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The Jurassic gabbroic intrusions of Utpostane and Muren: insights into Karoo-related plutonism in Dronning Maud Land, Antarctica

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Abstract: Middle Jurassic continental flood basalts of Vestfjella, western Dronning Maud Land are cut by gabbroic intrusions that represent rare exposures of Karoo-related mafic plutons in Antarctica. The gabbros and numerous associated dolerites indicate high magmatic activity along the continental margin of Dronning Maud Land during the break-up of Gondwana. The scattered nunataks of Utpostane (~25 km^2) are dominated by olivine gabbronorite and olivine mela-gabbronorite, which can be grouped into four zones. The Utpostane intrusion exhibits inclined sheet-like geometry, is at least ~3 km thick and shows moderate enrichment of incompatible element contents from its base towards the exposed roof contact (e.g. Zr from ~15 to ~60 ppm). High MgO contents (~8–36 wt%) indicate that the parental magma of Utpostane was more primitive than a typical Karoo tholeiite (MgO ~6 wt%). At Muren, gabbroic outcrops record a cross section of a ~1.3 km thick inclined sheet-like intrusion. The intrusion can be divided to two main units, the upper and lower zones, which are dominated by olivine gabbro and gabbronorite, respectively. Parental melts of the geochemically differentiated upper zone and the homogeneous lower zone of Muren were typical low-MgO Karoo tholeiites, but they were chemically distinct and were emplaced as separate magma pulses.

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Key words: geochemistry, Gondwana, Karoo magmatism, lithostratigraphy, petrography

Introduction

Although dolerite dykes and sills are frequently associated with continental flood basalts in the Middle Jurassic Karoo and Ferrar large igneous provinces, exposures of pluton-size mafic intrusions are quite rare in Antarctica (Fig. 1). The Dufek layered intrusion of the Pensacola Mountains (Antarctica) is thought to form part of the Ferrar magmatic province and was originally proposed to be one of the largest layered mafic intrusions worldwide (Ford 1976, Behrendt *et al.* 1980, 1981, Ford & Himmelberg 1991). However, recent studies have demonstrated it to be considerably smaller than originally thought (Ferris *et al.* 1998). It is now known to consist of two intrusive phases and to be coeval with ~183 Ma rocks belonging to the Karoo province in southern Africa (Minor & Mukasa 1995, Brewer *et al.* 1996, Storey & Kyle 1997). Several gabbroic intrusions are associated with the Karoo igneous province in southern Africa. These include the Komatipoort Complex (Saggerson & Logan 1970, Logan 1979), the Birds River Complex (Allsopp *et al.* 1984), the Insizwa Complex (Lightfoot *et al.* 1987), and the New Amalfi sheet (Polderwaart 1944) (Fig. 1), all of which consist of one or more layered, sill-like intrusive bodies.

Most of the gabbroic intrusions of the Karoo igneous province record emplacement of relatively evolved low-Mg parental magmas similar to those of associated basalts and dolerites (Polderwaart 1944, Saggerson & Logan 1970, Eales 1980, 1990, Lightfoot *et al.* 1987). Parts of the Insizwa Complex may have been filled with fairly primitive magma with ~13 wt% of MgO (Scholtz 1937, Maske 1966, Cawthorn & Groves 1985, Cawthorn *et al.* 1988).

The Middle Jurassic continental flood basalts of western Dronning Maud Land represent an Antarctic extension of the Karoo igneous province (Faure & Elliot 1971, Harris *et al.* 1990, Luttinen & Furnes 2000). Outcrops of basalt lava are confined to three major areas at Kirwanveggen, Heimefrontfjella and Vestfjella (Fig. 1), whereas coeval dolerites are more widespread (Spaeth & Schüll 1987, Harris *et al.* 1991). Plutonic equivalents of the basalts have only been discovered at Utpostane and Muren, southern Vestfjella (Fig. 1).

The Utpostane area was first visited and its gabbroic rocks briefly described by Juckes (1968). Hjelle & Winsnes (1972) reported an intrusive contact between gabbro and basaltic rocks. They presented a single geochemical analysis and noted that, although being generally homogeneous, the gabbroic rocks locally exhibit layering and leucocratic veins. The Muren gabbros were first mentioned by Jonsson (1988) and later briefly described by Luttinen *et al.* (1994). Here we report on the results of systematic mapping and sampling of both outcrop areas during the period 1993–2001 (a part of the data has been previously presented as an unpublished MSc thesis; Räisänen 1996). We present structural, lithological and petrographical observations and geochemical and petrophysical data for the gabbros and associated rocks.

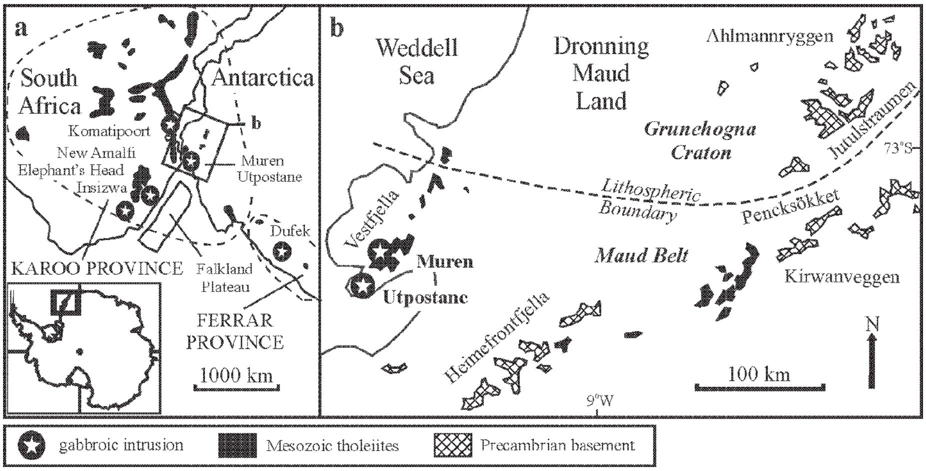

Fig. 1. Distribution of Mesozoic Gondwana break-up related tholeiites and gabbroic intrusions in **a.** South Africa and Antarctica (modified after Lavwer *et al.* 1992) and **b.** western Dronning Maud Land, Antarctica. Also shown in **b.** are outcrops of Precambrian basement and the boundary between the Archaean Grunehogna Craton and the Proterozoic Maud Belt (after Corner 1994).

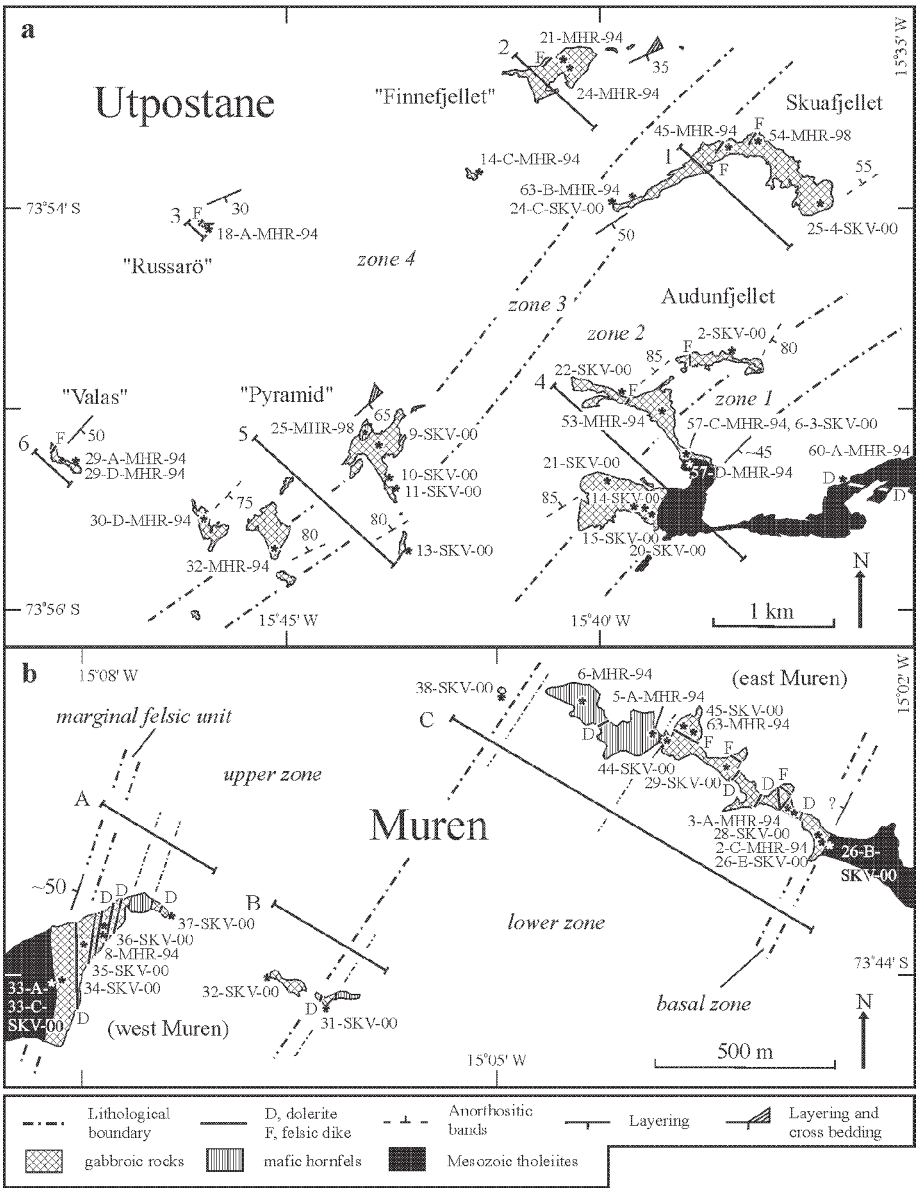

Fig. 2. Generalized geological maps of **a.** Utpostane, and **b.** Muren. Boundaries between lithological zones are indicated by dotted lines. Data from individual sample sites (*) at each nunatak group have been combined to yield sections 1–6 (Utpostane) and A–C (Muren).

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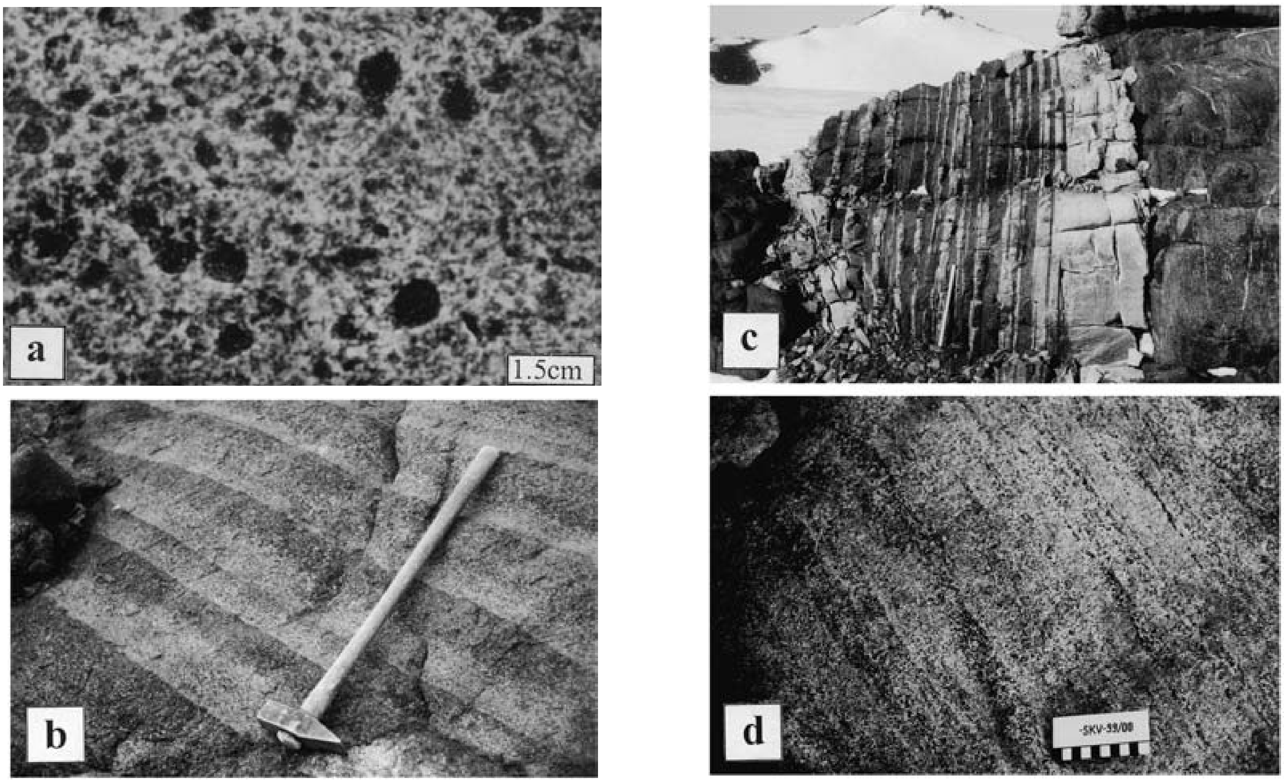

Fig. 3. Field photographs of **a.** spotted gabbro type of zone 1, Utpostane, **b.** inverse grading in zone 4 at "Pyramid" (below sample 9-SKV-00), Utpostane, **c.** anorthositic bands in zone 2 at "Pyramid" (below sample 13-SKV-00), Utpostane (note crosscutting anorthosite on the left) and **d.** pyroxene-rich stripes and leucocratic intercalations in the lower zone of Muren (sample 44-SKV-00) (length of scale is 10 cm). Length of hammer in **b.** and **c.** is 70 cm.

With these data we address the petrogenesis of the gabbroic rocks and discuss their regional geological significance.

Geological background

Vestfjella is located at the continental margin of western Dronning Maud Land. The exposed bedrock of Vestfjella is composed entirely of Phanerozoic rocks, mainly Jurassic continental flood basalts (Hjelle & Winsnes 1972). Elsewhere in Dronning Maud Land, Precambrian basement dominates and Jurassic basalts only occur at the southern Kirwanveggen and northern Heimefrontfjella at the East Antarctic Plateau escarpment (Fig. 1). The basalts are underlain by up to ~160 m thick Palaeozoic sedimentary sequence (Juckes 1972). The basement consists of an Archaean (Grunehogna) craton (Halpern 1970, Barton *et al.* 1987) and Mesoproterozoic (Maud) metamorphic belt (Groenewald *et al.* 1995). The Archean–Proterozoic lithospheric boundary coincides with the Jutulstraumen graben and, based on aeromagnetic measurements, Corner (1994) has interpreted the boundary to curve eastward from Pencksökket and run close to northern Vestfjella (Fig. 1).

The Kirwanveggen lavas at the escarpment are geochemically homogeneous low-Ti tholeiites (Harris *et al.* 1990). In contrast, the compositionally variable lavas of Vestfjella constitute four different magma series (Luttinen & Furnes 2000). The base of the ~1 km thick sub-horizontal Vestfjella lava sequence is unexposed, but basalt-hosted xenoliths suggest subsurface occurrence of Archaean basement as well as Permian sedimentary rocks (Luttinen & Furnes 2000). Minor sedimentary intercalations occur within the lava succession.

The presence of gabbroic plutons at Utpostane and Muren (Fig. 1) and the abundance of dolerite dykes and sills indicate that Vesfjella was at the locus of high intrusive activity during the break-up of Gondwana; dolerite dykes locally record up to 14% of crustal extension. Preliminary U–Pb zircon ages of a crosscutting granite dyke at Utpostane and gabbro pegmatite at Muren (I. Mänttäri, personal communication 2002) overlap with the peak of Karoo magmatism that occurred at about 183 ± 3 Ma (Encarnación *et al.* 1996, Duncan *et al.* 1997). Three felsic plutons in the Jutulstraumen area record coeval alkaline magmatism (Harris & Grantham 1993), whereas ~159 Ma lamproite dykes record the youngest magmatic event related to continental break-up in the Vestfjella region (Luttinen *et al.* 2002).

Field observations

The gabbros of Utpostane and Muren are fairly monotonous and lack obvious large-scale layered structures, but detailed field observations reveal lithological zoning. Only the largest two nunataks of Utpostane have official names (Skuafjellet and Audunfjellet). In this paper, we refer to the unnamed nunataks in the northern and western parts of Utpostane by the names used during fieldwork (Fig. 2a & b).

Utpostane

The scattered nunataks of Utpostane (Fig. 2a) consist mainly of gabbroic rocks that occur over an area of ~25 km^2. The intrusive contact is exposed at Audunfjellet, where it strikes SW–NE sub-parallel to the prevalent strike of the regional dolerite dykes and dips SE under the wall-rock basalts in an angle of ~ 45 degrees. A 1.5 to 2.5 m wide zone of fine- to medium-grained hornfels occurs between gabbros and aphanitic wall-rock basalts.

Immediately below the contact zone there is a 0.5 to 1.5 m wide band of dark olivine-rich gabbroic rock, which grades rapidly to greyish gabbroic rock. The latter rock type has a distinctive spotted appearance due to large (~1 cm) glomerocrysts of olivine and pyroxene (Fig. 3a). The spotted type is medium-grained and homogeneous apart from sporadic and small (< 50 cm), coarse-grained (~1.5 cm) pegmatoidal batches at the top. Collectively, these two gabbroic types record the uppermost exposed part of the intrusion and comprise the 300 to 500 m wide zone 1 of Utpostane. The basalts of Audunfjellet (Fig. 2a) are crosscut by a ~60 m thick medium- to coarse-grained dyke that is macroscopically similar to the spotted variety of zone 1.

Further away from the contact, zone 2 gabbros in the northern and western parts of Audunfjellet, southern and south-eastern parts of "Pyramid", and at Skuafjellet (Fig. 2a) exhibit a markedly different appearance. They are brownish, even to medium-grained and weakly banded on a decimetre-scale due to diffuse modal layering that runs sub-parallel to the intrusive contact (Fig. 2a). Zone 2 is 1.2 to 1.5 km wide and, locally, the gabbros contain small (dm-scale) inclusions akin to gabbros of zone 1.

Zone 3 is exposed at "Pyramid" and Skuafjellet (Fig. 2a). It is relatively narrow (300–500 m) and characterized in the upper part by 1 to 5 m thick units of leucocratic gabbros intercalated with gabbros that resemble those of zone 2. These rocks are underlain by more homogeneous melanocratic gabbros that are only exposed at "Pyramid" and the adjacent small nunataks. Layering of zone 3 is concordant with the contact of the intrusion.

Zone 4 includes the northernmost ("Finnefjellet") and westernmost ("Russarö" and "Valas") outcrops (Fig. 2a), which are dominated by rather homogeneous olivine-rich gabbros that resemble those of zone 2. As in zones 2 and 3 above, magmatic layering strikes SW–NE and dips 30–50° towards the south-east. This over 2 km wide zone represents the lowest exposed part of the Utpostane intrusion and includes all of the observed cross-bedded and graded units (Fig. 3b).

The Utpostane intrusion contains numerous though sporadic bands (Fig. 3c), lenses, and irregular batches of anorthositic material. The bands typically strike parallel to the layering, but dip steeply towards north-west or south-east. Some of them show kink folds, whereas some have a radiating appearance. The anorthositic bands are thickest (~0.5 m) and most abundant in zone 2, whereas the lenses and batches appear to be randomly distributed.

The graded and cross-bedded zone 4 gabbros at northern "Pyramid" (Fig. 2a) overlie a ~50 m wide heterogeneous unit, which contains intercalated 0.1 to 2 m wide and 1 to 10 m long lenses of fine-grained, greyish brown rock and 1 to 10 cm wide bands of olivine-rich gabbro. The fine-grained lenses are oxide-rich and contain up to 5 cm thick veins of massive oxide. Some of these rocks are folded.

Muren

At Muren, mafic plutonic rocks are exposed at two main outcrops, east Muren and west Muren (Fig. 2b). These comprise a ~2 km wide zone of gabbroic rocks that is bounded to the east and west by intrusive contacts with basalts. The western contact strikes SSW–NNE and dips 50° towards west under the basalts. The eastern contact strikes SW–NE, but the dip angle is undefined due to limited exposure.

A thin (< 1 m thick) layer of greyish and fine-grained felsic rock occurs between gabbroic rocks and wall-rock basalts at the western contact (Fig. 2b). The contact with basalt is typified by a thin (10 cm thick) zone with abundant dendritic amphibole crystals. Locally, small felsic apophyses intrude the brecciated wall-rock. This complex contact felsite is referred to as the marginal felsic unit and it contains basaltic xenoliths and dendritic and fine-grained globular autholiths. Judging from the dip of the western contact, the marginal felsic unit represents the roof of the Muren intrusion and corresponds to capping granophyres that have been described in many gabbroic intrusions (e.g. Lexington granophyre in the Dufek layered intrusion; Ford 1976).

Adjacent to the marginal felsic unit is light-coloured and coarse-grained leucocratic gabbro that grades rapidly to darker brownish, medium-grained, and massive olivine gabbro variety towards the east. This 600 to 700 m wide unit constitutes the upper zone of the Muren intrusion (Fig. 2b).

An abrupt decrease in modal olivine in the small nunataks between the east and west Muren (Fig. 2b) marks the top of the lower zone. The lower zone gabbros superficially resemble those of the upper zone, but they are poor in olivine and contain sporadic pegmatoid batches and narrow

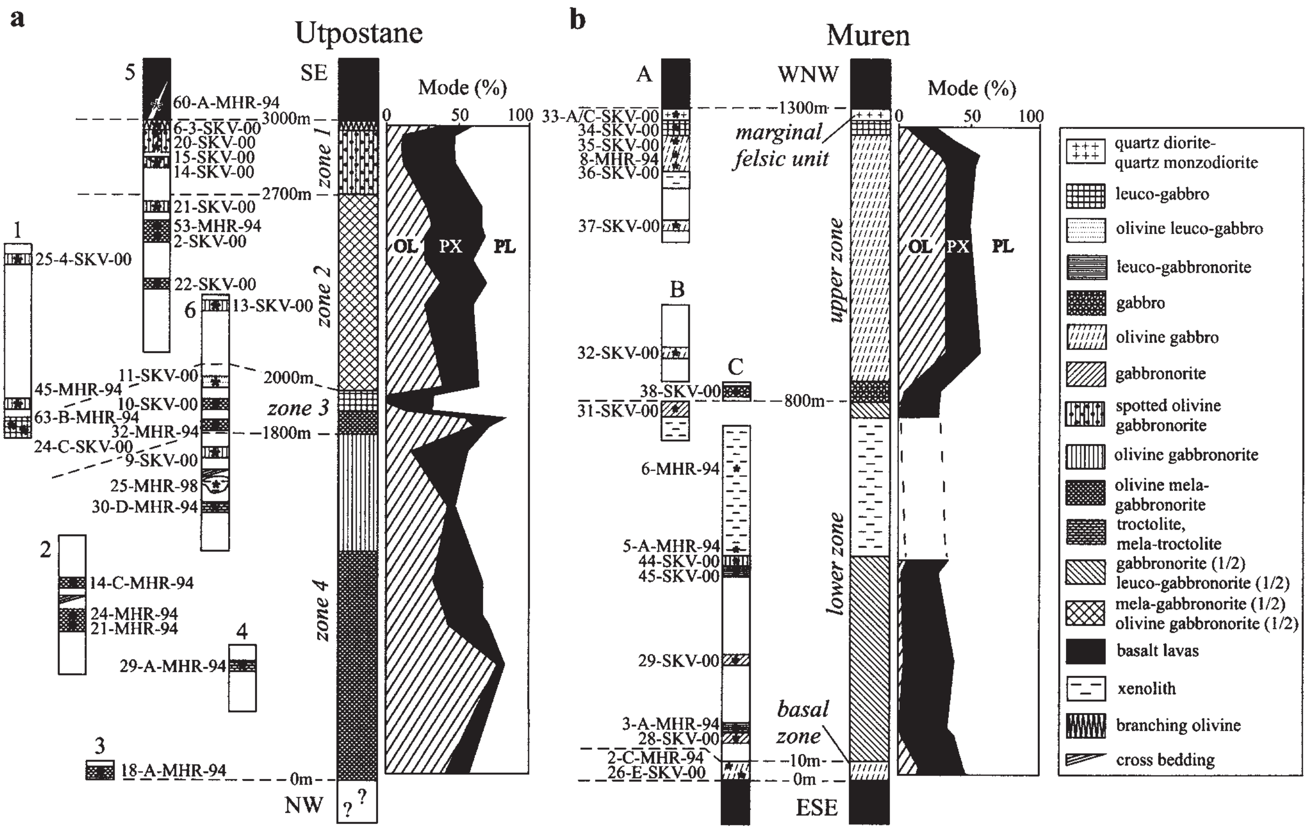

Fig. 4. Lithostratigraphical columns and modal compositions of representative samples of **a.** Utpostane and **b.** Muren intrusions. Generalized lithostratigraphical traverses of both intrusions are constructed based on structural data (Fig. 2) by combining individual sampled sections. OL = olivine, PX = pyroxene, and PL = plagioclase.

Table I. The main features of the Utpostane and Muren gabbroic intrusions from Vestfjella, Dronning Maud Land, Antarctica..

Utpostane	size	thickness	intrusion type	strike and dip	magmatic structures
	≥ 25 km^2	≥ 3 km	inclined sheet	~045 / 45 / SE	banding, layering, grading, cross bedding

internal zoning	zone 1	zone 2	zone 3	zone 4
thickness	~300 m	~700 m	~200 m	≥ 1800 m (?)
main rock types	olivine gabbronorite	olivine gabbronorite	leuco-gabbronorite olivine mela-gabbronorite	olivine mela-gabbronorite
texture	hypidiomorphic granular	hypidiomorphic granular	hypidiomorphic granular	hypidiomorphic granular
main minerals	Pl, Ol, Cpx, Opx	Pl, Ol, Cpx, Opx	Pl, Ol, Cpx, Opx	Pl, Ol, Cpx, Opx
accessory minerals	Bt, Op, Ap, Zr	Bt, Op	Bt, Op	Bt, Op

Muren	size	thickness	intrusion type	strike and dip	magmatic structures
	≥ 2 km^2	~1.3 km	inclined sheet	~025 / 50 / NW	no

internal zoning	marginal felsic unit	upper zone	lower zone	basal zone
thickness	~1m	~500m	~800m	~10m
main rock types	quartz monzodiorite	olivine gabbro	gabbronorite, leuco-gabbronorite	olivine gabbro, olivine leuco-gabbro
texture	hypidiomorphic granular	poikilitic	intergranular	poikilitic
main minerals	Pl, Q, Amf, Kfs	Pl, Cpx, Ol	Pl, Cpx, Opx	Pl, Cpx, Ol
accessory minerals	Bt, Op, Ap, Zr, Cpx	Bt, Op, Ap	Bt, Op, Ap, Zr, Q, Kfs	Bt, Op

Abbreviations: Amf = amphibole, Ap = apatite, Bt = biotite, Cpx = clinopyroxene, Kfs = potassium feldspar, Ol = olivine, Op = opaque, Opx = orthopyroxene, Q = quartz and Zr = zircon.

(1 to 3 cm thick) bands of pyroxene.

A large part of the lower zone at east Muren consists of heterogeneous porphyritic rocks that grade from apahanitic, black and amygdaloidal to fine-grained and greyish. On the basis of their distinctive appearance and chemical composition, these oxide-rich rocks are considered to be metamorphosed basalts (Fig. 2b). Their position within the lower zone gabbros suggests that they represent a large xenolith. The easternmost part of this xenolith contains rocks with 1 to 3 cm thick massive oxide veins. Petrographically similar but considerably smaller basalt xenoliths also occur in the overlying upper zone gabbros (Fig. 2b). Immediately below the large xenolith of east Muren, a narrow part of the lower zone gabbros contains pyroxene-rich stripes and bands of leucocratic gabbro (Fig. 3d).

In contrast to the western contact, the eastern contact lacks a felsic unit. Instead, there is a ~10 m wide zone dominated by greyish brown olivine gabbro, which we regard to represent the base of the intrusion and designate as the basal zone (Fig. 2b). Close to the contact (< 2 m), the basal zone contains pyroxene-rich stripes similar to those below the xenolith in the lower zone.

Felsic dykes and wall-rock basalts

The Utpostane intrusion is cut by several subvertical felsic dykes, which vary in thickness from a few centimetres to ~1 m and strike mainly NE–SW and N–S. They have chilled margins against the gabbroic wall-rocks and contain mafic clots and miarolitic cavities. Felsic dykes also occur at Muren. A 1 m thick, NW–SE trending and sub-vertical dyke cuts the gabbroic rocks of the lower zone. It has chilled margins against the gabbro and includes miarolitic cavities as well as mafic to intermediate enclaves, some of which have diffuse contacts to the host dyke. In addition, 0.5 to 1.5 cm thick and usually 20 to 30 cm long felsic veins occur in the fine-grained xenolith. Crosscutting, NNE–SSW trending (1 to 5 m thick) dolerite dykes occur across Muren. In the vicinity of some of the dolerite dykes, gabbroic rocks are brecciated on a millimetre-scale. Basaltic wall-rocks at the intrusive contacts of the Utpostane and the Muren intrusions are hornfelsed. They are black, fine-grained and high in oxides.

Petrography and lithostratigraphy

The alignment of the magmatic layering and the intrusive contact of Utpostane give an impression of an inclined sheet-like intrusion. Assuming such a simple geometry and an average dip angle of 45°, the minimum thickness of Utpostane can be calculated to be ~3 km. To obtain a complete traverse through the intrusion, we have combined the individual subsections of each sampling site (Figs 2a & 4a). At Muren, the contacts and the lithological variations are also consistent with inclined sheet-like intrusion geometry. The three subsections (Fig. 2b) have been combined to generate a traverse of the intrusion (Fig. 4b). The total thickness of the Muren intrusion, including the xenolith of the lower zone, is ~1.3 km. Based on the sub-horizontal dips of wall-rock basalts, post- magmatic tilting of the gabbroic intrusions is insignificant. The main petrographical and lithological features of Utpostane and Muren are listed in Table I.

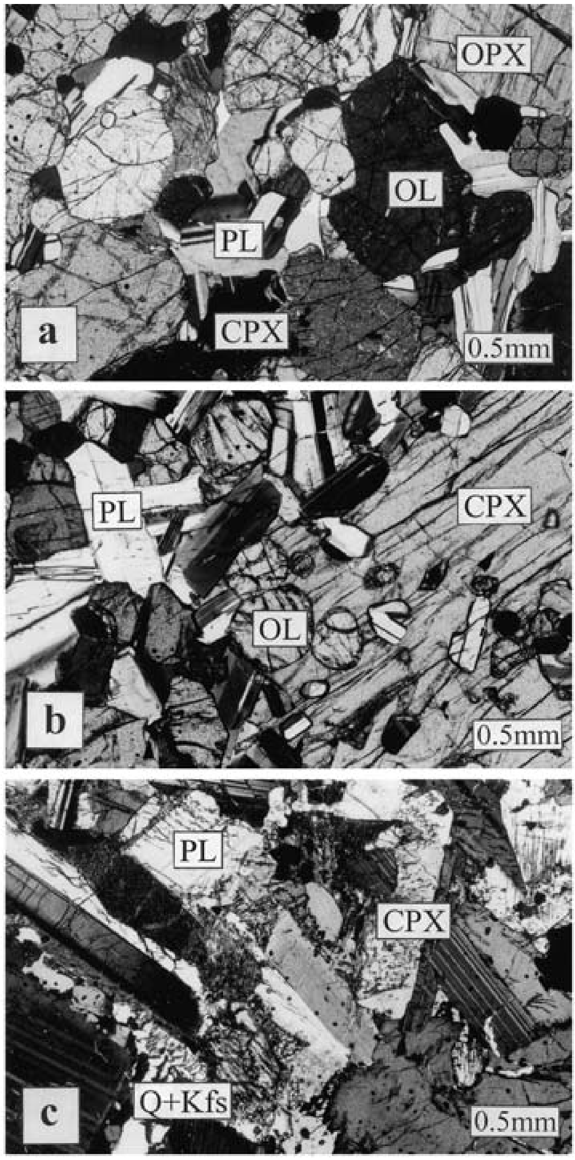

Fig. 5. Photomicrographs of **a.** olivine mela-gabbronorite (21-MHR-94) in zone 4, Utpostane, **b.** poikilitic olivine gabbro (32-SKV-00) in the upper zone, Muren and **c.** gabbronorite with granophyric texture (31-SKV-00) in the lower zone, Muren. OL = Olivine; CPX = clinopyroxene; OPX = orthopyroxene, PL = plagioclase, and Q+KF = granophyric intergrowth of quartz and potassium feldspar.

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Utpostane

The samples from Utpostane are nearly unaltered. Despite of their rather monotonous field-appearance, they can be classified as mela-troctolite, troctolite, olivine mela-gabbronorite, olivine gabbronorite, olivine leuco-gabbro, leuco-gabbro and anorthosite. Hypidiomorphic granular olivine mela-gabbronorite (Fig. 5a) and olivine gabbronorite are the predominant types. Adopting the cumulus terminology (Wager & Brown 1968, Irvine 1982), most of the olivine mela-gabbronorite and olivine gabbronorite varieties should be classified as olivine-plagioclase-pyroxene adcumulates.

Zone 1 consists mainly of homogeneous, medium-grained, spotted olivine gabbronorite that has 3–9 mm mafic glomerocrysts with olivine in the core mantled by smaller clinopyroxene grains. Modal olivine content averages 12% (Fig. 4a). Olivine (< 3 mm) is subhedral and contains spinel and plagioclase inclusions. Some of the olivine grains are partly altered to serpentine. Reaction coronas of orthopyroxene around olivine are common. Non-pleochroic orthopyroxene (< 3 mm) is sub- or euhedral, colourless and contains clinopyroxene exsolution lamellae and plagioclase and olivine inclusions. Clinopyroxene (< 2 mm) is anhedral to subhedral, commonly twinned, and shows pale green pleochroism. Plagioclase (< 1.5 mm) is subhedral to euhedral and zoned. Opaque, biotite, apatite and zircon are accessory minerals, the latter two of which only occur in zone 1. The olivine-rich (~40 vol.%) band between the spotted gabbro type and the contact zone has a distinctive harrisitic-like texture with branching olivine crystals aligned approximately perpendicular to the plane of the contact.

The gabbros of zones 2, 3 and 4 are quite similar; they are typically rich (~30–50 vol.%) in olivine, but lack mafic glomerocrysts. Plagioclase is weakly zoned and pyroxenes are mainly subhedral and coarser-grained than in zone 1. Opaque and biotite are the only accessory phases.

Zone 2 is medium-grained and consists of intercalated, equally abundant olivine gabbronorite and olivine mela-gabbronorite. The modal olivine content of olivine gabbronorite and olivine mela-gabbronorite is typically 26–39% and 26–44%, respectively (Fig. 4a). The base of zone 2 has notably coarse clinopyroxene (≤ 8 mm) and plagioclase (≤ 4 mm) and contains euhedral orthopyroxene.

Zone 3 is characterized by markedly variable lithology. The leuco-gabbro of Skuafjellet mark the top of this zone and is correlated with olivine leuco-gabbro at “Pyramid”. The underlying main part of zone 3 at “Pyramid” and nearby outcrops consists of olivine mela-gabbronorite that include nearly troctolitic types. The leuco-gabbro and olivine leuco-gabbronorite (modal olivine 0–14%) have herringbone exsolutions in pyroxenes and lack biotite. The olivine mela-gabbronorite (modal olivine 53–60%) is texturally and mineralogically similar to that of zone 2.

The upper part of zone 4 consists of intercalated troctolite and olivine gabbronorite the latter of which predominates. Biotite is absent and clinopyroxene show herringbone exsolutions at the very top of zone 4. The lower part consists of olivine mela-gabbronorite and minor mela-troctolite. As in zone 2, the modal olivine content of olivine gabbronorite and olivine mela-gabbronorite shows enrichment towards the base (17–40% and 19–46%, respectively). The olivine mela-gabbronorite and rare olivine gabbronorite in the basal part of this zone are biotite-bearing. Mela-troctolite (77% modal olivine) represents the most mafic rock of the Utpostane intrusion (Fig. 4a). Magmatic lamination is common and most pronounced in zone 4, which locally exhibits draping of plagioclase around olivine as well as bending of plagioclase and pyroxene grains.

Muren

The gabbroic rocks from Muren include olivine gabbro, gabbro, leuco-gabbro, gabbronorite, olivine leuco-gabbronorite and leuco-gabbronorite. Three predominant types are poikilitic olivine gabbro (Fig. 5b) in the upper zone and intergranular gabbronorite (Fig. 5c) and leuco-gabbronorite in the lower zone.

The marginal felsic unit consists of two rock types. The predominant type is strongly altered, hypidiomorphic granular, amphibole-bearing quartz monzodiorite. Plagioclase is extensively albitized. Opaque, biotite, apatite, clinopyroxene, and zircon are accessory phases. Alteration products include carbonate, epidote, and chlorite. The other type is medium-grained quartz diorite, which occurs along the intrusive contact to basalts and is characterized by dendritic hornblende and granophyric texture.

The upper zone leuco-gabbro immediately below the marginal felsic unit is coarse-grained, poikilitic and strongly altered. Coarse euhedral plagioclase (< 7 mm) is strongly zoned, bent, and moderately altered to sericite and epidote. Pale green-reddish pleochroic, anhedral clinopyroxene (< 5 mm) oikocrysts enclose plagioclase and olivine. Subhedral olivine (< 0.5 mm) has been partly altered to serpentine-group minerals and opaques. Minor anhedral orthopyroxene has been almost totally altered to talc, carbonate and opaques. Interstitial quartz and K-feldspar exhibit a granophyric texture. Other accessory minerals include opaques, apatite, biotite, and zircon. The upper zone is mainly composed of poikilitic medium-grained olivine gabbro with 16 to 33% of modal olivine (Fig. 4b). Large anhedral clinopyroxene oikocrysts (< 6 mm) have euhedral plagioclase and rounded olivine inclusions. Plagioclase (< 3 mm) is weakly zoned and contains olivine and spinel inclusions. Anhedral pale reddish orthopyroxene is rare and contains abundant exsolution lamellae of clinopyroxene. Subhedral olivine (< 2 mm) has plagioclase and spinel inclusions. Biotite, opaque and apatite are accessory phases.

Table II. Geochemical data of Utpostane and Muren gabbroic intrusions and related rocks from Vestfjella, Dronning Maud Land, Antarctica.

	Utpostane zone 1			Utpostane zone 2								Utpostane zone 3		
Sample	6-3-SKV-00	20-SKV-00	15-SKV-00	14-SKV-00	21-SKV-00	53-MHR-94	2-SKV-00	24-5-SKV-00	22-SKV-00	13-SKV-00	45-MHR-94	63-B-MHR-94	24-C-SKV-00	11-SKV-00
wt.% *														
SiO_2	45.56	50.81	50.15	50.49	47.04	47.20	46.98	49.18	47.24	47.35	45.77	52.32	52.03	49.73
TiO_2	0.17	0.63	0.86	0.86	0.38	0.40	0.33	0.43	0.41	0.37	0.29	0.19	0.22	0.20
Al_2O_3	11.03	14.38	13.47	13.39	10.30	9.73	9.97	12.55	9.33	11.18	8.75	18.06	17.56	18.92
FeOt†	9.53	8.52	9.66	9.86	11.22	11.53	11.31	9.53	11.01	10.22	12.43	5.55	5.48	5.00
MnO	0.16	0.16	0.16	0.17	0.19	0.19	0.18	0.17	0.19	0.18	0.20	0.13	0.14	0.10
MgO	25.48	13.23	13.81	13.26	21.40	21.71	22.21	17.29	20.97	19.43	23.69	8.14	8.55	10.31
CaO	7.01	10.06	9.34	9.42	7.99	7.81	7.52	9.22	9.51	9.78	7.64	13.17	13.76	13.61
Na_2O	0.95	1.79	1.92	1.92	1.25	1.19	1.26	1.37	1.09	1.27	1.01	2.29	2.14	2.00
K_2O	0.09	0.35	0.50	0.47	0.20	0.20	0.20	0.22	0.21	0.20	0.18	0.14	0.12	0.12
P_2O_5	0.02	0.08	0.13	0.18	0.05	0.04	0.05	0.04	0.04	0.03	0.04	0.01	0.02	0.02
ppm														
Ni	935	329	338	312	598	593	614	484	510	334	614	48	39	179
Cr	2569	1266	1213	1083	1880	1740	1911	1699	2017	1563	1790	454	292	961
Sc	17	27	35	35	19	34	26	28	33	29	30	36	43	24
V	87	188	189	201	167	174	152	179	207	194	161	226	268	173
Ba	19	114	136	140	59	63	62	72	71	67	59	69	64	50
Rb	1	7	9	7	3	3	2	4	3	3	3	n.d	1	n.d
Sr	109	182	186	188	145	133	128	159	120	135	109	258	231	249
Zr	14	44	59	58	24	26	20	26	26	26	23	8	8	12
Y	5	12	17	17	8	8	6	10	10	10	7	6	6	6
Nb	1.9	3.5	4.4	5.5	2.3	1.8	3.6	3.0	1.9	3.1	1.8	1.3	1.3	2.8
Ga	5	11	11	11	11	9	11	9	8	8	7	18	15	15
Cu	57	60	29	52	52	42	38	44	34	14	38	28	56	7
Zn	64	63	76	77	76	85	79	67	76	63	77	38	34	32
Ti/Zr	74	86	87	89	95	92	98	100	94	86	76	144	161	99

	Muren marginal felsic unit		Muren upper zone							Muren lower zone	
Sample	33-C-SKV-00	33-A-SKV-00	34-SKV-00	35-SKV-00	8-MHR-94	36-SKV-00	37-SKV-00	32-SKV-00	38-SKV-00	31-SKV-00	45-SKV-00
wt.% *											
SiO_2	57.04	65.68	49.43	48.05	48.13	46.53	46.87	44.87	50.55	53.90	52.89
TiO_2	2.01	1.00	1.55	1.57	1.06	1.05	0.88	0.79	1.48	0.99	0.92
Al_2O_3	14.45	15.09	17.62	13.13	14.69	14.18	14.26	11.02	17.09	15.45	15.66
FeOt †	11.20	5.94	12.23	14.69	12.28	13.71	13.16	‡15.98	10.76	9.14	9.89
MnO	0.20	0.10	0.17	0.22	0.18	0.20	0.19	0.23	0.16	0.16	0.16
MgO	2.52	0.93	5.12	9.96	11.35	13.03	13.10	17.15	5.44	6.15	6.95
CaO	6.04	2.73	10.46	9.16	9.39	8.53	8.76	7.78	10.57	10.38	9.73
Na_2O	4.63	5.78	2.73	2.48	2.31	2.26	2.29	1.83	3.03	2.78	2.85
K_2O	1.06	2.50	0.54	0.60	0.48	0.41	0.41	0.27	0.75	0.90	0.84
P_2O_5	‡0.85	0.25	0.15	0.16	0.12	0.11	0.09	0.06	0.17	0.15	0.12
ppm											
Ni	8	7	92	265	357	430	444	605	113	89	157
Cr	1	1	52	266	545	575	611	1512	200	182	56
Sc	17	6	16	27	19	18	20	17	25	25	26
V	112	47	315	302	248	227	204	264	303	254	234
Ba	840	1246	179	261	208	175	177	123	304	359	309
Rb	19	28	11	10	9	6	9	3	15	20	18
Sr	414	262	320	290	301	290	293	227	359	347	359
Zr	192	715	110	108	82	74	69	45	123	113	109
Y	68	63	24	23	16	16	14	11	24	22	18
Nb	28.6	28.2	8.0	8.8	5.5	5.8	6.3	3.8	9.1	7.8	7.9
Ga	24	25	22	16	17	17	19	15	22	19	19
Cu	‡222	103	‡200	‡223	137	143	111	81	174	100	72
Zn	127	73	91	109	86	96	89	108	81	73	77
Ti/Zr	63	8	84	87	78	85	76	105	72	53	50

The samples have been analysed with X-ray fluorecence (XRF/Rigaku 3370) spectrometer at the Geoanalytical Laboratory, Washington State University. The analytical procedures, accuracy and precision are described by Johnson *et al*. (1999).

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Table II. (continued) Geochemical data of Utpostane and Muren gabbroic intrusions and related rocks from Vestfjella, Dronning Maud Land, Antarctica.

Utpostane zone 4									anort-hosite	Xenolith	Hornfels	felsic dyke	gabbroic dyke
10-SKV-00	32-MHR-94	9-SKV-00	30-D-MHR-94	14-C-MHR-94	24-MHR-94	21-MHR-94	29-A-MHR-94	18-A-MHR-94	29-D-MHR-94	25-MHR-98	57-D-MHR-94	54-MHR-98	60-A-MHR-94
44.07	43.70	48.49	45.77	46.54	47.06	46.05	41.31	46.52	49.63	42.64	47.22	75.47	50.40
0.30	0.26	0.25	0.07	0.23	0.30	0.40	0.18	0.20	0.06	2.48	2.08	0.18	1.00
4.18	7.10	12.50	16.51	9.02	9.83	7.52	4.64	12.83	31.36	14.91	13.43	13.14	13.11
14.30	12.53	9.36	8.68	11.49	11.07	12.69	14.00	9.90	0.50	‡ 17.39	13.08	1.35	8.69
0.24	0.19	0.17	0.13	0.20	0.19	0.21	0.20	0.16	0.01	0.14	0.19	0.02	0.16
29.35	29.72	18.32	17.88	23.11	22.33	25.60	36.29	20.56	0.39	6.68	8.14	0.46	13.59
6.90	5.64	9.42	9.48	8.35	7.93	6.45	2.63	8.31	15.18	13.57	14.12	0.54	8.84
0.53	0.70	1.39	1.40	0.95	1.14	0.88	0.62	1.35	2.74	2.15	1.66	3.35	1.85
0.10	0.13	0.10	0.06	0.09	0.14	0.17	0.10	0.13	0.13	0.02	0.06	5.41	0.61
0.03	0.03	0.01	0.01	0.02	0.02	0.04	0.03	0.02	0.01	0.01	0.03	0.07	0.12
719	766	509	474	386	563	636	969	501	1	128	93	12	350
2458	2659	1763	961	1709	2075	2156	3257	1420	19	121	334	13	1104
29	20	27	11	31	32	30	15	21	n.d	18	42	6	31
184	122	173	59	178	163	165	81	111	12	642	553	9	201
41	41	42	20	35	49	59	33	48	49	n.d	29	684	151
n.d	1	n.d	n.d	1	1	3	1	1	1	n.d	1	240	10
52	90	172	201	116	134	101	60	170	382	462	252	103	196
20	18	9	7	13	15	25	15	15	8	12	25	179	70
9	6	6	2	7	7	8	4	5	1	3	16	31	17
2.3	1.3	1.2	1.0	3.2	0.3	2.6	2.3	2.2	1.4	2.8	3.1	33.4	4.9
7	9	10	10	8	9	10	5	11	20	24	20	17	15
25	22	46	0	20	24	22	7	16	3	15	192	57	40
93	76	63	59	75	76	89	88	74	3	83	94	43	75
90	88	168	59	106	118	95	74	82	45	1239	499	6	86

Muren basal zone					xenolith	hornfels	felsic dyke
29-SKV-00	3-A-MHR-94	28-SKV-00	2-C-MHR-94	26-E-SKV-00	5-A-MHR-94	26-B-SKV-00	63-MHR-98
51.97	53.86	53.71	49.64	49.27	48.55	46.84	75.24
1.02	1.14	1.21	0.45	0.50	1.64	0.93	0.28
14.93	14.78	15.03	16.77	15.48	17.29	11.17	13.27
11.25	10.53	10.58	9.03	9.24	10.56	12.47	1.58
0.17	0.16	0.16	0.14	0.15	0.17	0.19	0.02
7.74	6.66	6.26	9.66	10.88	6.08	13.72	0.08
9.18	8.80	8.70	11.61	12.10	13.01	13.30	0.51
2.66	2.91	2.96	2.35	2.06	2.46	1.26	4.23
0.94	1.00	1.21	0.30	0.27	0.15	0.10	4.75
0.13	0.16	0.18	0.05	0.05	0.10	0.03	0.04
218	152	148	268	297	81	305	6
72	61	52	606	830	267	558	n.d
20	25	20	27	28	28	38	6
251	236	235	171	195	378	307	12
317	392	447	125	123	119	54	745
27	19	26	5	4	1	1	150
332	326	331	326	302	411	228	89
125	152	164	39	38	37	30	324
20	24	26	8	10	14	12	41
9.2	9.0	10.4	2.5	2.8	3.6	2.0	20.6
19	18	20	17	17	22	15	16
94	90	120	37	38	69	33	34
87	88	90	53	57	76	79	20
49	45	44	69	79	266	186	5

* Values normalized to 100% volatile free, FeOt † is total iron, n.d. = not detected, ‡ denotes values >120% of highest standard.
Concentrations for Ni, Cr, Sc, V and Ba are semi-quantitative when < 30 ppm and for Rb and Y when < 3 ppm.

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Table III. Trace element data of Utpostane and Muren gabbroic intrusions and related rocks from Vestfjella, Dronning Maud Land, Antarctica.

Utpostane Sample	gabbroic dyke 60-A-MHR-94	zone 1 15-SKV-00	zone 2 53-MHR-94	zone 3 32-MHR-94	zone 4 24-MHR-94	felsic dyke 54-MHR-98	xenolith 25-MHR-98	hornfels 57-D-MHR-94
La	8.06	6.59	2.74	1.73	1.60	27.03	0.11	1.55
Ce	15.45	13.18	5.55	3.54	3.22	49.92	0.26	4.33
Pr	1.97	1.66	0.70	0.46	0.43	5.64	0.05	0.84
Nd	8.51	7.37	3.22	2.18	2.07	21.06	0.37	5.27
Sm	2.43	2.13	0.97	0.66	0.65	5.24	0.25	2.27
Eu	0.95	0.87	0.49	0.32	0.43	0.96	0.22	1.11
Gd	2.80	2.54	1.14	0.82	0.79	4.96	0.40	3.03
Tb	0.49	0.45	0.22	0.15	0.15	0.93	0.07	0.53
Dy	3.14	2.88	1.42	0.98	1.03	5.66	0.40	3.28
Ho	0.66	0.62	0.30	0.22	0.23	1.16	0.07	0.63
Er	1.85	1.74	0.89	0.60	0.65	3.28	0.14	1.54
Tm	0.27	0.26	0.13	0.09	0.10	0.49	0.02	0.20
Yb	1.69	1.65	0.82	0.57	0.63	3.06	0.09	1.15
Lu	0.26	0.26	0.13	0.09	0.10	0.44	0.01	0.16
Ba	151	135	63	38	49	685	7.3	41
Th	0.74	0.87	0.34	0.18	0.13	12.79	0.16	0.04
Nb	4.85	3.91	1.27	0.78	0.46	33.19	0.09	0.63
Y	17.29	16.24	7.79	5.58	5.89	30.85	1.47	15.1
Hf	1.78	1.60	0.63	0.39	0.31	5.16	0.10	0.80
Ta	0.27	0.24	0.07	0.04	0.02	2.30	0.01	0.03
U	0.15	0.16	0.07	0.03	0.02	1.94	0.01	0.03
Pb	2.30	2.01	0.79	0.42	0.49	36.43	0.25	0.28
Rb	10.1	8.4	3.5	1.8	1.3	231.5	0.8	0.8
Cs	0.20	0.07	0.06	0.02	0.02	2.23	0.03	0.02
(La/Sm)n*	2.14	2.00	1.82	1.69	1.59	3.33	0.28	0.44
(Sm/Lu)n*	1.55	1.38	1.24	1.22	1.08	1.98	3.50	2.36
Th/Ta	2.74	3.65	4.86	4.50	6.50	5.56	13.33	1.33

Muren	marginal felsic unit 33-C-SKV-00	marginal felsic unit 33-A-SKV-00	upper zone 8-MHR-94	lower zone 29-SKV-00	basal zone 26-E-SKV-00	felsic dyke 63-MHR-98	xenolith 5-AMHR-93	hornfels 26-B-SKV-00
La	47.50	50.85	10.90	20.37	4.90	60.82	3.00	2.22
Ce	99.41	99.61	21.56	38.44	9.85	118.38	7.51	5.90
Pr	12.55	11.84	2.63	4.38	1.24	11.82	1.19	0.97
Nd	56.71	49.79	11.88	18.03	5.73	42.11	6.76	5.44
Sm	15.12	12.63	3.24	4.40	1.66	8.50	2.40	2.02
Eu	3.85	3.32	1.17	1.40	0.77	0.91	1.17	0.83
Gd	15.26	12.51	3.52	4.31	1.80	6.91	2.97	2.38
Tb	2.41	2.09	0.57	0.68	0.31	1.17	0.49	0.40
Dy	13.89	12.59	3.35	4.07	1.87	7.31	2.90	2.36
Ho	2.60	2.49	0.64	0.79	0.36	1.49	0.55	0.45
Er	6.29	6.64	1.67	2.04	0.89	4.36	1.42	1.14
T	0.85	0.93	0.22	0.29	0.13	0.68	0.19	0.15
Yb	4.77	5.67	1.39	1.70	0.73	4.50	1.07	0.85
Lu	0.68	0.86	0.20	0.25	0.11	0.70	0.16	0.13
Ba	867	1288	200	344	122	743	115	52
Th	4.38	7.39	1.26	2.95	0.51	24.88	0.09	0.12
Nb	29.09	28.83	5.36	7.62	1.71	20.35	2.10	0.69
Y3	67.12	65.18	16.96	20.39	9.00	42.50	14.37	11.32
Hf	6.46	18.16	2.14	3.35	0.95	9.10	1.01	0.99
Ta	1.60	1.70	0.31	0.45	0.10	2.06	0.17	0.05
U	0.71	1.21	0.23	0.53	0.08	11.05	0.02	0.02
Pb	5.30	11.18	2.38	5.99	1.59	30.27	0.40	0.60
Rb	19.3	25.7	9.5	27.3	4.2	145.0	1.5	1.1
Cs	0.20	0.19	0.11	0.87	0.07	1.54	0.03	0.02
(La/Sm)n*	2.03	2.60	2.17	2.99	1.90	4.62	0.81	0.71
(Sm/Lu)n*	3.69	2.44	2.69	2.88	2.60	2.02	2.49	2.67
Th/Ta	2.74	4.35	4.06	6.62	5.26	12.08	0.53	2.33

* Chondrite normalized values, normalizing data from Sun & McDonough (1989). Elements have been analysed with inductively coupled plasma source mass spectrometer (ICP-MS) at the Geoanalytical Laboratory, Washington State University. Analytical procedures, accuracy and precision are described by Knaack *et al.* (1994).

The degree of alteration is low. The base of the upper zone is a plagioclase-rich and olivine-poor gabbro that lacks poikilitic texture, but is otherwise similar to the leuco-gabbro at the top of the zone. Plagioclase and olivine are cumulus phases in the upper zone (cf. Irvine 1982).

The lower zone consists of olivine-poor (< 1–4 vol.%), medium-grained, intergranular gabbronorite and leuco-gabbronorite, which are equally abundant (Fig. 4b). Plagioclase (< 4 mm) is euhedral, zoned and slightly bent throughout the zone. Clinopyroxene (< 3 mm) and inverted pigeonite (< 3 mm) are subhedral and have abundant herringbone exsolution lamellae. Olivine (< 0.5 mm) is anhedral and moderately altered. Minor phases include opaque, biotite and granophyric quartz and K-feldspar. Apatite and zircon are accessory minerals. The pegmatoid portions at the base of the lower zone also contain accessory hornblende. Immediately below (< 5 m) the xenolith rock, the gabbros with pyroxene stripes contain olivine oikocrysts. Overall, these rocks are similar to the underlying lower zone gabbronorite, but due to slightly higher olivine (~6%) content they can be classified as olivine gabbronorite.

The basal zone of Muren is rather high in olivine (13 and 14 vol.%), which distinguishes it from the gabbros of the lower zone (Fig. 4b). Petrographically, the olivine gabbro and olivine leuco-gabbro of the basal zone are similar to the olivine gabbro at the top of the upper zone.

The xenolith rock within the lower zone consists of heterogeneous, aphanitic to fine-grained and dark-coloured plagioclase and clinopyroxene glomeroporphyritic rocks that are markedly different from the enclosing gabbros. The fine-grained type is predominant. The aphanitic type in the centre contains amygdules with quartz, biotite, carbonate and euhedral orthopyroxene fillings. This type grades west- and eastwards to a fine-grained granoblastic variety that contains small (< 1 mm) clusters of euhedral orthopyroxene instead of amygdules. Some of the clinopyroxene phenocrysts have opaque-rich reaction rims. Hornblende, epidote, talc and chlorite are minor minerals.

Felsic dykes and wall-rock basalts

The crosscutting felsic dykes of Utpostane and Muren are granites and alkali feldspar granites, which are characterized by granophyric texture. In addition to alkali feldspar, quartz, plagioclase and minor biotite, they contain accessory opaques, apatite, and zircon.

At Utpostane, the country-rock basalts form a metamorphic aureole with three mineralogically distinctive zones indicating progressively higher temperatures towards the intrusive contact. The actinolite-chlorite zone includes most of the basalts at Audunfjellet (Fig. 2a) and is characterized by actinolite pseudomorphs of augite phenocrysts. The pyroxene zone, 5–50 m from the intrusive contact, is granoblastic and contains two groundmass pyroxenes in contrast to the unmetamorphosed basalts, which lack groundmass orthopyroxene. The olivine zone occurs within 5 m from the contact zone and has a granoblastic polygonal matrix of two pyroxenes, plagioclase and opaque. Rare olivine occurs mainly as ribbons and stripes. Next to the contact zone (< 1 m), the olivine zone contains fine-grained veins (< 5 mm) and globular batches of plagioclase. The wall-rock basalt samples from the Muren are similar to those described above, but do not contain plagioclase segregations.

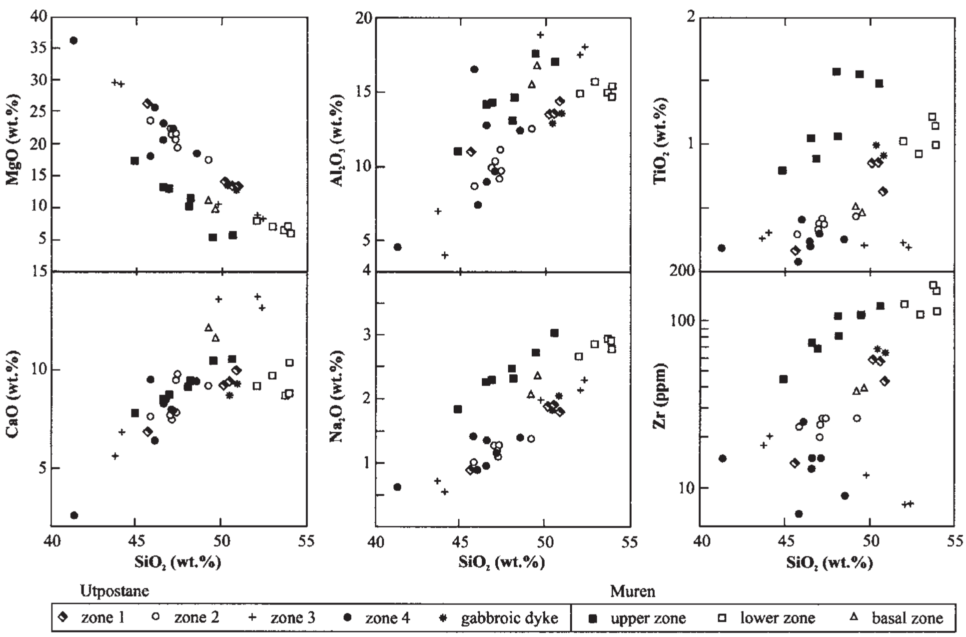

Fig. 6. Variations in SiO_2 and selected major element oxides and trace elements for gabbroic rocks of Utpostane and Muren.

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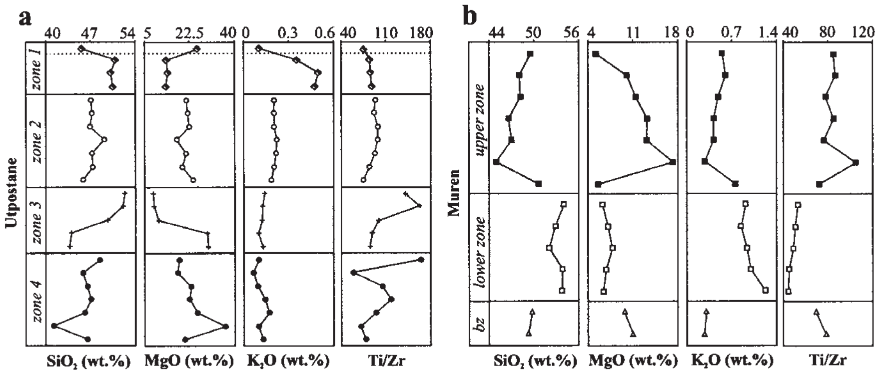

Fig.7. Geochemical traverses of **a.** Utpostane and **b.** Muren intrusions. The order of samples is the same as in Fig. 4 (data for sample 44-SKV-00 are not available). Symbols are the same as in Fig. 6. The harrisitic unit of Utpostane is separated from the underlying zone 1 gabbros by a dotted line. Heights of samples are not to scale. Also note different scales for Utpostane and Muren. bz = basal zone.

Geochemistry

General geochemistry

Geochemical compositions of gabbros and related felsic rocks from Utpostane and Muren are listed in Tables II and III. Overall, the rocks show large geochemical variations and comparison between the gabbroic rocks of Utpostane and Muren demonstrates profound differences (Fig. 6). The Muren gabbros are fairly similar to the tholeiitic wall-rock basalts with SiO_2 ranging from 45 to 54 wt% and MgO from 5 to 17 wt% (cf. Luttinen & Furnes 2000). In comparison, Utpostane is characterized by somewhat higher MgO and lower Al_2O_3, TiO_2, Na_2O, K_2O and P_2O_5 at given SiO_2 (Fig. 6 and Table II). In both intrusions SiO_2 correlates negatively with MgO and positively with Al_2O_3 and Na_2O. The two intrusions are also different in terms of trace element compositions. Muren resembles the basalts and has high concentrations of incompatible trace elements (e.g. Zr 40–160 ppm, Sr 200–350 ppm and Ba 100–500 ppm) compared to Utpostane (Zr 5–60 ppm, Sr 50–260 ppm and Ba 20–140 ppm). Incompatible trace elements, such as Zr, show broad positive correlation with SiO_2, but the leuco-gabbro of zone 3 from Utpostane has distinctly low Zr contents at given SiO_2 (Fig. 6). Loss on ignition values for Utpostane and Muren have been previously shown to be very low, always below 1.5 wt% and mainly below 0.7 wt% (Räisänen 1996). Hence, loss on ignition was not determined in this study.

Geochemical traverse of Utpostane

The geochemical traverse of Utpostane indicates systematic differences between the zones (Fig. 7a). Variations of major oxides reflect modal compositions and the abundance of olivine in particular. Zone 1 is geochemically uniform apart from the < 1.5 m thick MgO-rich harrisitic part at the top and is characterized by relatively high concentrations of incompatible elements, such as Zr (44–59 ppm), TiO_2 (0.6–0.9 wt%) and K_2O (0.4–0.5 wt%). Zone 2 is the most uniform zone at Utpostane; for example, MgO is confined to 17–24 wt%. In comparison, zone 3 records notably wide compositional ranges (MgO 8–30 wt%). Zone 4 is in many respects similar to zone 2, but includes the most MgO-rich rocks exposed at Utpostane and records the lowest incompatible element concentrations (Zr 7–25 ppm, K_2O 0.1–0.2 wt%). Overall, concentrations of incompatible elements show a gradual increase from the base to the top. The majority (~80%) of gabbroic rocks, excluding the most leuco- and melanocratic-varieties, have rather constant Ti/Zr values of 80–100. The gabbroic dyke of Audunfjellet (Fig. 2a) is geochemically nearly identical to zone 1.

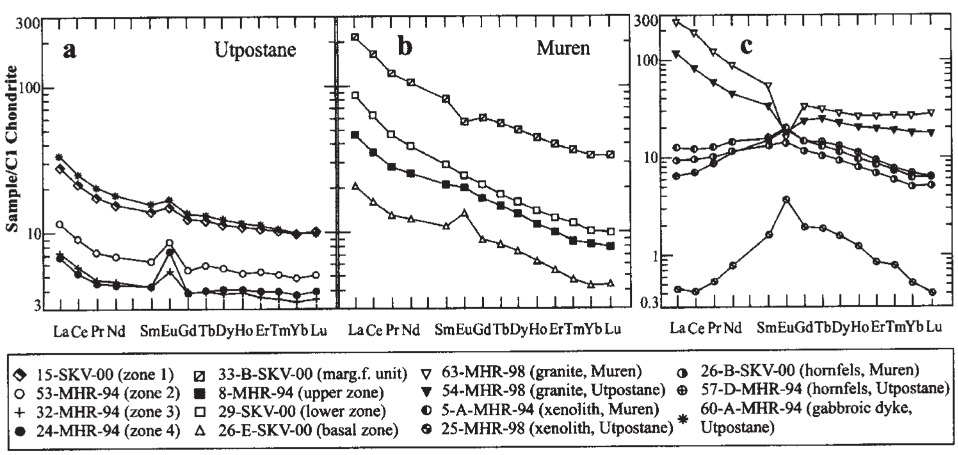

Fig. 8. Chondrite-normalized diagrams of **a.** gabbroic rocks of Utpostane, **b.** gabbroic rocks and the marginal felsic unit of Muren and **c.** felsic dykes, contact hornfelses and xenoliths of both intrusions. Normalizing values after Sun & McDonough (1989). For sampling localities see Fig. 2. Marg.f. unit = marginal felsic unit.

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Representative rare-earth element (REE) data for zones 1, 2, 3 and 4 are listed in Table III. Concentrations of REE in zones 2, 3 and 4 are markedly low compared to zone 1. Chondrite-normalized REE-diagrams show positive Eu-anomalies and coupled gradual increase in REE contents and $(La/Sm)_n$ (1.6–2.0) and $(Sm/Lu)_n$ (1.1–1.4) values from zones 4 to 1 (Fig. 8a, Table III).

Geochemical traverse of Muren

The geochemical traverse of Muren shows clear zoning (Fig. 7b). The differences between the marginal felsic unit and the gabbroic rock types are such that the former is excluded from this section. The upper zone is low in SiO_2, K_2O and Na_2O, but high in MgO and Ni in comparison with the lower zone. The leuco-gabbro at the top and the plagioclase-rich gabbro at the base of the upper zone are geochemically quite similar and have low MgO (~5 wt%). The central part shows negative correlation between MgO and SiO_2 that reflects increasing olivine abundance towards the base of the upper zone. Within the upper zone, concentrations of incompatible elements, such as K and Zr, vary by a factor of ≥ 2. The upper zone has Ti/Zr of 72–87, excluding the most olivine-rich sample that shows strong adcumulus growth of pyroxene and low Zr content (45 ppm).

The boundary between the upper zone and the lower zone is manifested by a marked change in SiO_2 and Ti/Zr. The lower zone has rather constant, low MgO (6–8 wt%) and high Zr (110–160 ppm) contents and lower Ti/Zr (44–53) than the upper zone (Fig. 7b). The basal zone is also easily recognizable (Fig. 7b). It has comparable MgO contents (10–11 wt%) and Ti/Zr values (69–79) with some of the upper zone gabbros, but records the lowest concentrations of incombatible elements (e.g. Zr < 40 ppm) of the intrusion.

Chondrite-normalized REE-diagrams exhibit different concentration levels in different zones (Fig. 8b). The patterns for the upper and lower zones are nearly linear and subparallel between Lu and Eu, but diverge from Sm to La so that the lower zone has higher $(La/Sm)_n$ (3.0) than the upper zone (2.2) (Table III, Fig. 8b). The basal zone has clearly lower REE concentrations and somewhat lower $(La/Sm)_n$ (1.9) than the upper and lower zones. It further exhibits a marked positive Eu abundance anomaly. The $(Sm/Lu)_n$ values for the upper zone (2.7), lower zone (2.9), and basal zone (2.6) are fairly similar.

Marginal felsic unit, felsic dykes and wall-rock basalts

The marginal felsic unit of Muren has intermediate SiO_2 (~57–66 wt%) coupled with low MgO (~1–3 wt%) (Table I). It is subalkaline and metaluminous and has markedly high Zr (545–715 ppm), Sr (262–305 ppm) and Ba (1104–1246 ppm) contents. Chondrite-normalized REE-diagrams for the marginal felsic unit resemble those of the underlying Muren gabbros with regard to $(La/Sm)_n$ (2.0–2.6) and $(Sm/Lu)_n$ (2.4–3.7) (Fig. 8b, Table III).

The felsic dykes have high SiO_2 (~75 wt%), and low MgO (< 0.5 wt%) contents and show subalkaline and slightly peraluminous affinities (Table I). Compared to the marginal felsic unit, concentrations of Zr (179–324 ppm), Sr (89–103 ppm), and Ba (684–745 ppm) are low. The dykes exhibit high $(La/Sm)_n$ (3.3–4.6) but fairly low $(Sm/Lu)_n$ (2.0) and a marked negative Eu-anomaly (Fig.8c).

The most distinctive geochemical feature of the wall-rock basalts is the low concentrations of highly incompatible elements, such as light REE (Fig. 8c, Table II). The contact basalts exhibit markedly lower $(La/Sm)_n$ values (0.4 and 0.7) than any other basaltic lavas of Vestfjella (Table IV, Luttinen & Furnes 2000). The $(Sm/Lu)_n$ values (2.4–2.7), on the other hand, resemble those of unmetamorphosed basalts. Ti/Zr values are exceptionally high (~190–500). The aphanitic to fine-grained rock type within the lower zone has indistinguishable REE-patterns and $(La/Sm)_n$ (0.8), $(Sm/Lu)_n$ (2.5) and Ti/Zr (265) values from the wall-rock basalts, which lends support to our interpretation that it is a large xenolith of basaltic country rock sandwiched between gabbros. Judging from their markedly low $(La/Sm)_n$ and high Ti/Zr values (0.3 and 1239), the small fine-grained lenses in zone 4 of Utpostane are also xenoliths.

Magnetic susceptibilities and density

The mineralogically and geochemically different zones of Utpostane and Muren are also distinguishable in terms of magnetic susceptibility and density. Representative petrophysical data from both localities are illustrated in

Table IV. Selected element ratios of gabbroic rocks and flood basalts from Vestfjella, Dronning Maud Land, Antarctica.

	Ti/Zr	Th/Ta	(La/Sm)n*	(Sm/Lu)n*
Utpostane				
gabbroic dyke	86	2.7	2.1	1.6
zone 1	87	3.7	2.0	1.4
zone 2	92	4.9	1.8	1.2
zone 3	88	4.5	1.7	1.2
zone4	118	6.5	1.6	1.1
Muren				
upper zone	78	4.1	2.2	2.7
lower zone	49	6.6	3.0	2.9
basal zone	79	5.3	1.9	2.6
Flood basalts†				
CT 1 a	60 ± 7	4.4 ±1.0	2.3 ± 0.4	2.3 ± 0.1
CT 2	102 ± 9	3.9 ± 1.1	1.5 ± 0.3	2.6 ± 0.3
CT 3	105 ± 10	1.5 ± 0.5	1.3 ± 0.2	2.1 ± 0.2
CT 4	122 ± 1	0.9 ± 0.2	1.7 ± 0.1	5.5 ± 0.01

* Chondrite-normalized ratios (Sun & McDonough 1989).
† Values report average ± standard deviation. Data sources Luttinen *et al.* (1998) and Luttinen & Furnes (2000).

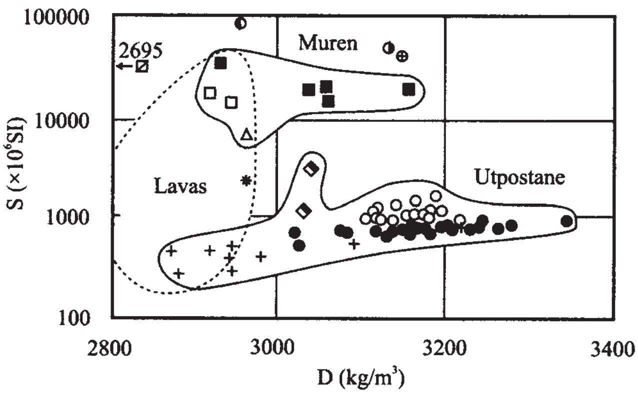

Fig. 9. Susceptibility and density data for representative gabbroic rocks, wall-rock basalts and a xenolith from Utpostane and Muren. Symbols are the same as in Fig. 8. Data sources: Tapio Ruotoistenmäki (personal communication 2001) and Ruotoistenmäki & Lehtimäki (1997).

Fig. 9. Full susceptibility and density data set is available from the first author on request.

Utpostane

Our new data on Utpostane define a broad trend with a positive correlation between magnetic susceptibility and density (Fig. 9). Overall, the Utpostane gabbros are characterized by a wide range of density coupled with fairly constant, low susceptibility values in comparison with basalts. Zone 1 and the gabbroic dyke plot above the main trend and have rather high susceptibility values (1190 × 10^6–3110 × 10^6 SI) that are comparable with those of typical basalts of Vestfjella (Ruotoistenmäki & Lehtimäki 1997), but the densities are somewhat higher (2960–3040 kg m^{-3}). Zone 2 gabbros define a relatively tight cluster with susceptibility and density ranges of 930 × 10^6–3180 × 10^6 SI and 3100–3220 kg m^{-3}, respectively. The leuco-gabbro of zone 3 records low susceptibilities (280 × 10^6–530 × 10^6 SI) and densities (2880–2980 kg m^{-3}) compared to the underlying olivine mela-gabbronorite (570 × 10^6–870 × 10^6 SI and 3090–3220 kg m^{-3}). The latter resembles the underlying gabbros of zone 4, which record a wide density range (3020–3340 kg m^{-3}) and include the densest rocks discovered from Vestfjella. Zone 4 is distinguished from zone 2 by low susceptibility (540 × 10^6–980 × 10^6 SI) at given density.

Muren

The Muren intrusion is typified by higher susceptibility values and a narrower density range than Utpostane (Fig. 9). Representative samples from the lower zone are almost identical. They have low density (< 2950 kg m^{-3}), but similar susceptibility compared to the olivine gabbro of the upper zone (15360 × 10^6–34580 × 10^6 SI), which records a wide density range (3040–3160 kg m^{-3}) due to variation in modal olivine content. Leuco-gabbro at the top of the upper zone is rather similar to the lower zone rocks, however. A gabbroic pegmatite from the lower zone records the highest susceptibility value of Muren intrusion (81260 × 10^6 SI). The basal zone has the lowest susceptibility (6650 × 10^6 SI) at Muren, but its density is comparable to those of the lower zone gabbros. The susceptibility value of the marginal felsic unit is indistinguishable from the values of Muren gabbros, but the density value (2670 kg m^{-3}) is distinctively lower.

Felsic dykes and wall-rock basalts

The felsic dykes that cut Utpostane and the lower zone of Muren have similar, distinctively low susceptibility (60 × 10^6 and 90 × 10^6 SI) and density (2570 and 2530 kg m^{-3}) values. The xenolith of Muren shows affinity to unmetamorphosed basalt lavas, although susceptibility (96070 × 10^6 SI) and density (2950 kg m^{-3}) are exceptionally high. The wall-rock basalts from Utpostane (45700 × 10^6 SI and 3140 kg m^{-3}) and east Muren (51450 × 10^6 SI and 3150 kg m^{-3}) are almost identical. They have quite similar susceptibilities compared to the xenolith, but the densities are markedly higher.

Petrogenesis

Utpostane

The geochemical trends of Utpostane (Fig. 6) can be largely explained by variable contents of cumulus olivine and plagioclase. Crossbedding and igneous lamination indicate that both dynamic and non-dynamic processes have been operating. Universal lamination, notably low contents of minor and accessory mineral phases and bending of minerals in zone 4 point to compression, strong adcumulus growth of minerals, and removal of interstitial residual liquids in partly crystallized magma. These processes can account for the universally low incompatible element contents in the Utpostane gabbros, even close to roof contact where residual liquids are expected to concentrate such elements. The effect of adcumulus growth on modal compositions and incompatible element concentrations is particularly clear in the leuco-gabbros and the nearly monomineralic anorthosites (Fig. 6, Table I). Folding and complex cutting relationships of some anorthosite veins indicate compression and deformation of solidifying crystal-liquid mush.

Zone 1 gabbros and the compositionally similar gabbroic dyke lack obvious cumulus textures and thus provide the best estimate of parental melt compositions for Utpostane. They are markedly more magnesian (MgO ~13 wt%) than the vast majority of Karoo basalts, which are evolved tholeiites with MgO < 7 wt% (Erlank 1984, Sweeney *et al.* 1994, Marsh *et al.* 1997, Harris *et al.* 1990, Luttinen & Furnes 2000). The high abundance of mafic glomerocrysts in zone 1 raises the question as to whether the parental melt

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was exceptionally high in MgO or a low-MgO melt with accumulated olivine phenocrysts (cf. Insizwa Complex: Scholtz 1937, Maske 1966, Eales 1980, Lightfoot & Naldrett 1983, Cawthorn & Groves 1985). The effect of possible olivine accumulation can be constrained by removing all modal olivine (~12%) from the whole-rock composition. Mass-balance calculation suggests that the MgO content of the melt was over 10 wt%. The harrisitic texture in the contact is also consistent with high-MgO melt composition (Cox *et al.* 1979). Utpostane, therefore, represents a voluminous emplacement of primitive magma rather similar to that recorded by the high-MgO dolerites of the Ahlmannryggen region (Harris *et al.* 1991) (Fig. 1).

The gradual enrichment of incompatible elements, the concomitant depletion of compatible elements, and the fairly uniform Ti/Zr (~80–100) from the base to the roof contact (Fig. 7) suggest that Utpostane may record a single differentiation cycle of homogeneous mantle-derived parental magma. Petrographical, mineralogical, and geochemical observations indicate that the intrusion consists mainly of cumulates and that the complementary residual liquids have been effectively removed, probably as dykes or lavas. Given the apparent thickness of ~3 km of the cumulate pile, the volume of tapped melts must be considerable. We envisage that Utpostane represents an open magma chamber, possibly a dyke-like conduit, which gradually grew thicker as a consequence of continuous crystal accumulation and flux of new magma from a deep parent magma reservoir. The sheet-like intrusion may well have acted as a major passage for ascending basaltic lavas in southern Vestfjella.

Incompatible element ratios can be used for a robust comparison between basalts and cumulates if the latter contain a fair amount of trapped intercumulus liquid. Previous studies of Vestfjella flood basalts and associated dolerites have established the usefulness of Ti/Zr, Th/Ta and $(La/Sm)_n$ for discriminating between different magmatic lineages in the region (Luttinen & Siivola 1997, Luttinen *et al.* 1998, Luttinen & Furnes 2000). Chemical type 1 is characterized by low Ti/Zr (< 70) and high Th/Ta (> 3) and $(La/Sm)_n$ (> 2.0) (Table IV). Chemical types 2 and 3 share high Ti/Zr (> 80) and low $(La/Sm)_n$ (< 1.8) but are distinguished on the basis of high (> 3) and low (< 2.3) Th/Ta, respectively. Chemical type 4 is a volumetrically minor intrusive type that has high Ti/Zr (> 120) and fairly high $(La/Sm)_n$ (~1.7) combined with low Th/Ta (< 1.5) (Luttinen *et al.* 1998). The Utpostane gabbros have high Ti/Zr (80–100) and low $(La/Sm)_n$ (1.6–2.0) typical of chemical types 2 and 3. High Th/Ta (> 3.7) lend support to correlation with chemical type 2 (Table IV).

Muren

At Muren, magmatic layering is rare and only occurs as pyroxene-rich stripes and bands adjacent to the eastern intrusive contact in the basal zone and in the lower zone immediately below the large xenolith. We consider that these bands record non-dynamic differentiation processes. Cumulation of olivine can account for the principal geochemical trends and the modal grading at the top of the upper zone. The underlying zones are compositionally fairly uniform.

The Muren gabbros can be grouped into two geochemically distinctive categories: low-SiO_2 and high-SiO_2 gabbros (Fig. 6), which characterize the upper zone and the lower zone, respectively. The low-MgO (5–8 wt%) gabbros at the top and the base of the upper zone and in the lower zone contain least cumulus olivine and thus provide the best estimate of parental melt compositions in each group. Geochemical comparison of the high-SiO_2 and low-SiO_2 types suggests different parental magmas. The upper zone and the basal zone are characterized by low SiO_2 (< 50 wt%) and near-chondritic, relatively high Ti/Zr values (> 69). In contrast, the lower zone has high SiO_2 (>50 wt%) coupled with notably low Ti/Zr (< 53). Titanium and zirconium have fairly similar, low mineral-melt distribution coefficients for olivine, plagioclase and pyroxene in basaltic systems (Rollinson 1993). Accordingly, differentiation of a gabbroic assemblage (cf. Cox 1980) is ineffective in producing marked changes in Ti/Zr. Fractionation of Fe-Ti oxides could facilitate a pronounced decrease in Ti/Zr and would also lead to an increase in SiO_2 in the residual melt. Alternatively, combined fractional crystallization and assimilation of felsic crustal material also leads to an increase in SiO_2 and decrease in Ti/Zr. An increase in Ti/Zr during differentiation of tholeiitic basaltic magmas is uncommon. Judging from the lower SiO_2 and higher Ti/Zr, the upper zone could therefore be parental to the lower zone, but the opposite is highly unlikely. The position of a more primitive rock type at the top of a more evolved type

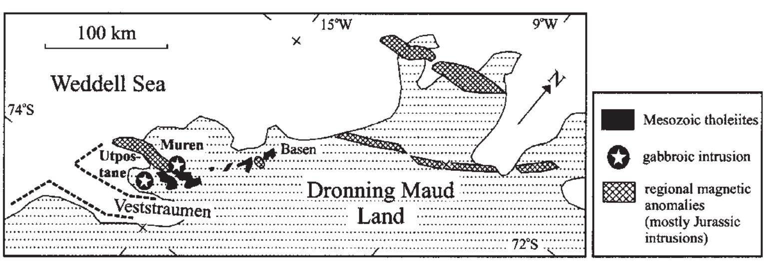

Fig. 10. Distribution of Middle Jurassic Vestfjella basalts, Utpostane and Muren gabbroic intrusions and regional magnetic anomalies in western Dronning Maud Land. (Modified after Corner (1994) and Ruotoistenmäki & Lehtimäki (1997)). Dotted line represents a possible graben-like offset of the Weddell Sea rift system.

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strongly implies two separate pulses of magma. The order of emplacement of different magmas is presently undefined.

The predominance of olivine cumulates in the upper zone indicates removal of complementary residual liquids. These may have been emplaced as dykes or lavas, but it is also possible that the marginal felsic unit records remnants of a significant segregation of highly evolved residual liquid.

Low Ti/Zr values (44–53) coupled with high $(La/Sm)_n$ value (3.0) and Th/Th (6.6) link the lower zone gabbros to the chemical type 1 basalts of Vestfjella, whereas gabbros of the upper and basal zones (Ti/Zr 69–105, $(La/Sm)_n$ 1.9–2.2 and Th/Ta 4.1–5.3) show broad affinities to the Utpostane gabbros and chemical type 2 of Vestfjella (Table IV). Judging from their high $(La/Sm)_n$ values, however, both types may represent transitional types between chemical types 1 and 2.

Felsic rocks and interaction of gabbros with country rocks

The marginal felsic unit of the Muren intrusion is markedly different from the granitic dykes that cut Muren and Utpostane. The marginal felsic unit is metaluminous, "sodic" ($Na_2O > K_2O$), relatively low in SiO_2 (dacitic), and has affinities to Muren gabbros with respect to moderate $(La/Sm)_n$ (2.6) and $(Sm/Lu)_n$ (2.4) values and the overall chondrite-normalized REE-pattern (Fig. 8b). We regard it to contain a major component of late-stage fractionates of the underlying gabbros. The granite dykes are peraluminous, "potassic" ($K_2O > Na_2O$), high in SiO_2 (rhyolitic), and strongly enriched in the light REE relative to the heavy REE, and their chondrite-normalized REE-patterns exhibit a pronounced negative Eu anomaly (Fig. 8c). Such features indicate that the granites are partial melts of wall-rocks, possibly Permian sedimentary rocks that underlie the Jurassic lava sequence (Luttinen & Furnes 2000) or sandstone interbeds between the flood basalt flows.

The contact basalts of both intrusions and the xenoliths at Muren and Utpostane exhibit distinctive light REE-depleted chondrite-normalized patterns (Fig. 8c). The presence of metamorphic olivine and small felsic segregations adjacent to the intrusive contacts indicates extreme contact metamorphic temperatures (> 800°C) (Tracy & Frost 1991). Collectively, the evidence suggests removal of incompatible-element-enriched partial melt from the contact basalts and xenoliths.

Regional considerations

Aeromagnetic and ground-based geophysical measurements suggest several unexposed pluton-size mafic intrusions in Vestfjella and adjacent area. Ruotoistenmäki & Lehtimäki (1997) have reported a 10 km wide and at least 10 km long magnetic and gravity anomaly on the south-western side of Basen (Fig. 10). Other highly magnetic anomalies occur in the nunatak-free area north of Vestfjella (Corner 1994, Leitchenkov *et al.* 1996) as well as in southern Vestfjella (Fig. 10). More specifically, Corner (1994) has reported a large positive aeromagnetic anomaly WSW of Muren and interpreted it as a mafic intrusion. This large anomaly (~400 km^2) partly overlaps the Muren intrusion suggesting that Muren may be a satellite or a part of a notably larger intrusion, possibly a cone sheet similar to the Jurassic Eureka dolerite of Tasmania (Spry 1958). The Utpostane area, on the other hand, is distinguished in aeromagnetic maps by a marked negative anomaly (Corner 1994). It is uncertain as to whether this anomaly is the negative component of the above-mentioned positive anomaly or records subsurface presence of gabbros with low susceptibility.

The data on the gabbroic Muren and Utpostane intrusions complement the picture of the Jurassic rifted continental margin of western Dronning Maud Land. Utpostane and Muren represent two surface exposures of the several geophysically defined mafic plutons that comprise a 350 km long series of intrusions along the continental margin of western Dronning Maud Land (Fig. 10). The plutons and the abundant coast-parallel dolerites are presumably the result of high intrusive activity in the Vestfjella region during the Middle Jurassic. Specifically, SW–NE trending dolerite dykes immediately east of the Muren gabbro indicate 14% of crustal stretching.

Overall, the association of flood basalts and different kinds of intrusions in Vestfjella is quite similar to that of the East Greenland rifted margin (Brooks & Nielsen 1982), where abundant mafic intrusions are closely related to Tertiary continental break-up magmatism (Tegner *et al.* 1998a). In Greenland, emplacement of MORB-type magmas occurred some 5–10 Ma after low-Ti flood basalt magmatism (Tegner *et al.* 1998a, Bernstein *et al.* 1998). The geochemical compositions and field relationships of the basalts and dykes of Vestfjella indicate that, as in Greenland, low-Ti (chemical type 1) magmatism gradually gave way to MORB-like (chemical type 2) magmatism (Luttinen & Furnes 2000). Bearing in mind the geochemical affinities of the Muren (chemical type 1) and Utpostane (chemical type 2) gabbros and the numerous (chemical type 2-like) crosscutting dolerites at Muren, it is probable that Muren is somewhat older than Utpostane.

Ratios of REE have been widely used as monitors of residual mantle mineralogy during partial melting and generation of basaltic magma (e.g. Tegner *et al.* 1998b). Compared to the Muren gabbros and the basalts of Vestfjella, the Utpostane gabbros have notably lower $(Sm/Lu)_n$ values (Table IV) and probably record low-pressure melting of garnet-free peridotite within a zone of thinned lithosphere.

Evidence of rifting and lithospheric thinning is abundant in western Dronning Maud Land. Geophysical measurements reveal a more than 500 km long graben system that extends south-west from Jutulstraumen towards the Weddell Sea (Ravich & Solov'ev 1966, Hungeling & Thyssen 1991). In addition, orientation of mafic dykes, faults and joints indicate broadly east–west trending crustal lineaments that also control ice flow patterns and the underlying bedrock topography (Hjelle & Winsnes 1972, Spaeth & Schüll 1987, Grantham & Hunter 1991, Marsh 1991).

A radio-echo sounding profile across Veststraumen shows Utpostane to be located on the fringe of a more than 40 km wide and 800 to 1000 m deep subglacial topographic low (Holmlund *et al.* 1992). We suggest that this topographic feature is the remnants of a graben structure, possibly a Middle Jurassic failed rift arm that extended eastward from the main rift system along the Weddell Sea margin in proximity to the junction of East Antarctica, Africa and the Falkland Plateau (Figs 1a & 10). Assuming that Muren predates Utpostane, as suggested above, the two intrusions with different REE patterns may record successive mantle melting events beneath a subordinate triple junction that was located between the Weddell Sea and Limpopo triple junctions (Elliot & Fleming 2000) during the early stages of Gondwana break-up.

Conclusions

Utpostane and Muren represent the only presently known exposures of Jurassic gabbroic intrusions in Dronning Maud Land, Antarctica. The plutons crosscut sub-horizontal basalt lavas in Vestfjella and form an integral part of the previously recognized Karoo-related continental flood basalt succession of Dronning Maud Land. Utpostane is an inclined sheet-like intrusion with minimum thickness of ~3 km. It consists mainly of MgO-rich (20–25 wt%) olivine gabbronorite and olivine mela-gabbronorite that can be grouped to four major zones (1–4) using modal and textural criteria. Variations in major element oxides reflect modal mineralogy and the amount of cumulus olivine in particular. Incompatible elements show gradual enrichment from zone 4 at the base to zone 1 at the top. Zone 1 gabbros close to the roof contact lack obvious cumulus textures and indicate that the parental magma of Utpostane was unusually primitive (MgO ~13 wt%) compared to typical Karoo tholeiites.

Muren is also an inclined sheet-like intrusion. Field observations indicate total thickness of the gabbroic sheet to be ~1.3 km. Muren can be divided into two major units: the upper zone and the lower zone, which consist mainly of olivine gabbro and gabbronorite, respectively. Differentiation of olivine in the upper zone has led to enrichment of incompatible elements from the base towards the capping granophyre, which is designated as the marginal felsic unit. In contrast, the lower zone is homogeneous and compositionally resembles basaltic country rocks. It is underlain by the narrow basal zone, which consists mainly of olivine gabbro. Overall, Muren represents an emplacement of typical low-MgO Karoo magmas. The upper and lower zones had compositionally distinct parental melts, however.

Utpostane and Muren are the only two exposures of several geophysically defined mafic plutons that comprise a 350 km long series of intrusions along the continental margin of western Dronning Maud Land. The plutons and the abundant coast-parallel dolerites suggest high intrusive activity in the Vestfjella region during the Middle Jurassic time. Based on geochemical affinities, the intrusions represent shallow-level magma chambers and possible feeder systems of basalt lavas belonging to chemical types 1 (Muren) and 2 (Utpostane) of Vestfjella. Comparison of $(Sm/Lu)_n$ values suggests that the parental magma of Utpostane was generated at lower pressure than those of Muren and the associated basalts, possibly as a result of progressive lithospheric thinning during the initial stages of Gondwana break-up.

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