	0.88	0.96	0.96
As	0.77	0.9	3.51	2.82	1.97	0.47	0.94	0.67	0.42
Ba	1189	1760	508	1035	1031	1343	1599	211	571
Be	2.69	4.02	4.46	2.47	3.63	4.66	4.69	5.29	8.88
Bi	0.02	0.02	0.05	0.01	traces	0.14	0.03	0.02	0.06
Cd	0.21	0.07	0.12	0.33	0.07	0.18	0.31	0.1	0.0
Co	4.18	1.14	2.68	13.1	1025	61.0	50.7	58.5	53.6
Cr	72.4	91.2	91.3	80.8	140	4.69	6.61	1.6	1.43
Cs	1.51	1.5	5.4	1.35	2.09	3.47	3.62	2.54	1.71
Cu	11.0	4.65	8.4	17.1	20.5	4.26	10.4	2.37	3.11
Ga	20.4	23.0	20.5	23.2	22.6	24.4	26.6	27.8	27.5
Hf	17.3	15.1	11.8	18.1	16.4	13.6	19.2	19.3	12.8
Mo	4.16	1.58	4.44	3.31	4.76	1.47	2.77	2.83	2.29
Nb	34.1	40.4	36.5	36.4	35.8	35.7	34.2	90.2	39.8
Ni	5.57	2.93	7.49	6.28	767	2.65	4.3	1.19	5.35
Pb	16.8	27.3	29.5	14.6	21.5	30.4	30.9	30.6	23.7
Rb	133	158	281	101	155	217	175	207	271
Sc	8.8	4.8	4.08	15.6	8.8	6	10.3	4	2.79
Sb	0.13	0.07	0.4	0.11	0.19	0.06	0.08	0.04	0.07
Sn	3.94	4.54	8.31	3.84	5.48	5.91	6.21	4.91	8.64
Sr	144	162	66.6	179	154	152	199	43.2	67.8
Ta	2.76	2.99	4.01	2.79	3.07	3.09	2.74	5.92	4.36
Th	14.8	17.6	38.8	12.6	16.7	23.3	22.7	58.6	58.3
Tl	0.41	0.43	0.54	0.21	0.33	0.61	0.51	0.57	0.72
U	3.32	2.91	5.61	2.08	3.09	4.28	4.68	15.0	18.4
V	17.6	2.63	13.7	56.4	27.7	8.04	17.0	0.22	0.96
W	0.54	0.83	1.41	1.16	2.2	577	441	544	520
Y	63.8	65.1	58.3	74.0	66.1	74.8	77.7	169	78.9
Zn	63.9	64.1	42.4	118	85.0	88.3	136	58.3	24.5
Zr	540	444	298	582	498	404	589	419	258
K/Rb	254.6	257.9	160.7	263.0	222.8	186.3	203.9	196.9	151.3
Nb/Ta	12.36	13.51	9.10	~~9.10~~	~~13.05~~	11.55	12.48	15.24	9.13
$10^3\cdot$ Ga/Al	3.02	3.47	3.11	3.41	3.23	3.75	4.09	4.40	4.13

Table 2. Major (%) and trace element (ppm) analyses. Abbreviations; LOI= loss on ignition, * -total Fe given as Fe_2O_3, ASI = Alumina Saturation Index (the definition is given in the text). SGUL and SG(CNRS) are the same Standard Granite, analysed in Lund and France independently.

Samples	PC9214	PC9215	PC9216	PC9225	PC9228	PC9230	SGUL	SG(CNRS)
SiO_2	76.06	70.00	75.56	75.95	76.31	78.53	68.66	68.84
Al_2O_3	12.35	12.88	11.91	12.30	12.19	11.10	14.54	14.38
Fe_2O_3*	1.45	4.80	2.45	1.27	1.46	1.51	3.35	3.54
MnO	traces	0.08	0.03	traces	traces	traces	0.05	0.04
MgO	0.11	0.64	0.17	0.02	0.08	0.07	0.79	0.79
CaO	0.65	2.08	0.60	0.54	0.64	0.25	2.18	2.27
Na_2O	3.54	3.50	3.82	3.59	3.32	3.33	3.03	3.07
K_2O	5.12	4.29	4.58	5.12	5.40	4.76	5.41	5.34
TiO_2	0.13	0.68	0.20	0.04	0.14	0.13	0.48	0.45
P_2O_5	0.03	0.17	0.02	0.02	0.03	0.02	0.13	0.17
LOI	0.32	0.52	0.34	0.11	0.27	0.10	0.86	0.63
Total	99.76	99.64	99.68	98.96	99.84	99.80	99.35	99.52
K_2O/Na_2O	1.45	1.23	1.20	1.43	1.63	1.43		
Fe_2O_3*/ (Fe_2O_3*+MgO)	0.93	0.88	0.94	0.98	0.95	0.96		
ASI	0.98	0.91	0.97	0.99	0.98	1.00		
As	0.62	1.67	0.38	0.46	0.71	0.36		
Ba	172	881	617	88.4	179	136	1516	1420
Be	6.16	4.29	3.0	13.0	5.33	2.99		
Bi	traces	0.12	0.5	traces	traces	0.07		
Cd	0.03	0.19	0.07	0.01	traces	0.04		
Co	63.3	52.2	61.2	65.2	72.4	75.5	36	34.6
Cr	2.78	4.87	0.47	3.96	1.81	1.61	11.2	7.14
Cs	1.18	2.6	1.54	1.62	1.25	0.52		
Cu	3.26	4.83	2.9	6.06	1.5	9.68		
Ga	21.9	22.3	23.7	24.1	21.9	16.2	18.5	20.2
Hf	9.12	15.8	15.1	8.18	9.82	8.98	9.3	11.3
Mo	1.68	3.95	1.17	3.81	2.84	0.39		
Nb	27.7	34.2	31.1	43.0	29.0	25.3	23	18.4
Ni	2.75	4.02	1.01	0.81	1.02	1.02	3.9	4.76
Pb	35.7	21.2	15.4	45.4	33.0	16.3		
Rb	298	167	132	279	259	176	180	176
Sc	2	7.08	3.2	1.2	1.7	1.88	6.87	6.8
Sb	0.05	0.1	0.01	0.04	0.07	0.05		
Sn	0.4	8.96	3.38	1.06	0.43	3.91		
Sr	34.4	139	22.4	23.8	36.4	23.5	362	384
Ta	4.79	3.44	2.42	6.58	4.69	1.98	1.68	1.77
Th	64.8	21.3	14.4	38.3	51.4	16.2	24.5	20.6
Tl	0.65	0.41	0.47	0.49	0.55	0.73		
U	12.2	4.35	3.48	11.5	7.16	2.34		
V	0.81	22.5	0.76	0.66	1.5	6.96		
W	591	413	539	594	650	696		
Y	53.0	67.2	65.5	35.5	54.3	33.3	42	40.4
Zn	16.7	74.5	89.6	24.0	13.8	31.8		
Zr	175	460	505	108	189	212	368	373
K/Rb	142.6	213.2	288.0	152.3	173.1	224.5		
Nb/Ta	5.78	9.94	12.85	6.53	6.18	12.78		
$10^3 \cdot$ Ga/Al	3.35	3.27	3.76	3.70	3.40	2.76		

Table 2. (cont.)

Samples	J91006	J91013	J91017	LP9116	L9013	PC9209	PC9210	PC9211	PC9213
REE ppm									
La	75.4	133.9	92.13	72.98	72.78	105.3	122.5	126.7	139.8
Ce	166.1	297.9	183.9	162.0	157.3	217.1	252.6	275.7	271.0
Pr	18.27	31.02	18.31	19.43	17.81	23.62	28.48	30.61	27.5
Nd	70.05	111.1	63.52	75.48	67.86	88.49	108.9	115.1	94.46
Sm	13.66	18.82	11.23	15.73	13.68	15.11	18.84	24.99	15.47
Eu	2.85	3.21	1.33	3.67	2.8	3.17	4.51	0.71	1.69
Gd	11.48	14.86	9.72	13.96	11.7	13.57	16.31	22.2	13.1
Tb	1.8	2.07	1.44	2.19	1.86	2.04	2.42	4.01	1.8
Dy	10.73	12.25	9.23	13.12	11.48	12.16	14.17	25.3	11.07
Ho	2.26	2.42	1.97	2.7	2.33	2.54	2.87	5.84	2.46
Er	6.35	6.63	5.67	7.06	6.35	7.07	7.76	16.58	7.23
Tm	0.99	1.05	0.97	1.14	1.08	1.21	1.27	2.89	1.37
Yb	6.2	6.5	6.39	6.59	6.22	7.41	7.62	17.42	9.29
Lu	0.89	0.91	0.88	0.98	0.91	0.99	1.12	2.41	1.35
$(La/Lu)_{ch}$	8.75	15.19	10.81	7.70	8.25	11.0	11.32	5.45	10.70
$(La/Sm)_{ch}$	3.41	4.39	5.05	2.86	3.28	4.30	4.01	3.13	5.58
$(Gd/Lu)_{ch}$	1.59	2.01	1.36	1.76	1.58	1.69	1.80	1.13	1.20
$(Eu/Eu^*)_{ch}$	0.68	0.57	0.38	0.74	0.66	0.67	0.77	0.09	0.35

	PC9214	PC9215	PC9216	PC9225	PC9228	PC9230	SGUL	SG(CNRS)
La	108.1	80.66	110.6	22.2	97.09	75.88	117	118.7
Ce	200.5	167.2	227.8	44.42	181.2	148.0	222	237.1
Pr	17.86	17.23	24.92	4.81	16.61	14.86		
Nd	54.77	64.6	90.88	18.13	55.77	52.97	85	87.97
Sm	8.89	13.21	14.32	3.88	9.19	8.16	13.7	13.36
Eu	0.72	2.31	1.54	0.206	0.64	0.194	1.74	1.84
Gd	8.05	10.58	11.24	3.59	7.65	6.51	10.1	10.13
Tb	1.22	1.78	1.77	0.75	1.21	0.9	1.41	1.4
Dy	7.21	10.37	10.04	4.73	7.25	5.19		
Ho	1.68	2.35	2.11	1.2	1.69	1.12		
Er	5.24	6.19	6.08	3.57	5.0	3.08		
Tm	0.97	1.07	1.03	0.76	0.91	0.55		
Yb	6.66	7.05	6.81	5.55	7.2	3.81	3.53	3.76
Lu	1.07	1.05	0.96	0.85	1.0	0.53	0.51	0.52
$(La/Lu)_{ch}$	10.43	7.94	11.92	2.7	10.04	14.78		
$(La/Sm)_{ch}$	7.50	3.77	4.77	3.53	6.51	5.74		
$(Gd/Lu)_{ch}$	0.93	1.24	1.44	0.52	0.94	1.51		
$(Eu/Eu^*)_{ch}$	0.26	0.58	0.36	0.17	0.23	0.08		

Table 3. Rare Earth Element analyses (ppm) and $(La/Lu)_{ch}$-, $(La/Sm)_{ch}$-, $(Gd/Lu)_{ch}$- and $(Eu/Eu^*)_{ch}$- ratios. $_{ch}$- chondrite normalized ratio. The chondrite values reported by Nakamura (1974) are used for the normalization. SGUL and SG(CNRS) are the same Standard Granite, analysed in Lund and France independently.

terbox. The samples PC9209, PC9210, PC9211, PC9213, PC9214, PC9215, PC9216, PC9225, PC9228 and PC9230 were crushed and powdered at the Geological Institute, University of Lund. The sample-sizes varied between 3 and 7 kg depending on grain-size and homogeneity of the rock. The samples were trimmed of weathering products before being crushed and powdered in a tungsten carbide shatterbox. Contamination by W and Co from the shatterbox explains the high contents of these elements in these samples (Table 2).

The analyses were performed by Analytical Services (CNRS), Vandoeuvre, France. The major element analyses are done using inductively coupled plasma (ICP) atomic emission spectrometry. All the trace element analyses were made by using the combination of ICP and a mass spectrometer (MS).

The granites are moderately to highly fractionated. The term "fractionated" is used loosely in this text, without specific reference to a particular physical mechanism such as, *e.g.* removal of crystals from a melt. The most mafic rock has 62.70 wt% SiO_2, the most felsic rock has 78.53 wt% SiO_2. The arithmetic mean is 71.93 wt%. The alkali contents are high; K_2O varies between 2.84 and 5.44 wt%. The sample 329 (Manby, 1990), with the lowest content of K_2O is reported to be a mylonitic gneiss that probably has been leached of K_2O and other mobile elements and been enriched in Na_2O. This sample is highlighted in all diagrams. If sample 329 is excluded, the lowest K_2O-content is 3.20 wt%. Na_2O ranges between 2.74 and 3.82 wt% (sample 329, 4.56 wt%, Manby (1990)). The rocks are K-rich with K_2O/Na_2O-ratios between 0.93 and 1.81 (sample 329, 0.62, Manby (1990)). Calcium and magnesium contents are low to moderate; 0.25-3.50 wt% CaO and 0.02-1.76 wt% MgO, but the content of iron is relatively high; 1.27-9.49 wt% Fe_2O_3* (total Fe). The ratio Fe_2O_3*/(Fe_2O_3*+MgO) varies between 0.83 and 0.98 (mean=0.91).

Harker variation diagrams for major elements are displayed in Fig. 11. Al_2O_3, Fe_2O_3, MgO, CaO, P_2O_5 and TiO_2 all decrease with increasing silica content, the Na_2O content is more or less constant and K_2O increases with increasing silica content. In the ternary K_2O-Na_2O-CaO plot (Fig. 12) there is a high correlation between these elements. This plot suggests a control of the chemical evolution of the granites by fractionation of plagioclase. However, the high negative correlations between SiO_2 and Fe_2O_3, MgO and TiO_2 indicate that also the mafic minerals took part in the fractionation.

In the SiO_2 versus K_2O plot (after Peccerillo & Taylor, 1976, not illustrated) the granites plot mostly in the high-K calc-alkaline field.

Fig. 13 shows a Qz-Ab-Or normative diagram. The Bangenhuk granites plot in the minimum melt field for typical granites reported by Tuttle & Bowen (1958).

The classification scheme designed by Debon & Le Fort (1982) is used for the general rock classification. The following parameter definitions are applied: Al-(K+Na+2·Ca), B=Fe+Mg+Mn+Ti, P=K-(Na+Ca), Q=Si/3-(K+Na+2·Ca/3) and F=555-(Q+B). All chemical symbols correspond to mole proportions of the corresponding oxide, multiplied by 10^3. The A parameter determines the aluminous character, B is proportional to the contents of mafic mi-

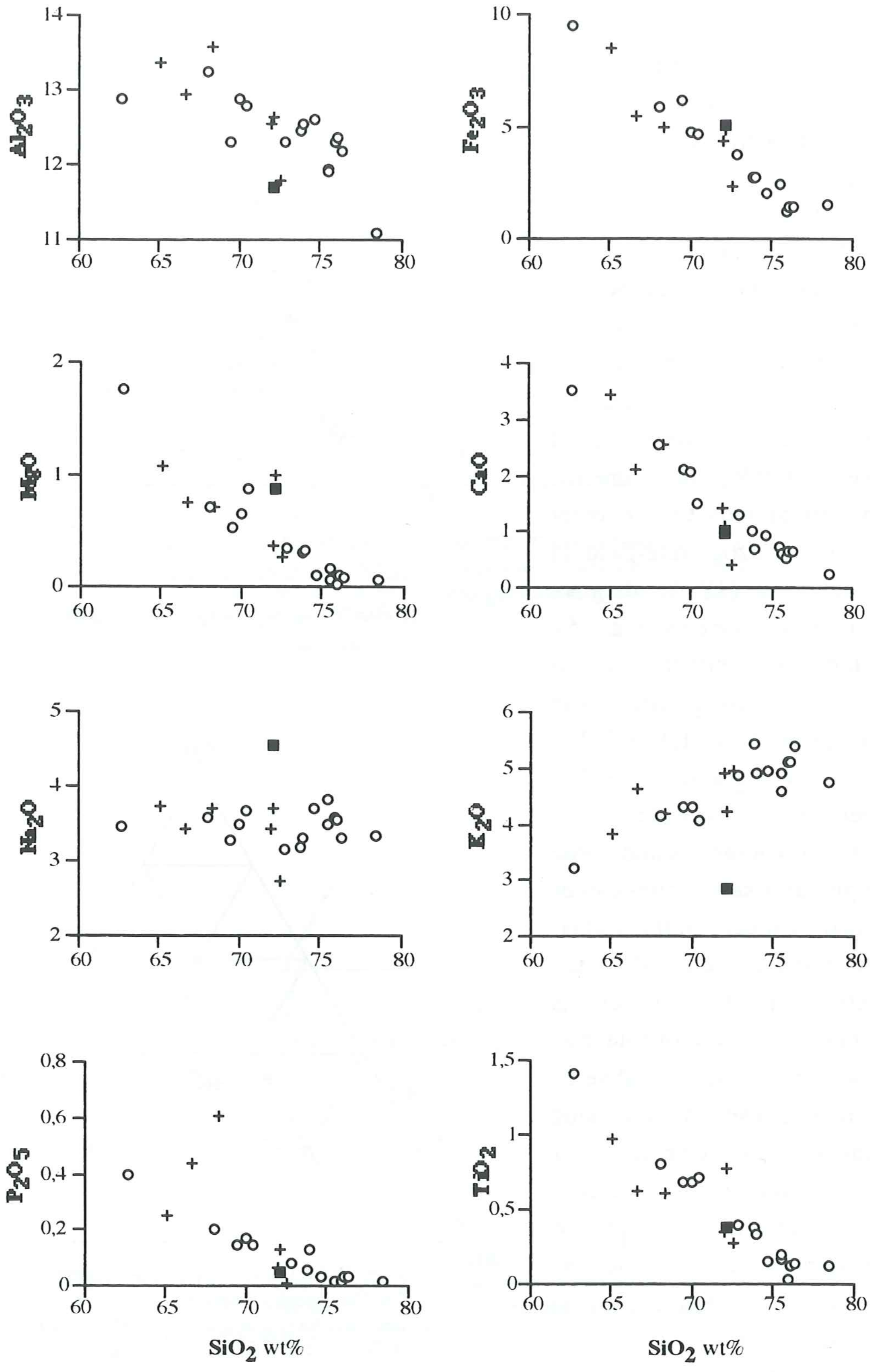

FIGURE 11. Harker variation diagrams for major elements. Circles=samples from this paper; crosses=samples from Manby (1990); solid square=mylonitic gneiss (sample 329), Manby (1990).

nerals, an increasing P means increasing potassium feldspar and/or decreasing plagioclase contents and Q is proportional to the quartz content.

According to the Q-P diagram (Fig. 14), the rocks are classified as granites, adamellites, with a few granodiorites. The granite group in this scheme includes the alkaligranites, the syenogranites and part of the monzogranites of Streckeisen (1976); the adamellite group corresponds to the other part of the monzogranite-field. In a Streckeisen (1976) diagram (normative components, Fig. 15), the samples plot either as alkaligranites or monzogranites with the exception of sample LP9116 that plots as a granodiorite. The gap between the samples which plot as monzogranites and those which plot as alkaligranites can be explained by means of the normative anorthite content. When the normative anorthite content is lower than 10 percent of total plagioclase content, the normative albite content is used in the making of alkali-feldspar. If on the other hand the normative anorthite content is higher than 10 percent of total plagioclase content, the normative albite content is used in the making of plagioclase.

The granites are metaluminous and show a calc-alkaline orogenic trend in a scattergram with B versus A (Fig. 16). The most fractio-

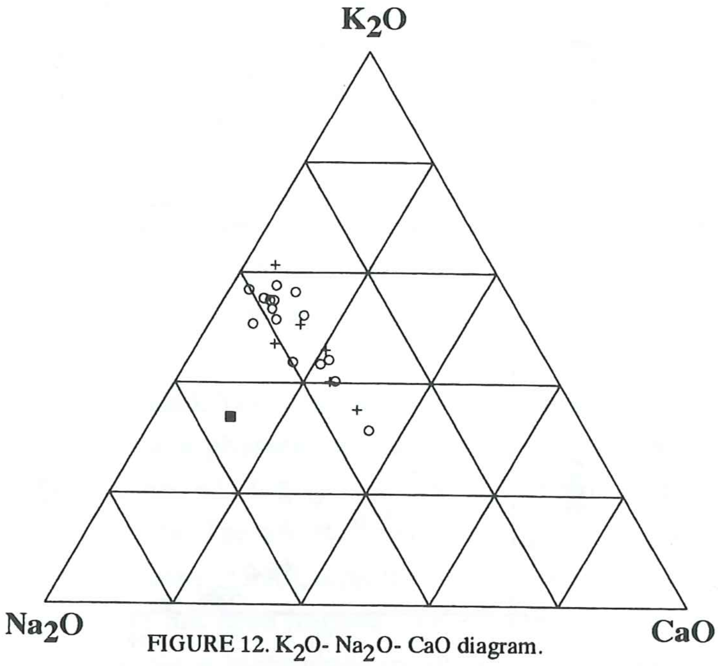

FIGURE 12. K_2O- Na_2O- CaO diagram. Symbols as in Fig. 11.

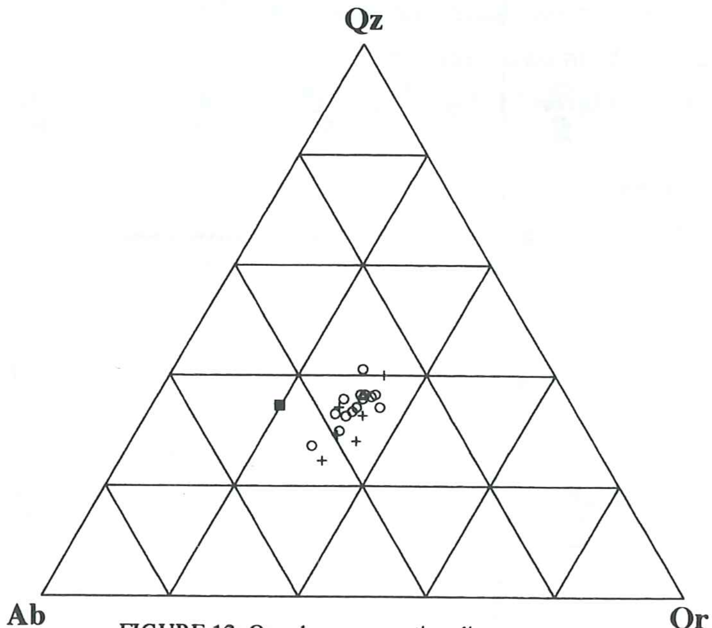

FIGURE 13. Qz- ab- or normative diagram. The Bangenhuk granites plot in the minimum melt field for typical granites reported by Tuttle & Bowen (1958). Symbols as in Fig. 11.

No field!

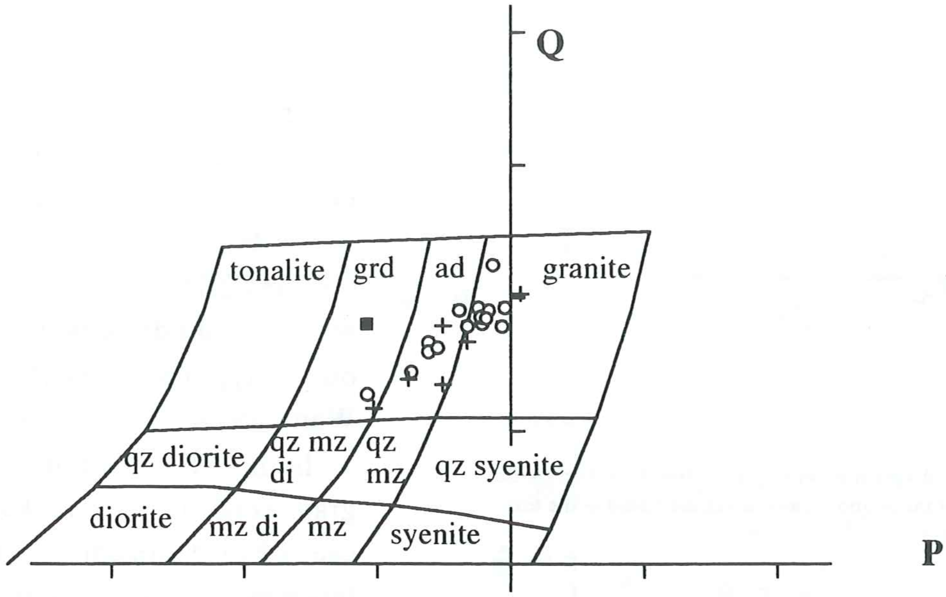

FIGURE 14. PQ- diagram according to Debon & Le Fort (1982). The definitions of the Q and P parameters are found in the text. Abbreviations; grd= granodiorite, ad= adamellite, qz diorite= quartz diorite, qz mz di= quartz monzodiorite, qz mz= quartz monzonite, qz syenite= quartz syenite, mz dz= monzodiorite, mz= monzonite. Symbols as in Fig. 11.

mz di

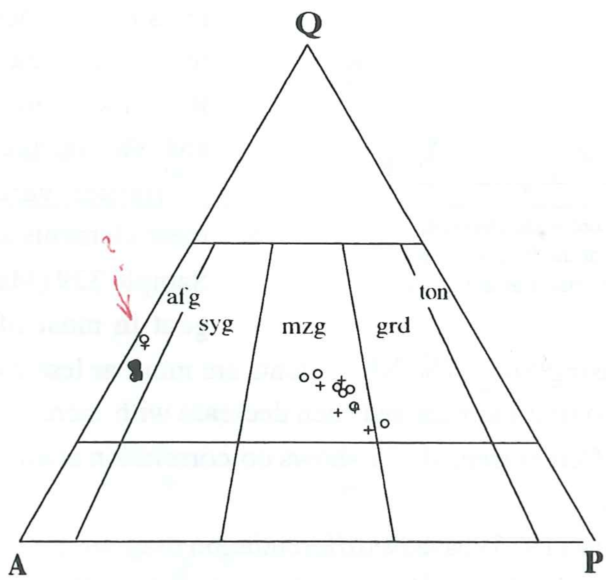

FIGURE 15. Quartz- Alkali feldspar- Plagioclase (QAP) classification after Streckeisen (1976). Abbreviations; afg= alkali feldspar granite, syg= syenogranite, mzg= monzogranite, grd= granodiorite, ton= tonalite. Symbols as in Fig. 11.

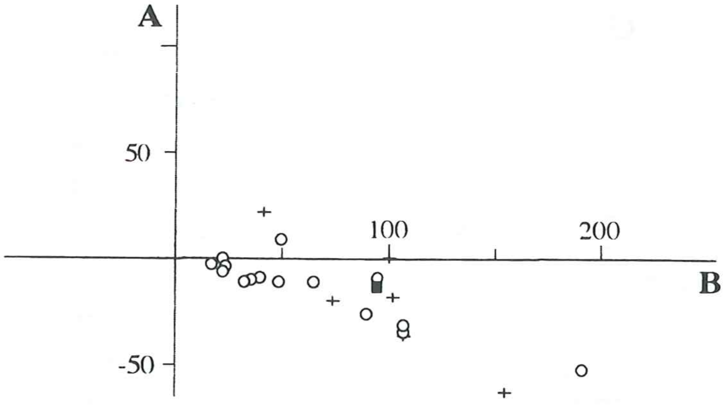

FIGURE 16. BA- diagram according to Debon & Le Fort (1982). The definitions of the A and B parameters are found in the text. Symbols as in Fig.11.

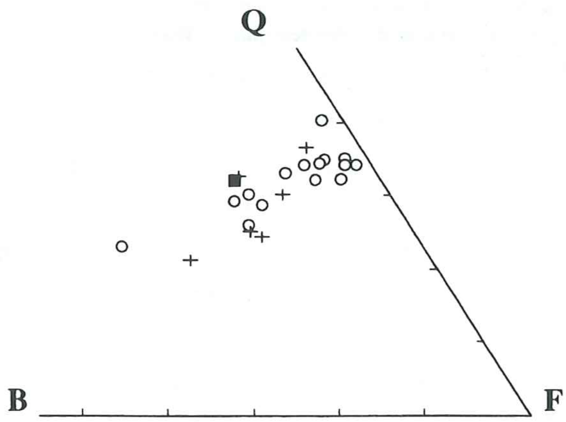

FIGURE 17. BQF- diagram according to Debon & Le Fort (1982). The definitions of the B, Q and F parameters are found in the text. Symbols as in Fig. 11.

nated members enter the peraluminous domain. The aluminous character can also be expressed by the Alumina Saturation Index (ASI = molar $Al_2O_3/(CaO+ Na_2O+K_2O)$, Zen (1986)). ASI varies between 0.81 and 1.11 (mean=0.95, Table 3, which is considered typical of igneous (I-type) sources (Chappel & White, 1984).

In the differentiation B-Q-F diagram (Fig. 17) the rocks show a calc-alkaline orogenic trend, even if this trend is to some extent controlled by the two most mafic samples (sample LP9116 and 298 (Manby, 1990)).

When compared with typical S-type and I-type granites, the Bangenhuk granites have high contents of the incompatible trace elements (Rb, Ba, Sr, Zr, Th, U, Y, REE (with the exception of Eu)) and Nb, Ga, and Zn.

Harker variation diagrams for trace elements are shown in Fig. 18. Sample 329 (Manby, 1990) is divergent in most of these plots. Sr, Zr and Y decrease with increasing SiO_2. The Nb contents are more or less constant. Ba scatters a lot, but can be interpreted to first increase and then decrease with increasing silica content (alternatively it shows two different trends). Ga shows no correlation at all. Rb and Th rise with increasing SiO_2.

El Bouseily & El Sokkary (1975) based a differentiation diagram for granitoids on the relations between the three large ion lithophile trace elements (LILE) Rb, Ba and Sr. They found this relation to be useful in tracing differentiation trends in acidic suites and also in distinguishing magmatic granites from metasomatic or "granitized" granites. However, Lindh & Johansson (1991) have questioned whether the field termed "anomalous granite field" is only restricted to metasomatically depleted granites due to the fact that there exist compositions of granites intermediate between "normal granites" and "granodiorites". Anyhow, the Bangenhuk granites plot mostly in the fields for "normal granites" and "evolved granites"

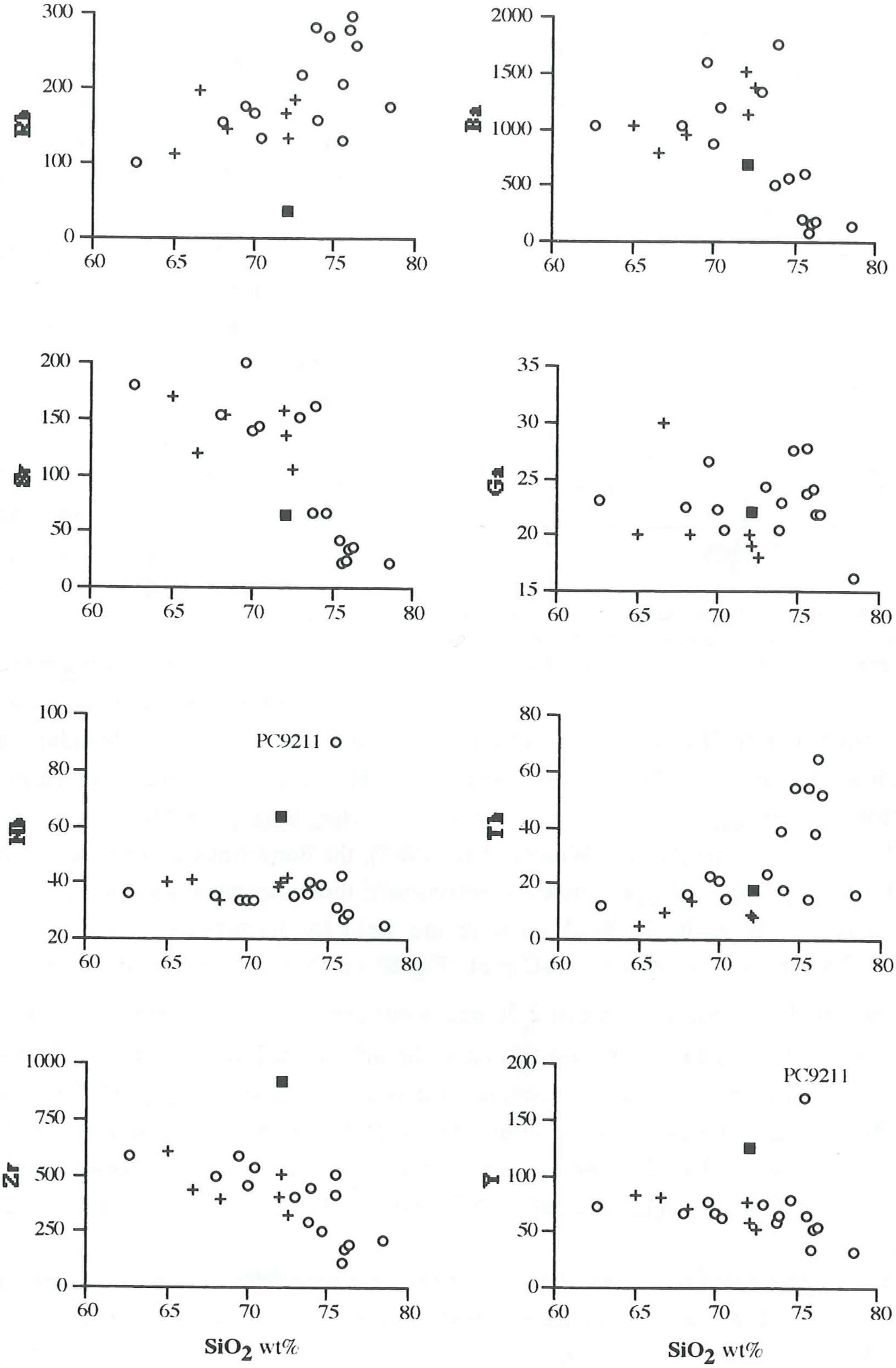

FIGURE 18. Harker variation diagrams for trace elements. Symbols as in Fig. 11. Sample PC9211 is marked in the SiO_2 versus Nb and SiO_2 versus Y diagrams.

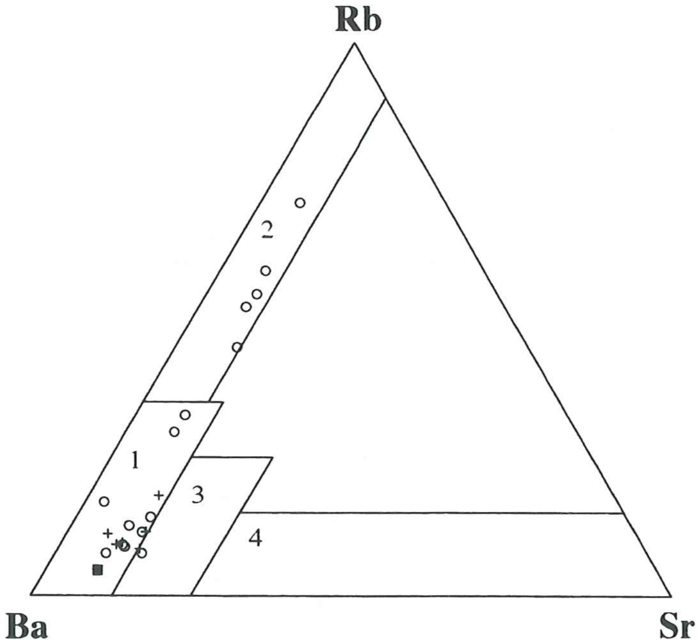

FIGURE 19. Rb- Ba- Sr diagram according to El Bousely & El Sokkary (1975). 1- normal granites, 2- evolved granites, 3- anomalous granites, 4- granodiorites. Symbols as in Fig. 11.

(Fig. 17), which is considered to be a normal trend. The rocks that plot as "evolved granites" are the most felsic samples PC9211, PC9214, PC9225, PC9228 and PC9230. One sample, the granodiorite LP9116, plots in the field for "anomalous granites". This plot speaks against a significant depletion of trace elements during the metamorphic event.

The K/Rb-ratio is fairly high and varies between 143 and 288 (sample 329, Manby (1990), 620). This ratio is not correlated to the differentiation expressed by the SiO_2 content.

The geochemical coherence of Ta and Nb in magmatic rocks is well established. The Nb/Ta-ratio varies between 5.78 and 15.24 (Manby's (1990) data, 4.3-64.0) which is considered as a broad interval and suggest heterogeneties in the collected material. An effort to correlate this ratio to major elements and other trace elements has failed.

In the discrimination diagrams of Whalen et al. (1987), the Bangenhuk granites plot within the fields for anorogenic or A-type granites. A selection of these diagrams is shown in Fig. 20. Only one sample, the aplite PC9225, plots in the field for fractionated granites in the (Zr+Nb+Ce+Y) versus $(K_2O+Na_2O)/CaO$ plot (Fig.20 a). Due to their distinctly elevated Ga/Al-ratios ($10^3 \cdot Ga/Al$ varies between 2.76 and 4.40) they identify themselves as A-type granites (Fig.20 c-f). This ratio is not correlated to the differentiation expressed by the SiO_2 content. In the more commonly used discrimination diagrams of Pearce et al. (1984), (see also Manby, 1990) the granites plot mostly within the fields for Within-Plate Granites (WPG). These plots are shown in Fig. 21. There is a high degree of correspondence between the A-type granites as defined by Whalen et al. (1987) and the Within-Plate granites defined by Pearce et al. (1984).

REE-data are given in Table 3 and the compositions are depicted on chondrite normalized diagrams in Fig. 22. The chondrite values reported by Nakamura (1974) are used for the normalization. Manby's data (1990) are excluded due to the large scattering in the heavy REE's (Fig. 23).

The absolute REE contents are fairly high when compared to both S- and I-type granites. The sum varies between 115 ppm and 671 ppm. The arithmetic mean is 441 ppm. Sample

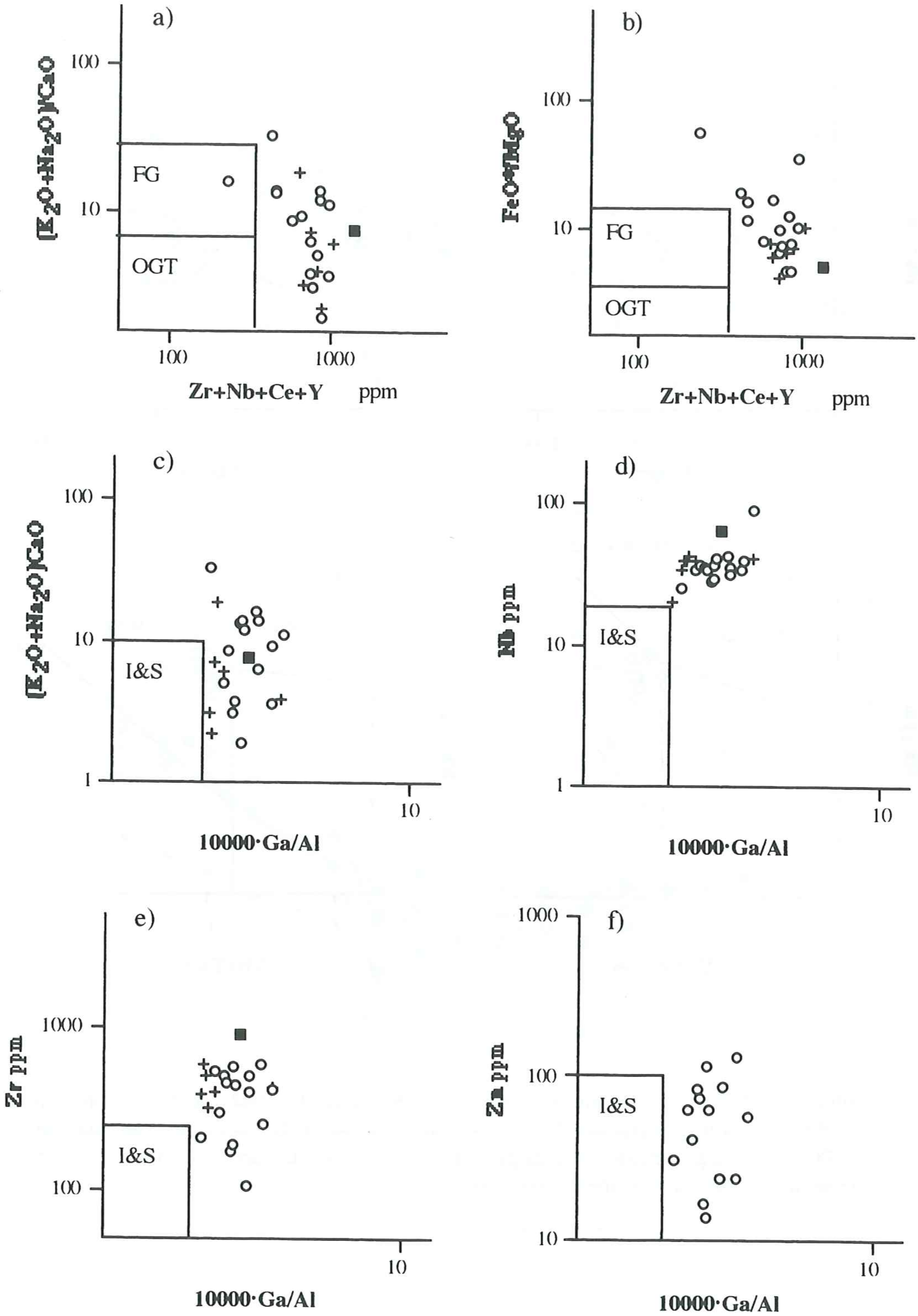

FIGURE 20. A selection of diagrams after Whalen et al. (1987). a-b)- Zr+Nb+Ce+Y (ppm) versus $(K_2O+Na_2O)/CaO$ and FeO*/MgO. FeO* - total Fe. FG- field for fractionated granites. OGT- field for unfractionated I- and S- type granites. c-f)- 10000·Ga/Al versus $(K_2O+Na_2O)/CaO$, Nb, Zr and Zn (ppm). Rectangular boxes- fields for I- and S-type granites. The Bangenhuk granites plots outside these fields i.e. A-type granites. Symbols as in Fig 11.

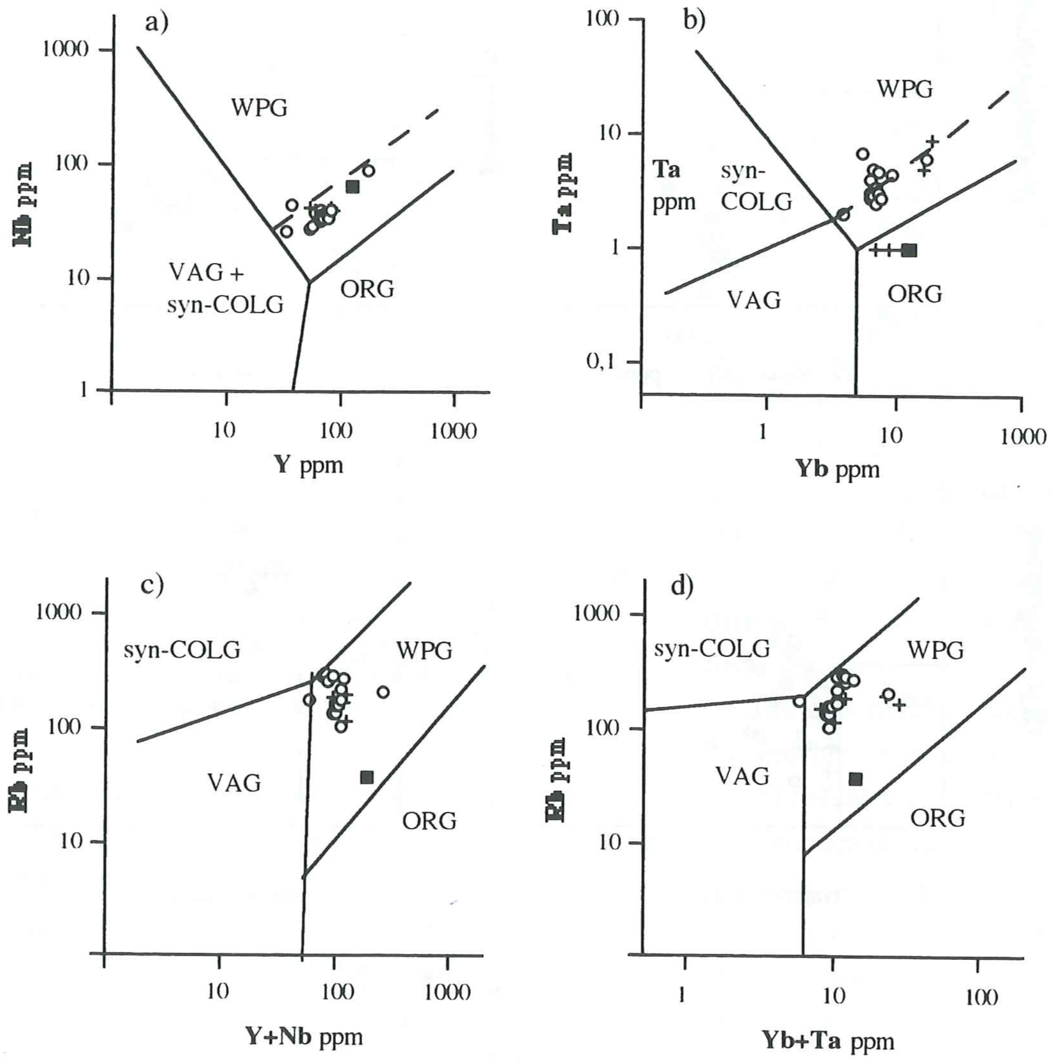

FIGURE 21. Tectonic discrimination plots of Pearce et al. (1984). Abbreviations:syn-COLG- syn-collision granites, VAG- volcanic arc granites, ORG- ocean ridge granites, WPG- within plate granites. The dashed line in a) and b) is the upper boundary for ORG from anomalous ridge segments. Symbols as in Fig. 11.

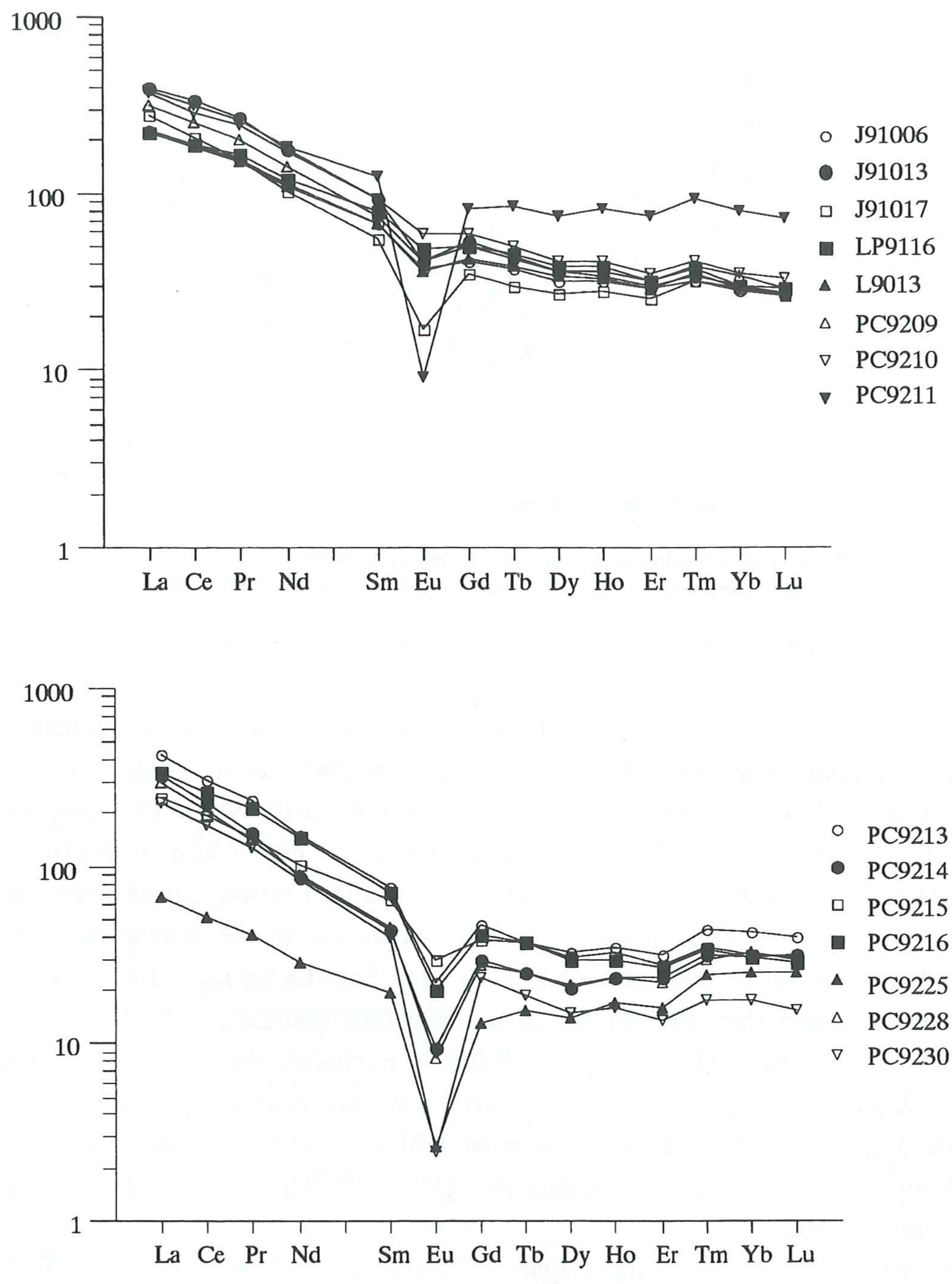

FIGURE 22. Chondrite normalized REE diagrams. The chondrite composition reported by Nakamura (1974) is used for normalization.

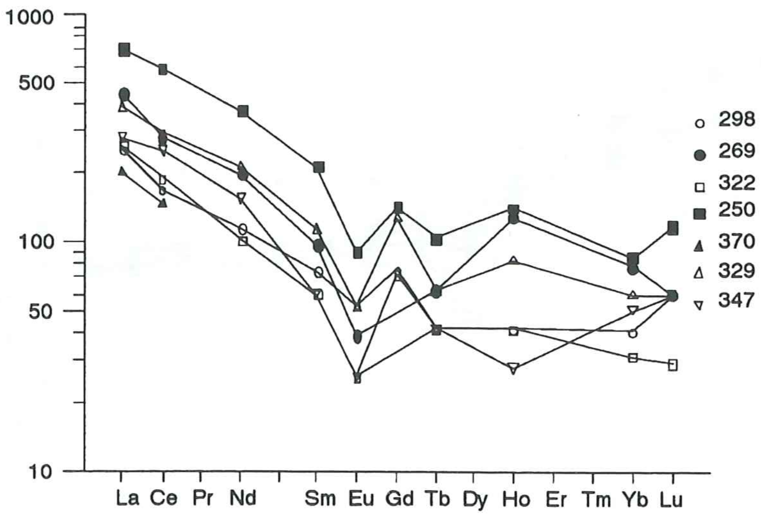

FIGURE 23. Chondrite normalized REE diagram for Manby's (1990) data. The chondrite composition reported by Nakamura (1974) is used for normalization.

PC9225, with the lowest content is somewhat anomalous. If sample PC9225 is excluded, the lowest sum is 322 ppm (mean=464). These high values are characteristic of A-type granites (Loiselle & Wones,1979; Collins et al. 1982; White & Chappell, 1983). The granites are slightly enriched in the light REE's (LREE) compared to the heavy REE's (HREE). The $(La/Lu)_{ch}$- ratios (ch is subscript for a chondrite normalized ratio), varies between 2.7 (PC9225) and 15.2 (mean=9.8). If sample PC9225 is excluded, the lowest ratio is 5.5 (mean=10.3). LREE values decrease somewhat from La to Sm; $(La/Sm)_{ch}$ varies between 2.9 and 7.5 (mean=4.5) and the HREE's are essentially flat; $(Gd/Lu)_{ch}$ are between 0.52 (PC9225) and 2.0 (mean=1.38). If sample PC9225 is excluded, the lowest ratio is 0.93 (mean=1.44). Variation diagrams for SiO_2 (wt%) versus $(La/Lu)_{ch}$, $(La/Sm)_{ch}$ and $(Gd/Lu)_{ch}$ are displayed in Fig. 22 a-c). The most evolved samples are those showing the steepest REE and LREE patterns. The samples PC9211 and PC9225 are divergent in Fig. 22 a-b) and are therefore marked.

The granites have moderate to large negative Eu anomalies. The value of $(Eu/Eu^*)_{ch}$, where Eu* is the interpolated value between Sm_{ch} and Gd_{ch}, varies between 0.09 and 0.77 (mean=0.45). The most fractionated granites are those that show the deepest negative Eu anomalies (Fig. 22 d).

The Eu anomalies are indicative of feldspar fractionation. Plots of SiO_2, CaO, Sr, Ba, and K_2O versus $(Eu/Eu^*)_{ch}$ are shown in Fig. 22 d-h). The CaO and Sr abundances show a systematic decrease with increasing Eu depletion. Since Sr isomorphously replaces Ca, this can be explained in terms of plagioclase-dominated fractionation. However, Ba also decreases with increasing Eu depletion. Since Ba only substitutes for K (but is concentrated relative to K in the early minerals), this must be explained by fractionation of alkali feldspar or biotite.

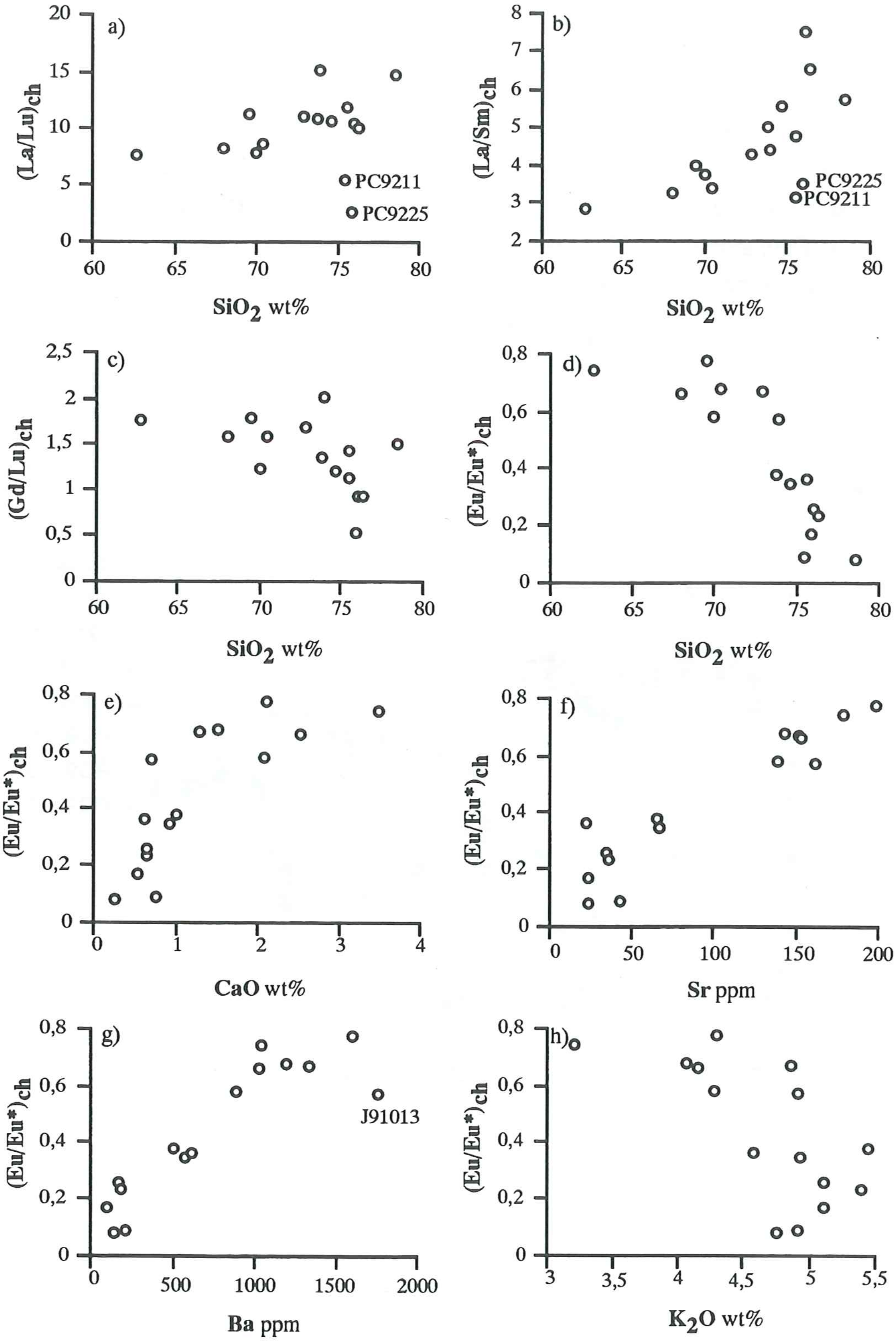

FIGURE 22. a-c)- SiO_2 (wt%) versus $(La/Lu)_{ch}$, $(La/Sm)_{ch}$ and $(Gd/Lu)_{ch}$. d-h)- SiO_2, CaO (wt%), Sr, Ba (ppm) and K_2O (wt%) versus $(Eu/Eu^*)_{ch}$. Samples PC9211 and PC9225 marked in a) and b). Sample J91013 marked in g).

Nocholds & Allen (1953) and Kolbe & Taylor (1966) observed that Ba will be depleted in the magma in late stages of differentiation. This is in accordance with the Rb-Ba-Sr plot (Fig. 17). K_2O versus $(Eu/Eu^*)_{ch}$ scatter somewhat, but increase with decreasing $(Eu/Eu^*)_{ch}$.

In multielement plots or "spidergrams" (Fig. 23 and 24 (Manby's (1990) data) of Thompson et al. (1984), the Bangenhuk granites show similar geochemical features. Such features includes marked depletions at Ba, Nb, Sr, P and Ti and enrichment in the other LILE, LREE and Th. The samples PC9211 and PC9225 are somewhat divergent in Fig. 23. Manby's (1990) data (Fig. 24) scatter somewhat, but follow the same pattern.

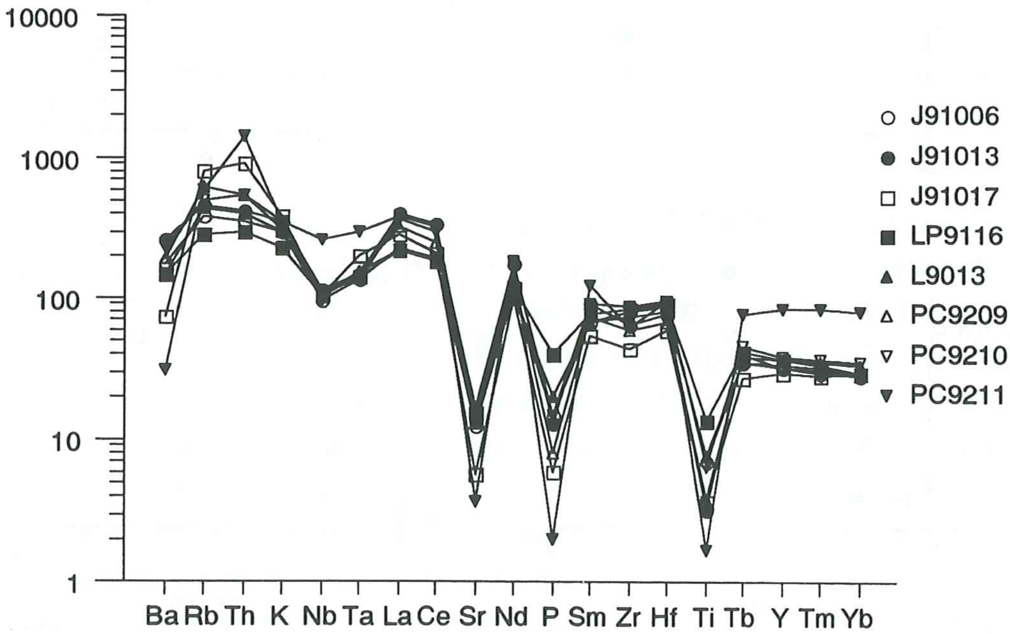

FIGURE 23. Multielement plots after Thompson et al. (1984).

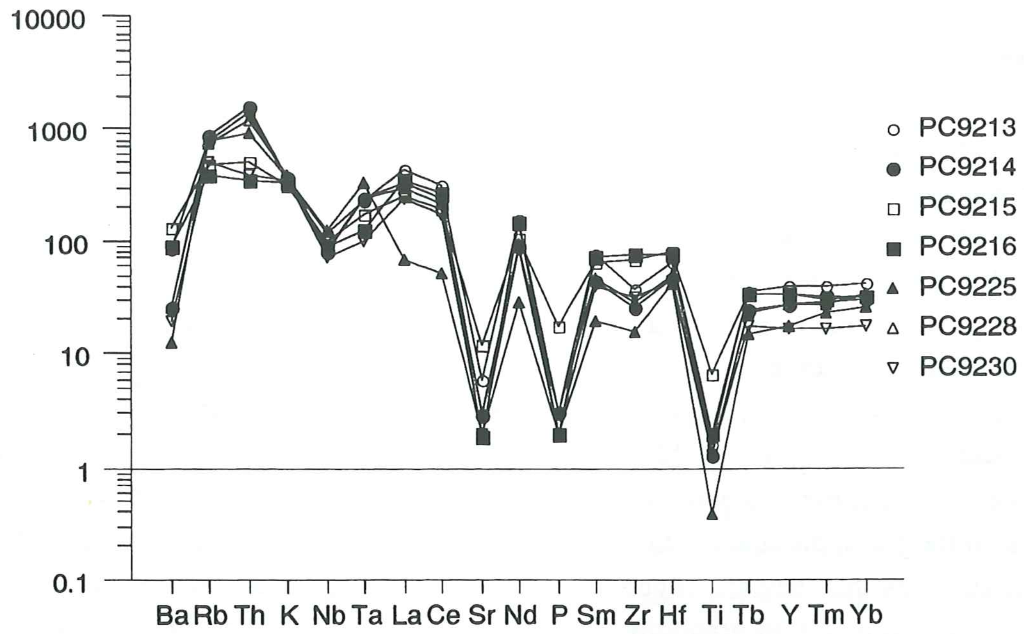

FIGURE 23. (cont.).

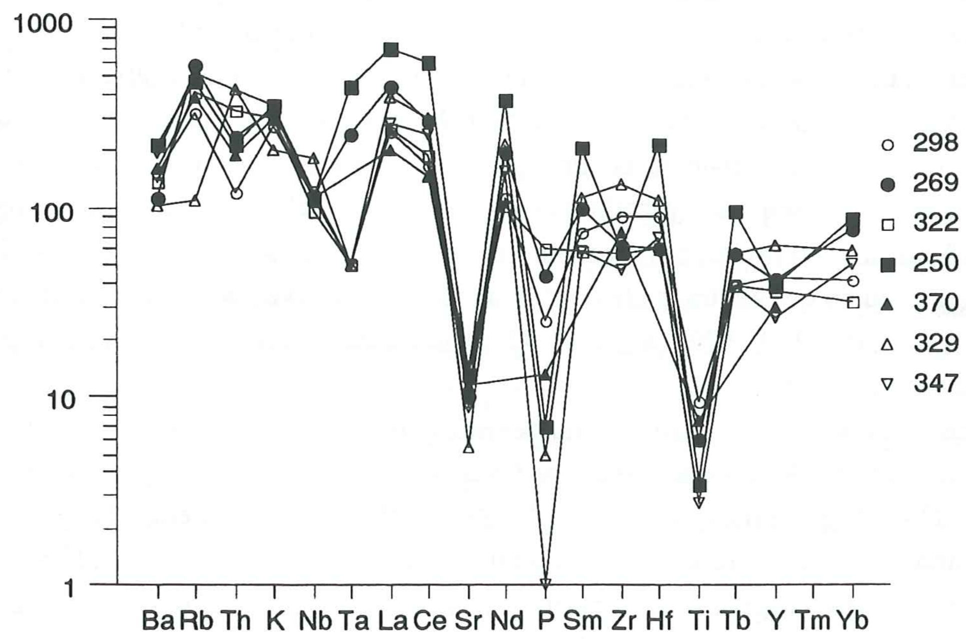

FIGURE 24. Multielement plot after Thompson et al. (1984). Manby's (1990) data.

7. Discussion

Due to the characteristic concordance between Lower Hecla Hoek lithologies, most authors have interpreted the Harkerbreen Group feldspathitic gneisses as acid metavolcanics, extruded in a Caledonian "geosyncline" (Harland, 1959; Harland et al., 1966; Harland et al., 1992; Gayer & Wallis, 1966; Manby, 1990). New U/Pb zircon age-determinations (Gee et al., 1992; Å. Johansson, pers. commun., 1993) and new field evidence suggest that the gneisses originated as Early Proterozoic granites.

There is little doubt that the Bangenhuk granites represent related magmatic events. The new isotope datings (Gee et al., 1992; Å. Johansson, pers. commun., 1993) and the new geochemical evidence presented here show the homogeneity of the rocks. The latter is obvious in most of the plots, particularly in the chondrite-normalized REE and multi-element diagrams. This suggests that they are cogenetic members of a single fractionation series. Thus the variation in the suite (from granodiorites to granites) should be explained by 1) crystal fractionation or 2) different degrees of partial melting in the magmatic source region. Though the relative importance of these processes is controversial, there has lately been doubts concerning the effectivity of crystal fractionation in granitic magmas due to their high viscosities.

The Nb/Ta-ratio speaks against the interpretation of a common parental source for all samples. An attempt to divide the granites into chemical groups based on this ratio has failed. The variation in the Nb/Ta-ratio can be explained by 1) heterogeneity in the magmatic source region; 2) contamination of the magma, *i.e.* changes of the chemistry as a result of reaction with crustal material; 3) subsequent hydrothermal alteration. The relative importance of these processes is difficult to determine, but hydrothermal alteration is believed to play only a minor part as suggested by certain trace element plots. Xenoliths have been observed in some of the granites (L9013, PC9210, PC9214 and PC9215) and contamination is probably responsible for some of the variation.

Most of the characteristic features of the Bangenhuk granites indicate that they are A-type granites. They are rich in alkalies and have low CaO contents; they have high K_2O/Na_2O- and $Fe_2O_3^*/(Fe_2O_3^*+MgO)$-ratios, high REE, Zr, Zn, Y, Nb and Ga contents. They plot as A-type granites and WPG in the tectonic discrimination diagrams of Whalen et al. (1987) and Pearce et al. (1984). These diagrams are constructed by statistical analysis of a large number of chemical analyses of granites from well defined Phanerozoic tectonic environments. The question naturally arises whether or not these diagrams can be applied to early Proterozoic granites. Manby (1990) also interpreted the felsic rocks to be related to A-type magmas, but concluded that they were "derived from rhyodacitic and rhyolitic magmas in an attenuated Within-Plate setting".

However, the granites also have some of the characteristics of subduction-related magmas. Thus, they do not show any anorogenic trends in the BA and BQF-diagrams (Debon & Le Fort, 1982, Fig. 13 & 15). Furthermore, they have higher contents of Sr and much higher contents of Ba compared to most A-type granites in the literature.

The Rb-Sr whole rock age-determination of c. 1650 Ma, suggests some disturbance of the Rb-Sr system (Å. Johansson, pers. commun., 1993). The low initial Sr^{87}/Sr^{86} of 0.703 indicates that the granites were derived from a source that had separated only recently from the mantle. The high contents of incompatible elements and the highly fractionated REE patterns in the Bangenhuk granites suggest that they cannot be derived directly from the mantle; thus at least a two-stage magmatic model is suggested.

Anorogenic granites or A-type granites, first defined by Loiselle & Wones (1979) occur along rift zones and within stable continental blocks (Loiselle & Wones, 1979; Collins et al., 1982; Eby, 1990). They are chemically characterized by low CaO and Al_2O_3, high Fe_2O_3*/MgO, high K_2O/Na_2O, high absolute alkali contents, high REE (except Eu), Zr, Zn, Y, Nb, Ga, Ta, F, Cl abundances and low Cr, Co, Ni, Sc, Ba and Sr abundances. A variety of models have been proposed to explain the petrogenesis of A-type granites. Loiselle & Wones (1979) suggested that fractionation of an enriched mantle-derived basaltic magma could produce A-type magmas, but Collins et al. (1982) preferred melting of highgrade felsic rocks, from which a previous melt phase had been extracted. Creaser et al. (1991) calculated that 15-40 % partial melting of crustal rocks of tonalitic to granodioritic composition under vapour-absent conditions at about 900-950° C is required to produce A-type magmas. This necessitates high geothermal gradients and the introduction of mantle derived mafic melts into the crust. Eby (1990), in his review of A-type granites, identified a wide compositional diversity. Furthermore, despite the latter, he related all to an I-type source, implying that it is more correct to consider A-type granites as a sub-group of I-type granites.

When compared to data from A-type granites in Pearce et al. (1984), Whalen et al. (1987) and Eby (1990), the Ny Friesland rocks have much in common with the Skaergaard and Mull intrusions, but have sligthly higher REE contents. However, the Skaergaard intrusion is a layered basic intrusion with only minor amounts of granophyres, the latter probably representing the final melt fraction. However, they could also be interpreted as partial melts of the wall rocks. The great volumes of granites in the Harkerbreen Group exclude a direct comparsion with the Skaergaard intrusion. The intrusive complexes of Mull consist of both mafic and felsic rocks. Three intrusive centers have been identified, each containing a significant proportion of felsic rocks. Walsh et al. (1979) concluded that some of these granites are derived by partial melting of the basement while others have resulted from assimilation-fractionation crystallization (AFC) processes involving basaltic magmas and basement.

The most important of the world's Proterozoic anorogenic igneous rocks occur in a belt that extends from the Baltic Shield through southern Greenland and eastern Canada to southern USA (Windley, 1993). This belt includes rapakivi granites, rhyolites, peralkaline and peraluminous granites, anorthosites, gabbros, basic dykes and alkaline rocks. The ages range from about 1.8 Ga to 1.1 Ga, but most are from 1.76 Ga to 1.4 Ga. Whether the Bangenhuk granites can be correlated to some of these granites or not remains to be determined.

8. Conclusions

1) The field evidence and the petrographical and geochemical results of this study demonstrate that granites and granodiorites make up a major component of the Bangenhuk Formation.

2) The granites are classified as A-type with respect to alkali and CaO contents, K_2O/Na_2O- and $Fe_2O_3^*/(Fe_2O_3^*+MgO)$-ratios, REE, Zr, Zn, Y, Nb, Ga contents and tectonic discrimination plots.

3) Deformation and metamorphism have not influenced the element distribution significantly.

4) New age-determinations (Gee et al., 1992; Å. Johansson, pers. commun., 1993) and the geochemical data presented here and in Manby (1990) show that the granites probably represent related magmatic events.

5) Some of the trace element distributions, *e.g* the Nb/Ta ratio, indicates some heterogeneities in the rocks, suggesting variations in the magmatic source region and perhaps also contamination of the magmas.

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Sample No.	Location	Rock-description	Mineralogy & Classification	Datings
J91006	Northern of Gyldensköldsholmarne, Austfjorden. Western limb of the Atomfjella Antiform. 79 00'40"N/16 16'55"E.	Strongly foliated and lineated, medium-grained,reddish granite.	Major minerals:qz-26%, K-fsp-28%, plag-30%, (hbl)+bt-11%. Acc. minerals:op,sph,all, ep,zi,chl,ap. Monzogranite.	U-Pb-zircon-1728±21/18 Ma. (Å. Johansson, pers. commun., 1993).
J91013	Inner part of Reinsbukkbreen. Eastern limb of the Atomfjella Antiform. 79 11'55"N/16 51'25"E.	Relatively undeformed (lineated), medium-grained,reddish granite.	Major minerals:qz-31%, K-fsp-33%, plag-23%, bt-6%. Acc.minerals:hbl,op,sph,all, ep,zi,gt. Monzogranite.	U-Pb-zircon-1766±43/35 Ma. (Å. Johansson, pers. commun., 1993).
J91017	Reinsbukkdalen. Western limb of the Atomfjella Antiform. 79 13'35"N/16 11'10"E.	Foliated and lineated,medium-grained,reddish granite.	Major minerals:qz-36%, K-fsp-28%, plag-28%, bt-7%. Acc.minerals:hbl,op,sph,ep, zi,ap,gt. Monzogranite.	U-Pb-zircon-1724±14 Ma. (Å. Johansson, pers. commun., 1993).
LP9116	2 km north of Einsteinodden, Austfjorden. Western limb of the Atomfjella Antiform. 79 04'10"N/16 18'20"E.	Foliated and lineated,medium-grained, grey granodiorite.	Major minerals:qz-24%, K-fsp-18%, plag-34%, hbl+bt-22%. Acc.minerals:op,ep,zi, ap,gt,px. Granodiorite.	U-Pb-zircon-1748±8 Ma. (Å. Johansson pers. commun., 1993).
L9013	Brennkollen, south of Femmilsjøen. Western limb of the Atomfjella Antiform. 79 46'29"N/15 49'30"E.	Grey to slightly pinkish, medium-coarse grained granite. Randomly oriented, undeformed xenoliths. Cross cutting aplites.	Major minerals:qz-26%, K-fsp-26%, plag-30%, hbl+bt-16%. Acc.minerals:op,sph,all, ep,zo,zi,ap. Monzogranite.	U-Pb-zircon-1759±19/14 Ma. (Å. Johansson, pers. commun., 1993).

APPENDIX. Location, rock-description, mineralogy & classification and datings of the Bangenhuk granites. Abbreviations: qz-quartz, K-fsp-potassium-feldspar, plag-plagioclase, hbl-hornblende, bt-biotite,op-opaque minerals, sph-sphene, all-allanite, ep-epidote, zo-zoizite, zi-zircon, chl-chlorite, ap-apatite, px-pyroxen, mu-muscovite. Classification based on modal analyses and after Streckeisen (1976).

Sample No.	Location	Rock-description	Mineralogy & Classification	Datings
PC9209	Western spur of Irvinefjellet, Tryggvebreen. Eastern limb of the Atomfjella Antiform. 79 06'46"N/16 54'25"E.	Foliated and lineated medium-grained, grey-reddish granite (augengneiss).	Major minerals:qz-30%, K-fsp-33%, plag-23%, (hbl)+bt-10%. Acc.minerals:op,sph,ep, zo,zi,ap,gt. Monzogranite.	
PC9210	Western part of Junofjellet, Tryggvebreen. Eastern limb of the Atomfjella Antiform. 79 07'19"N/16 52'59"E.	Foliated and lineated medium-grained, grey-reddish granite (augengneiss). Xenoliths. Cross-cutting aplites.	Major minerals:qz-31%, K-fsp-34%, plag-20%, hbl+bt-13%t. Acc.minerals:op,sph,ep, zi,ap,gt. Monzogranite.	
PC9211	Western part of Junofjellet, Tryggvebreen. Eastern limb of the Atomfjella Antiform. 79 07'19"N/16 52'59"E.	Foliated,medium-grained,grey granite.	Major minerals:qz-38%, K-fsp-37%, plag-17%, bt-7%. Acc.minerals:hbl,op,sph, all,ep,zi,gt. Syenogranite.	
PC9213	Southern spur of Perriertoppen, Tryggvebreen. Eastern limb of the Atomfjella Antiform. 79 08'23"N/16 51'02"E.	Intrusive (in grey-reddish augen-gneiss), foliated and lineated, fine-grained, reddish granite.	Major minerals:qz-26%, K-fsp-41%, plag-25%, bt-5%. Acc.minerals:,op,mu,all,ep, zo,gt. Monzogranite.	
PC9214 (92011)	Bangenhuk. Western limb of the Atomfjella Antiform. 79 51'54"N/15 39'00"E.	Intrusive (in PC9215),fine-grained,reddish aplitic granite. Xenoliths.	Major minerals:qz-31%, K-fsp-34%, plag-31%, bt-<3%. Acc.minerals:,op,ep,ap. Monzogranite	U-Pb-zircon-1739±49/43 Ma. (Å. Johansson, pers. commun, 1993).
PC9215	Bangenhuk. Western limb of the Atomfjella Antiform. 79 51'54"N/15 39'00"E.	Intrusive,foliated and lineated, medium-grained, grey-reddish granite (augengneiss). Xenoliths.	Major minerals:qz-24%, K-fsp-30%, plag-29%, hbl+bt-14% Acc.minerals:,op,sph,ep, zi,ap. Monzogranite.	

APPENDIX. (cont.).

Sample No.	Location	Rock-description	Mineralogy & Classification	Datings
PC9216	South-east of lake Flåtan. Eastern limb of the Atomfjella Antiform. 80 46'29"N/16 07'41"E.	Foliated and lineated, medium-grained,grey-reddish granite.	Major minerals:qz-34%, K-fsp-32%, plag-28%, bt-11%. Acc.minerals:,hbl,op,ap. Monzogranite.	U-Pb-zircon-1778±53/43 Ma (Gee et al. 1992)
PC9225	Brennkollen,south of Femmil-sjøen. Western limb of the Atomfjella Antiform.	Aplite dyke. Intruding the Brennkollen granite (90071).	Major minerals:qz-35%, K-fsp-34%, plag-29%. Acc.minerals:bt,op,all,ep. Monzogranite.	
PC9228	Bangenhuk. Western limb of the Atomfjella Antiform. 79 51'54"N/15 39'00"E.	Fine-grained,reddish aplitic granite.	Major minerals:qz-34%, K-fsp-34%, plag-30%, bt-<3%. Acc.minerals:op,ep,ap, chl. Monzogranite.	
PC9230	Instrumentberget. Western limb of the Atomfjella Antiform.	Foliated and lineated,medium-grained,reddish granite.	Major minerals:qz-38%, K-fsp-35%, plag-24%, bt-<3%. Acc.minerals:op,all,ep, chl. Monzogranite.	

APPENDIX. (cont.).

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