The geochemistry of Middle Jurassic dykes associated with the Straumsvola – Tvora alkaline plutons, Dronning Maud Land, Antarctica and their association with the Karoo large igneous province

T. R. RILEY[1*], M. L. CURTIS[1], P. T. LEAT[1] AND I. L. MILLAR[2]

[1] British Antarctic Survey, Natural Environment Research Council, Madingley Road, High Cross, Cambridge CB3 0ET UK

[2] NERC Isotope Geosciences Laboratory, Keyworth, Nottingham, NG12 5GG, UK

*E-mail: t.riley@bas.ac.uk

Abstract

Jurassic dykes of western Dronning Maud Land (Antarctica) form a minor component of the Karoo large igneous province. An extensive local dyke swarm intrudes Neoproterozoic gneisses and Jurassic syenite plutons on the margins of the Jutulstraumen palaeo rift in the Svedrupfjella region. The dykes were intruded in three distinct episodes (~204 Ma, ~176 and ~170 Ma). The 204 Ma dykes are overwhelmingly low-Ti, olivine tholeiites including some primitive (picritic) compositions (MgO >12wt%; Fe_2O_3 > 12wt%; Cr >1000 ppm; Ni >600 ppm). This 204 Ma event precedes the main Karoo volcanic event by ~25 Myr, so any correlations to the wider province are difficult to make. However, it may record the earliest phase of rift activity along the Jutulstraumen. The 176 Ma dyke event is more intimately associated with the two syenite plutons. The dykes are alkaline (basanite/tephrite) and were small degree melts from an enriched, locally derived source and underwent at least some degree of interaction with a syenitic contaminant. This ~176 Ma dyke event is widespread elsewhere in the Karoo (southern Africa and Dronning Maud Land). Later stage (170 Ma) felsic (phonolite – comendite) dykes intrude the 176 Ma basanite – tephrite suite and represent the last phase of magmatic activity in the region.

KEYWORDS:

Gondwana, basanite, tephrite, phonolite, syenite, rift

Introduction

The Early to Middle Jurassic Karoo igneous province of southern Africa and its former conjugate margin, now represented by western Dronning Maud Land in East Antarctica (Marsh et al., 1997; Le Gall et al., 2002), exposes thick tholeiitic continental flood basalts that were erupted within a 3 – 4 Myr period at ~ 182 Ma (Riley and Knight, 2001). In addition to the voluminous flood basalts (Marsh et al., 1997), the Karoo igneous province is characterised by several giant dyke swarms (Jourdan et al., 2004; Riley et al., 2005), sill complexes (Galerne et al., 2008) and alkaline intrusions (Harris et al., 1990).

This paper provides the first detailed geochemical study of a significant suite of Karoo-age mafic-silicic dykes that intrude two Jurassic syenite plutons and their country rock Neoproterozoic gneisses in the Svedrupfjella region of western Dronning Maud Land (Fig. 1). The syenites range from Si-undersaturated (Straumsvola pluton) to Si-oversaturated (Tvora pluton) and this compositional diversity is reflected in the dykes, which range from basaltic to highly undersaturated foidites, and from Si-undersaturated phonolite to comendite (Harris and Grantham, 1993). The most differentiated rocks are peralkaline, Si-oversaturated rocks (trachytes and comendites). We examine the magma evolution that lead to the development of these compositions from dominantly Si-undersaturated mafic magmas.

The syenite plutons (Straumsvola and Tvora) form two of three Mesozoic alkaline bodies associated with the Jutulstraumen (a 20 – 50 km wide, north – south oriented present day ice stream), which is interpreted as a major, now inactive rift system (Ferraccioli et al., 2005a, b) that may represent a continuation of the East African rift system into Antarctica (Grantham and Hunter, 1991). The syenite plutons of Straumsvola and Tvora were intruded at ~180 Ma (Grantham et al., 1988) on the rift shoulders of the Jutulstraumen. The third syenite pluton in the region is the Sistefjell intrusion (Harris et al., 2002), which crops out further south along the Jutulstraumen ice stream (Fig. 1).

The dykes that intrude the syenite plutons and country rock gneisses are discussed in terms of their geochemistry, geochronology and orientation in an attempt to establish a chronology for the dyke suites and establish the magma source regions and magma evolutions.

This paper is one of a series that describe the results of the British Antarctic Survey 'Magmatism as a monitor of Gondwana break-up' project that investigates the volcanic history of the Dronning Maud Land area and its relationship to the Karoo large igneous province (Riley et al., 2005; Ferraccioli et al., 2005a, b; Leat et al., 2007; Curtis et al., 2008).

Previous work

As part of the South African National Antarctic Program, there have been numerous previous visits to the Straumsvola region (see Harris and Grantham, 1993). Workers have examined the Straumsvola alkaline complex (Harris and Grantham, 1993), the basement geology (Grantham et al., 1988) and the dyke suites of the surrounding Svedrupfjella region (Harris and Grantham, 1993; Grantham, 1996). Previous investigations on the dykes of western Svedrupfjella identified two orientations of dykes: a NE striking suite and a dominant WNW striking suite. Grantham (1996) attempted to correlate the dyke suites with regional tectonic events associated with the early stages of Gondwana break-up.

Curtis et al. (2008) have examined the structural geology and magma flow properties of over 500 dykes from two regions in western Svedrupfjella (Straumsvola and Jutulrøra; Fig. 1). They interpreted that one group of dykes around Straumsvola were sourced via vertical magma flow from a local magma centre and that they form one branch of a local radiating dyke swarm. They interpreted a second group of dykes around Jutulrøra to be older, and magma flow studies demonstrated that these possessed a significant component of lateral magma transport from a source close to Straumsvola, and opened in response to east-west extension.

Geological Setting

The geology of western Dronning Maud is summarised in Figure 1 (inset), and can be subdivided into two distinct geological provinces. The Grunehogna province, which occupies the Ahlmannryggen, Borg Massivet, and Straumsnutane areas, together with outlying nunataks to the west, is characterised by weakly metamorphosed and deformed sedimentary and volcanogenic rocks of the Neoproterozoic Ritscherfjella Supergroup that have been extensively intruded by large-scale tholeiitic sills and dykes of the Borgmassivet Intrusions (Wolmarans and Kent, 1982). The Borgmassivet Intrusions have been dated by several methods and are considered to lie within an age range of 900 – 1100 Ma (Wolmarans and Kent, 1982; Moyes et al., 1995). The basement to the Ritscherfjella Supergroup is considered to be Archaean age granitoids, similar to those exposed at Annandagstoppane in the west (Barton et al., 1987). The close similarity of basement and supracrustal geology between the Grunehogna and Zimbabwe – Kaapvaal (southern Africa) provinces suggest that both areas formed part of a contiguous crustal province from Archaean time until the Mesozoic break-up of Gondwana (Groenewald et al., 1991). To the south and east of the Grunehogna Province lie the Kirwanveggen and Svedrupfjella regions that form part of the Mesoproterozoic Maudheim province, an extension of the Namaqua – Natal metamorphic province of southern Africa (Jacobs et al., 1993), which is formed of amphibolite to granulite facies gneisses of the Svedrupfjella Group (Groenewald et al., 1995). Adjacent to the inferred boundary of the Grunehogna craton, the Svedrupfjella Group is dominated by hornblende biotite orthogneiss (Jutulrøra Formation).

The crustal boundary between these two distinct geological provinces lies unexposed beneath the Pencksokket and Jutulstraumen ice streams. However, a recent high-resolution aeromagnetic survey suggests that this boundary has been reactivated along the Jutulstraumen ice stream by a continental rift that was either amagmatic along its axis or contains a thick sedimentary succession (Ferraccioli et al., 2005a, b).

Basaltic lavas and minor intrusions of Early – Middle Jurassic age crop out at several localities in western Dronning Maud Land. Flood basalt lavas are exposed at Vestfjella, Heimefrontfjella and Kirwanveggen and their intrusive equivalents are exposed at Vestfjella, Ahlmannryggen, Heimefrontfjella, Svedrupfjella and Kirwanveggen (Fig. 1). Recent ^{40}Ar-^{39}Ar dating of the geochemically diverse Jurassic dykes from the Ahlmannryggen area record the presence of two distinct episodes of dyke emplacement at ~190 and ~178 Ma (Riley et al., 2005), spanning the emplacement of the Karoo large igneous province (LIP) as a whole. These two distinct dyke sets trend parallel to the local boundaries of the Grunehogna craton, i.e. subparallel to the Jutulstraumen and Pencksökket (Fig. 1) subglacial troughs (Riley et al., 2005) supporting the inference of Ferraccioli et al. (2005b) that continental rifting along the Jutulstraumen trough was Mesozoic in age. The presence of ferropicrite and picrite dykes, with their high Ti, Cr, Ni and depleted isotopic evidence suggests that many of the Ahlamanryggen dykes were sourced from great depth, corroborating the involvement of a depleted component of a mantle plume in the generation of the Karoo LIP (Riley et al., 2005). Along the eastern flank of the inferred Jutulstraumen rift are numerous mafic dykes that intrude hornblende-biotite amphibolite gneisses of the Jutulrøra Formation, as well as an associated nepheline-quartz syenite complex (Harris and Grantham, 1993). It is these dykes that are discussed here.

Detailed (1km line spacing) aerogeophysical investigations (Fig. 2) over the Jutulstraumen (Ferraccioli et al., 2005a,b) show that beneath the ice it is a distinct trough-like structure up to ~50 km wide and ~600 m deep in the north (72° S) shallowing to ~300 m deep near the junction with the smaller Pencksokket trough. Three-dimensional inversion of gravity data indicates a minimum of 10 km of crustal thinning under the northern part of the Jutulstraumen rift, assuming an original crustal thickness the same as that calculated beneath Svedrupfjella, to 27 km crustal thickness over Straumsnutane (Fig. 2). Significant crustal thinning is also interpreted from the gravity inversions under the Jutulstraumen trough as far south as 73° 30' S, and under the Pencksokket trough to 4° W. Both the Pencksokket and Jutulstraumen troughs are therefore interpreted as lithospheric rifts. Aeromagnetic data show that the axis of the Jutulstraumen trough is characterised by a marked magnetic low, contrasting with a large, broad magnetic high over Svedrupfjella and high frequency magnetic highs over the cratonic Ahlmannryggen and Borg Massviet areas. Straumsvola and Tvora correlate with distinct magnetic highs, up to 308 nT over Straumsvola (Fig. 2) and 271 nT over Tvora. The syenitic intrusion complexes are interpreted to be the sources of the anomalies (Ferraccioli et al., 2005b). A larger 889 nT) positive magnetic anomaly overlies Straumsnutane, possibly indicating a further Jurassic igneous complex in the northern part of the rift (Ferraccioli et al., 2005b). The linear magnetic low along the axis of the rift is interpreted to image sediments within the rift structure (Ferraccioli et al., 2005b). No lavas at similar or higher structural levels as the Jurassic intrusive complexes are imaged by the aeromagnetic data and the rift is therefore interpreted to be magmatically 'dry', with Jurassic magmatism restricted to the alkaline complexes and limited dyke swarms (Ferraccioli et al., 2005b; Leat et al., 2007; Curtis et al., 2008).

Syenite complexes

Jurassic intrusions in Svedrupfjella vary in composition from Si-undersaturated alkaline intrusions at Straumsvola, to Si-saturated syenites at Tvora and Sistefjell (Harris and

Grantham, 1993; Harris et al., 2002). Geochronology of the intrusions has yielded a range of ages, but the best estimates for the Straumsvola pluton are in the range, 174 – 180 Ma (Grantham et al., 1988), although an age of >178 Ma is interpreted based on cross-cutting dolerite dykes (Curtis et al., 2008). The Tvora syenite has yielded an $^{40}Ar/^{39}Ar$ (hornblende) age of 183 ± 2 Ma, although Grantham et al. (1988) regarded this as a reset age and favoured a 207 ± 5 Ma (Rb-Sr) age. The Sistefjell syenite (Fig.1) has been dated (Rb-Sr mineral/whole rock) at 173 ± 2Ma (Harris et al., 2002).

The Straumsvola alkaline complex is well exposed and approximately 7 km in diameter (Fig. 3) and intrudes Neoproterozoic banded gneisses of the Jutulrøra Formation. The pluton is, on the whole, relatively structureless, coarsely crystalline nepheline syenite, comprising a massive outer zone and a layered inner zone, which consists of a 350 m thick sequence where layering is defined by varying amounts of alkali feldspar and mafic minerals. Petrographically the syenites from both the outer and inner zones are dominated by alkali feldspar, nepheline (rarely haüyne) and variable quantities of mafic minerals (Na clinopyroxene, amphibole and biotite) (Harris and Grantham, 1993).

The Tvora complex crops out at the nunatak Tvora (Figures 1 and 3) and consists of a quartz syenite (Harris and Grantham, 1993) pluton approximately 3 km in diameter, which intrudes gneisses of the Jutulrøra Formation (Svedrupfjella Group). Very little previous fieldwork has been carried out on the Tvora pluton and its associated dyke swarm.

The detailed aeromagnetic data of Ferraccioli et al., (2005b) are consistent with the outcrop information in that the peak anomalies directly overlie the syenite outcrops (Fig. 2) and define wider concentric anomalies some 14 km across, which we interpret as indicating the extent of the complexes.

Dyke Swarms

Both syenite bodies and also the gneisses of the Jutulrøra Formation are extensively intruded by mafic (and to a lesser extent, felsic) dykes. Field evidence indicates that the dykes were emplaced both before and after the intrusion of the syenite plutons. The dykes are concentrated close to the syenite plutons and are also abundant in the Jutulrøra group of nunataks (Fig. 1). However further east towards Roerkulten (Fig. 1) there is a sharp decline in the number of exposed dykes. Ferraccioli et al. (2005b) identified the presence of a significant sub-syenitic mafic body, which extends beneath both Tvora and Straumsvola, but does not extend as far as the Jutulrøra nunataks.

Harris and Grantham (1993) assumed that the dykes intruding the Straumsvola syenite were associated with the Straumsvola complex and were not part of the regional Mesozoic tholeiite suite. This assumption by Harris and Grantham (1993) could be supported by the geophysical work of Ferraccioli et al. (2005b) who have identified a sub-pluton mafic body.

Dyke orientation and composition

A total of 561 dykes were recorded in the field and variously sampled within the Straumsvola, Tvora and Jutulrøra nunatak groups (Fig. 3). A detailed structural study of these dykes is provided by Curtis et al. (2008), but for the purposes of this study we include a summary. Overall, the total dyke population have a pronounced NNW-SSE trend (Fig. 3 inset) with a subcomponent of ENE-WSW trending dykes. The majority (>80%) of the dykes are doleritic, they are commonly feldspar phyric, possessing vesicular centres and displaying glassy chilled margins. Phonolite dykes account for ~10% of the total dykes observed (n=561) and are generally green/grey in colour, porphyritic, with feldspar and nepheline phenocrysts, (in some cases displaying flow banding). Associated with the phonolite dykes are a suite of other felsic dykes. Typically the phonolites are the final intrusive phase of the entire dyke population, cross-cutting dolerite dykes and syenitic pegmatites.

At Straumsvola, and the neighbouring nunataks of Joungane and Storjoen (Fig. 3), over 300 dykes were recorded, approximately half (n=172) of which intruded the nepheline syenite. The geometry of the dyke populations within and outside of the Straumsvola nepheline syenite pluton show marked differences. Within the pluton, dykes of almost every orientation are present, although there is a general trend toward NE-SW orientations (Fig. 3), whilst outside the pluton the dykes have a preferred orientation of ~160° (Fig. 3). The inclination of the dykes inside the pluton is also highly variable with almost half dipping relatively shallowly at <60°, whilst outside they dip more steeply (>70°), with sharp intrusive contacts with the gneisses.

88 dykes were recorded along a complete traverse of the ridges of Tvora, intruding both the gneissic country rocks and the syenite pluton. The Tvora dykes have a pronounced NNW-SSE trend with a subordinate E-W trending component. In general, the dyke population is steeply inclined with 84% dipping at >60°. Dyke width varies from 0.04 to 7.5 m. There are no significant differences between the geometry of dyke populations within or outside the Tvora pluton.

Approximately 15 km south of Straumsvola along the eastern margin of the Jutulstraumen ice stream are the two large nunataks of Jutulrøra (Fig.1). The nunataks are composed of orthogneisses of the Jutulrøra Formation (Svedrupfjella Group), which are intruded by at least 135 dykes. Aeromagnetic data indicates that there are no mafic bodies beneath the ice within the immediate vicinity of Jutulrøra (Ferraccioli et al., 2005b). The Jutulrøra dyke swarm is characteristically N-S (~170°) trending (Fig. 3) and steeply inclined, with 85% of dykes dipping at >60°, with widths varying from 0.04 to 22m. The dykes are overwhelmingly doleritic in composition, weathering a red/brown colour and generally display well-developed cooling joints perpendicular to the dyke margins. The dolerites often have vesicular centres, which are commonly reduced to friable scree, whilst the chilled margins remain intact.

Petrography

The dolerite dykes of the Svedrupfjella region typically have a fine-medium grained texture and are feldspar-phyric. Rare phenocrysts of augite and unaltered olivine can also be identified in hand specimen. The plagioclase phenocrysts are set in a groundmass of smaller plagioclase, augite and Fe-Ti oxides. Minor amounts of apatite, pyrite and biotite are sometimes present. The dykes typically have an intergranular and/or subophitic texture involving euhedral plagioclase laths and anhedral or equant augite crystals. At least one third of the samples contain olivine, which in most cases is altered or corroded, although relatively fresh cores are preserved in some cases and some grains retain their euhedral habit. Olivine replacement minerals include iddingsite, carbonate and serpentine. The dykes typically show an aphyric chilled margin at the contact with the host country rock.

The phonolites are typically finer grained, with phenocrysts of sanidine, nepheline and aegirine set in a green-grey groundmass of the same composition. The nepheline phenocrysts are up to 3mm in diameter and, in part, have a pseudo ‘perthitic’ texture, which may be an intergrowth of kalsilite and nepheline.

Geochronology

Previous work

Until recently there was only limited pre-existing geochronology of the dyke swarms of Straumsvola and Tvora. Grantham et al. (1998) reported $^{40}Ar/^{39}Ar$ (plagioclase) ages in the range 172 – 199 Ma, but there was no geochemical or structural control reported on the samples selected for analysis.

However, Curtis et al. (2008) have recently published $^{40}Ar/^{39}Ar$ (whole rock) age data from eight samples from the Straumsvola – Tvora – Jutulrøra region (Fig. 3). The samples chosen provide the best possible spread based on the geographical and structural information. The data are additionally presented here (Fig. 4).

Summary of recent work by Curtis et al. (2008)

The geochronological data presented by Curtis et al. (2008) reveals the presence of three temporally distinct dyke emplacement events that are also geographically distinct. At Jutulrøra nunataks, two dykes intruding the Jutulrøra Formation orthogneisses yield whole rock ages of 206.1 ± 2.6 and 203.8 ± 2.8 Ma. A third tholeiite dyke sample intruding Jutulrøra Formation gneisses at Straumsvola yields an isochron age of 201.5 ± 15.8 Ma. This dyke emplacement event predated the emplacement of the Straumsvola nepheline syenite. Another generation of dyke emplacement is recorded in the interval 174.8–178.5 Ma (Fig. 4) by four samples of mafic dykes, two of them intrude the Straumsvola syenite pluton, which has been dated at 178–180 Ma (Grantham et al., 1998). A third sample intrudes the country rock gneiss adjacent to the Straumsvola syenite, whilst the fourth sample is from a dyke intruding the neighbouring Tvora quartz syenite pluton. Sample Z.1911.7 is a late stage phonolite dyke, also from the Straumsvola pluton and has a whole rock age of 170.9 ±1.7 Ma, which is significantly younger than the mafic dyke suite, that it crosscuts. This date provides an upper age constraint on the duration of magmatism within the Straumsvola intrusive suite. Although the results of Curtis et al. (2008) broadly support those of Grantham et al. (1998) who also suggested that magmatism within the region was long lived (170–206 Ma), the data of Curtis et al. (2008) reveals that the mafic component of the entire dyke population is actually composed of two temporally distinct dyke emplacement events. In recognition of this, we will refer to the 175–178 Ma alkaline dykes that intrude the Straumsvola and Tvora syenite plutons as the Straumsvola dyke swarm, and the 206–204 Ma tholeiite dykes that predominate within the country rock gneisses as the Jutulrøra dyke swarm (Curtis et al., 2008).

A summary of the geochronology of the region is presented in Fig. 5, where the 175 – 178 Ma event overlaps with an event widespread elsewhere in the Karoo Volcanic Province (e.g. Le Gall et al., 2002; Zhang et al., 2003; Riley et al., 2005, 2006)

Geochemistry

Analytical techniques

Powders for geochemical analysis were prepared from 2 – 3 kg of fresh rock. Samples were reduced to pass a 1700 μm sieve using a hardened steel fly press. The powders were produced using an agate Tema-mill. Sr and Nd isotope compositions were measured at the NERC Isotope Geosciences Laboratory (Keyworth, UK) on a Finnigan-MAT 262 mass-spectrometer. Rb-Sr and Sm-Nd analysis followed procedures described by Pankhurst & Rapela (1995) and Riley et al. (2003). Sr isotope composition was determined in multidynamic peak-jumping mode. During the period of analysis, 22 analyses of the Sr isotope standard NBS987 gave a value of 0.710259 ± 0.000008 (2 sigma errors). Nd-isotope composition was determined in static collection mode. Twenty-four analyses of the in-house J&M Nd isotope standard gave a value of 0.511196 ± 0.000022 (2 sigma errors); reported $^{143}Nd/^{144}Nd$ values were normalised to a value of 0.511130 for this standard, equivalent to 0.511864 for La Jolla.

Major and selected trace element whole rock analysis was by standard XRF techniques at the Department of Geology, University of Keele, following the methods described in Floyd (1985). Higher precision trace element abundances were determined by ICP-MS at the University of Durham. The analytical methods, precision, and detection limits are detailed in Ottley *et al.* (2003).

Classification

There are three groups of dykes that have identified based on their composition, field occurrence and age data, 1) 204 – 206 Ma Jutulrøra tholeiitic dyke swarm, 2) 175 – 178 Ma Straumsvola alkaline dyke swarm (Curtis et al., 2008), and 3) 170 – 171 Ma Straumsvola – Tvora felsic dykes (this study). Full major, trace element and Sr-Nd isotope data of the entire dyke population are reported in Table 1. The analysed dykes from the Straumsvola dyke swarm are almost all alkaline (Fig. 6) and range in composition from alkali basalt/basanite/tephrite to phonolite and basalt to trachyte. The analysed samples from the Jutulrøra dyke swarm are typically subalkaline, overwhelmingly basaltic in composition and overlap with the field of quartz tholeiites from the nearby Ahlmannryggen region (Riley et al., 2005). The Straumsvola dyke swarm dykes are basanite – tephrite in composition based on their normative olivine content (basanite >10% normative olivine; tephrite <10% normative olivine).

When the data for the alkaline dykes from the Straumsvola dyke swarm are plotted against MgO (wt%) as an index of differentiation, Ni is strongly correlated with MgO (Fig. 7) suggesting olivine control during magmatic differentiation. Al_2O_3 increases as MgO decreases suggesting that plagioclase fractionation is not important, until MgO contents fall below 5%. Elements such as Zr, Y, TiO_2 all show broad negative correlations with MgO (Fig. 7).

The dykes of the Straumsvola dyke swarm can be separated into those that intrude the syenite and those that intrude the neighbouring country rock Jutulrøra Formation gneiss. The data are plotted using Na_2O +K_2O vs. Zr (Fig. 8), which demonstrates a distinction between the two groups. Those dykes intruded outside the pluton into the Jutulrøra Formation gneisses have characteristically low total alkali contents (<6%) and Zr contents typically <100 ppm. Whilst those intruded inside the syenite have higher Na_2O + K_2O (> 6wt%) and Zr >160 ppm. There is a group of seven dykes, which are intruded close to, but outside the pluton and have chemical characteristics akin to those intruded into the syenite. This group of seven dykes coincides with the small array of dykes in the outside pluton rose diagram (Fig. 3), which shows a small cluster with a strike direction of ENE and include the dated sample, Z.1904.3 (174.7 ± 1.7 Ma), all of which are interpreted as being part of the 178 – 175 Ma group (Straumsvola dyke swarm).

The Straumsvola dyke swarm dykes that intude the Tvora pluton shows a similar range in total alkali content and Zr to those Straumsvola dykes intruded inside the pluton (Fig. 8). There appears to be no consistent differences in dyke composition between those dykes intruded inside or outside of the Tvora syenite pluton. The age of sample Z.1919.5 from Tvora is 178.5 ± 1.5 Ma is considered to be representative of the alkaline dykes at Tvora, with the exception of the small group of ~160° striking dykes (Fig. 3), which are interpreted as part of the Jutulrøra dyke swarm (204 – 206 Ma).

The mafic dykes of the Jutulrøra dyke swarm are low-Ti-Zr tholeiitic basalts and chemically similar to the Group 1 quartz tholeiite dykes (Fig. 6) of the neighbouring Ahlmannryggen (Fig. 1) region (Riley et al., 2005) and also overlap with the subset of outside-pluton dykes from Straumsvola (Fig. 8). A small proportion of the Jutulrøra dykes are mildly alkaline in character, but on the whole, they are distinct from the tephrite – basanite suite from Straumsvola and Tvora. Several of the Jutulrøra dykes have near primary compositions, with MgO in the range 13 – 17 wt%, Cr contents up to 1300 ppm and Ni contents >500ppm (Fig. 7).

A separate intrusive phase consists of the phonolite – trachyte - commendite dykes of Straumsvola and Tvora (Straumsvola – Tvora felsic dykes). They are green/grey in colour and are feldspar – feldspathoid phyric. At least 12 dykes were identified at Straumsvola and they are seen to cross-cut the basanite – tephrite dykes, which is consistent with the phonolites' younger age (~170 – 171 Ma). The phonolites have high SiO_2 (up to 69 wt%), high alkali (typically 12 – 13wt% $Na_2O + K_2O$) and high incompatible element concentrations (Sr, Ba, Zr, La; Table 1).

REE chemistry

The rare earth element (REE) concentration of the different dyke groups are shown in Fig. 9. The Straumsvola dykes (175 – 178 Ma) intruded into the nepheline syenite form a tightly clustered group with strong enrichment in the light (L) REE (La/Yb_N ~ 18) and La_N values of almost 300. The group of six dykes that are intruded outside the nepheline syenite, but chemically overlap with the 'inside pluton' dykes also have the REE characteristics of the 'inside pluton' dykes (Fig. 9a). Whereas all other 'outside pluton' dykes (assumed to be 204 – 206 Ma) have flatter REE patterns (La/Yb_N ~ 7) and La_N values in the range 30 – 90 (Fig. 9b).

The alkaline dykes of Tvora (175 – 178 Ma) have REE patterns with strong enrichment in the LREE (La/Yb_N in the range 15 – 25) and La_N up to 400 (Fig. 9c). They broadly overlap with the alkaline dykes intruded inside the Straumsvola pluton although they exhibit a greater range at Tvora. A single analysed dyke from Tvora (Z.1924.4) has a much flatter REE pattern (Fig. 9c), which is also the same dyke that has low $Na_2O + K_2O$ and low Zr (Fig. 8). The dyke also forms part of a small group of dykes at Tvora, which have a strike direction of

~160° (Fig. 3), akin to the 'outside pluton' dykes of Straumsvola and are also assumed to be part of the 204 – 206 Ma suite.

The REE patterns of the Jutulrøra dykes are relatively flat, with La/Yb_N in the range 3 – 10 (Fig. 9d). They are similar to those dykes that are intruded outside the Straumsvola pluton and the Tvora sample, Z.1924.4, and all have a similar strike direction (~160° – 170°; Fig. 3). All of these dykes are interpreted to have been intruded in the interval, 204 – 206 Ma.

The REE patterns of the phonolite and felsic dykes are shown in Fig. 9e and are characterised by high La_N values (>700) and pronounced, but variable negative Eu anomalies (Eu/Eu* ~ 0.17).

Sr-Nd isotopes

The Straumsvola dykes (~178 Ma) have εNd_i values typically in the range -8 to -10 (Fig. 10), with $^{87}Sr/^{86}Sr_i$ exhibiting more variation (0.705 – 0.710; Fig. 10). The older (~204 Ma) dykes of the Jutulrøra dyke swarm have isotope characteristics distinct to the 178 Ma group (εNd_i: -2 to -5) and $^{87}Sr/^{86}Sr_i$ in the range, 0.7055 – 0.7065, although two samples from the ~204 Ma suite have positive εNd_i values (0.1 to 0.6) and $^{87}Sr/^{86}Sr_i$ of ~0.707.

The Straumsvola – Tvora phonolites (171 Ma) have εNd_i values also distinct to the basanite/tephrite dykes, with values in the range, -11 to -13. Their $^{87}Sr/^{86}Sr_i$ values are enriched and highly variable (0.709 – 0.724), but overlap in part, with the Straumsvola alkaline dykes. Only four of the analysed phonolites are plotted in Fig. 10, with those samples with $^{87}Sr/^{86}Sr_i$ >0.715 omitted to show greater detail for the other analyses.

Petrogenesis

The dyke suites of the Svedrupfjella region fall into three distinct groups: (1) the 204 – 206 Ma Jutulrøra dyke swarm tholeiites (including dykes from Straumsvola and Tvora that intrude the gneisses), (2) the 175 – 178 Ma Straumsvola alkaline dyke swarm (basanite/tephrite dykes) that intrude the syenite complexes and also the gneisses close to the syenite margins, and (3), the 170 – 171 Ma Straumsvola – Tvora phonolite (and other felsic) dykes.

Jutulrøra dyke swarm (204 – 206 Ma tholeiites)

The ~204 Ma Jutulrøra tholeiites are abundant (>100) across the Jutulrøra group of nunataks (Fig. 1) where they intrude Neoproterozoic orthogneisses of the Jutulrøra Formation (Svedrupfjella Group). They are also abundant across the Straumsvola nunatak group where they again intrude Jutulrøra Formation gneisses, but do not intrude the Straumsvola nepheline syenite, which they predate. At least one probable 204 Ma dyke has been identified at Tvora based on major and REE geochemistry, although structural information (~160° strike) suggests that several ~204 Ma dykes may intrude the orthogneisses of Tvora.

The ~204 Ma Jutulrøra dykes are low-Ti (typically <2wt%), low-Zr (typically <200 ppm) rocks and have near or subchondritic Zr/Hf ratios (Fig. 11). They also have Nb/Nb* (= $[Nb_N/\sqrt{(Th_N \times La_N)}]$ values of ~0.6, consistent with the involvement of crustal material and/or lithospheric mantle in their petrogenesis. They are, in some respects, akin to the 190 Ma (Group 1) dykes of the nearby Ahlmannryggen region (Riley et al., 2005), although this group of dykes has undergone a degree of post-magmatic alteration. The ~204 Ma tholeiites are all parallel to the Jutulstraumen subglacial rift at 160 – 170° and their intrusion may mark the onset of rift activity in the area, whereas the 190 Ma dykes of the neighbouring Ahlmannryggen region strike ~070°, which is parallel to the Pencksokket subglacial trough (Fig. 1), which is also thought to represent a major graben-like structure, active at the same time as the Jutulstraumen rift.

The petrogenesis of the 190 Ma dykes of the Ahlmannryggen region have been, in part, attributed to the role of a mantle plume, early in the history of the Karoo large igneous province (Riley et al., 2005), but it is difficult to confidently extrapolate any plume involvement in the 204 Ma event. Although there is geochemical evidence indicating a deep/primitive source (e.g. high MgO, Fe_2O_3, Cr, Ni) for at least some of the 204 Ma magmatism, it is ~25 Myr prior to the main Karoo event at ~180 Ma and although it is now generally believed that flood basalt provinces can have a prolonged history (Jerram and Widdowson, 2005; Riley et al., 2006) the timescale in Dronning Maud Land is too lengthy to make any robust correlations between the two events.

However, if the ~204 Ma dykes do record magmatism associated with the onset of rift activity along the Jutulstraumen, more importantly this may also mark the very early stages of Gondwana rifting prior to eventual break-up.

Straumsvola dyke swarm (175 – 178 Ma alkaline dykes)

The 175 – 178 Ma alkaline dykes that intrude the nunataks of Straumsvola and Tvora (Fig. 3) are overwhelmingly seen to cross-cut the nepheline and quartz syenite plutons, although a small group intrude into the adjacent country rock orthogneisses of the Jutulrøra Formation.

The dykes intruding the Straumsvola and Tvora plutons have no preferred orientation (Fig. 3) and restricted opening direction, although the small group of 175 – 178 Ma alkaline dykes that intrude the adjacent gneisses have a consistent 075° trend. This is interpreted to indicate high magma pressure equal to the maximum principal stress (Curtis et al., 2008). Aerogeophysical work by Ferraccioli et al. (2005a,b) has demonstrated the presence of two localised positive magnetic anomalies (Fig. 2) and gravity highs, suggesting that a highly localised intrusive complex underlies both alkaline plutons. Moreover, recent work by Curtis et al. (2008) on the anisotropic magnetic susceptibility (AMS) fabrics of the alkaline dyke suites demonstrated dominance of inferred sub-vertical magma flow in the Straumsvola dyke swarm, further suggesting that mafic magma was locally sourced. No such mafic body has been geophysically identified (Fig. 2) beneath the Jutulrøra nunatak group and AMS data from dykes of the Jutulrøra dyke swarm indicate magma flow was sub vertical in the Straumsvola area and predominantly laterally fed in the Jutulrøra area (Curtis et al., 2008) although no absolute flow direction was determined. Such flow patterns combined with the structural characteristics of the Jutulrøra swarm were interpreted as indicating the ~204 Ma dykes were sourced from the Straumsvola – Tvora sub-plutonic mafic magma bodies suggesting a long-lived mafic reservoir.

Although the 175 – 178 Ma dyke swarm of Straumsvola and Tvora is interpreted to have been locally sourced, the dyke event is contemporaneous with a more widespread Karoo Volcanic Province event at 175 – 178 Ma (Fig. 5). Curtis et al. (2008) interpret it to form one structural component of a ~178 Ma radiating dyke swarm in western Dronning Maud Land with other components in the Ahlmannryggen (Riley et al., 2005), Kirwanveggen and Vestfjella (Zhang et al., 2003), and extensively across southern Africa (Botswana, southern Lebombo and Rooi Rand; Le Gall et al., 2002, Jourdan et al., 2004), where dyking and extensive lava flows are reported. The 175 – 178 Ma Straumsvola – Tvora dykes are unusual amongst dyke swarms of the Karoo Volcanic Province as they are dominantly alkaline instead of tholeiitic. Therefore, a key question is to resolve whether the alkaline dykes of Straumsvola and Tvora represent localised alkaline melts from the lithospheric mantle or if they are contaminated tholeiitic melts. One of the 178 Ma dykes (Z.1904.3) that intrudes the country rock Jutulrøra Formation gneiss has many geochemical characteristics typical of the ‘inside pluton’ dykes with the exception of its isotope values ($^{87}Sr/^{86}Sr$: 0.7067; εNd: -3.7), which are more typical of the ~204 Ma dykes. The implication is that those 178 Ma dykes intruded outside the margins of the syenite body have not undergone significant interaction with a syenite melt/crystal mush. This would imply that the margins of the syenite body are steeply inclined. Therefore, the magma source for the ~204 and ~178 Ma dyke events was likely to be very similar in composition, although the dykes have subsequently undergone very different crustal processes. Using a 204 Ma Jutulrøra dyke (e.g. Z.1932.1) as a starting composition for an uncontaminated dyke and modelling AFC (EC-RAFC; Spera and Bohrson, 2004) with a syenitic (phonolitic) contaminant (Table 2), at least, some of the variability observed in the Straumsvola – Tvora alkaline dykes can be modelled (Fig. 10), particularly if combined with variable crustal contamination. Some of the compositions at lower $^{87}Sr/^{86}Sr$ values (<0.7065) for a given εNd value (-7) are more difficult to interpret.

The range in composition of the Straumsvola mafic dykes and their REE abundance is the result of variation in partial melting, with the Jutulrøra dykes resulting from higher degree melts, relative to the basanite/tephrite dykes of Straumsvola – Tvora, which were smaller degree melts from a presumed enriched source. Fig. 11 shows Zr/Hf vs Zr, with samples separated into three groups (Straumsvola, Tvora, Jutulrøra). The Jutulrøra dykes all have near chondritic Zr/Hf ratios and are interpreted to be higher degree partial melts relative to the alkaline dykes of Straumsvola. The enriched (superchondritic) Straumsvola dykes with Zr/Hf >35 are very low degree partial melts. All of the dykes that plot at subchondritic values (<35) are intruded outside of the Straumsvola syenite pluton (Fig. 11) into the Jutulrøra Formation gneisses and are depleted melts from the mafic source that presumably followed the melting event that generated the 204 Ma Jutulrøra dyke swarm as defined by Curtis et al. (2008). Also, the single dyke from Tvora with Jutulrøra-like characteristics is sub-chondritic.

Straumsvola – Tvora phonolite and felsic dykes (170 – 171 Ma)

Approximately 10% of the 150 dykes that intrude the nepheline syenite at Straumsvola are phonolitic or trachytic in composition. They are seen to cross-cut the basanite/tephrite dykes, but are in turn cross-cut by a small number of other silicic (comendite, trachyte) dykes. The phonolites are K-feldspar-nepheline phyric and are presumed to be relatively close to a syenitic melt composition. Three phonolites were also identified at Tvora and several were also seen to intrude the country rock gneiss. The Straumsvola – Tvora felsic dykes are generally sodic, but include both over- and undersaturated rock types, which is rare in a single eruptive centre (Macdonald et al., 1995).

Isotopically, the phonolites are extremely enriched (εNd ~ -12 and $^{87}Sr/^{86}Sr$ ~ 0.709 – 0.724) and point to the involvement of crustal material in their petrogenesis. Any crustal involvement would almost certainly involve the leucocratic orthogneisses of the Jutulrøra Formation (Svedrupfjella Group). There is limited isotopic data available for the gneisses of the Jutulrøra Formation, but data from Grantham et al. (1998) has been recalculated to 178 Ma and yields isotopic values of $^{87}Sr/^{86}Sr$ ~ 0.716 and εNd ~ -20 (Fig. 10). Crustal rocks with these isotopic values certainly make the Jutulrøra Formation gneisses a potential crustal contaminant of the phonolites. The phonolites typically contain a number of orthogneiss xenoliths.

Conclusions

- Three distinct generations (~204, ~178, ~171 Ma) of dyke emplacement have been identified in the Svedrupfjella region.
- The 202 – 206 Ma event (Jutulrøra dyke swarm) was probably related to the earliest phase of rifting along the Jutulstraumen subglacial trough. The dyke suites exposed at Jutulrøra and Straumsvola intrude orthogneisses of the Jutulrøra Formation and are

strike-parallel (160° – 170°) to the Jutulstraumen rift. The dykes are typically low Ti-Zr tholeiites and were sourced from a local magma body underlying the Straumsvola – Tvora nunataks, with those dykes exposed at Jutulrøra showing evidence of lateral magma flow.

- The interval 175 – 178 Ma is marked by the intrusion of the Straumsvola nepheline syenite and the Tvora quartz syenite bodies (>178 Ma), followed by the emplacement of numerous (>500 exposed) alkaline (basanite/tephrite) dykes dated in the interval, 175 – 178 Ma. The dykes (Straumsvola – Tvora dyke swarm) are interpreted to have been sourced from a mafic magma body beneath the Straumsvola – Tvora syenite bodies, which was also the probable source for the 204 – 206 Ma dyke event. Some of the variation in the basanite – tephrite suite can be explained by AFC with a syenitic contaminant.
- At 170 – 171 Ma there is the final expression of magmatism in the area. A relatively minor episode of phonolite dyking intrudes the nepheline and quartz syenite plutons, and also cross-cuts the alkaline dykes of Straumsvola and Tvora. This event is also coupled with the emplacement of other silicic (e.g. comendite) dykes. The phonolite dykes exhibit varied chemistry and are generally more SiO_2-rich and mafic-poor compared to the nepheline syenites they intrude (Harris and Grantham, 1993). The phonolites and silicic dykes are also associated with fenitisation of the country rock gneiss and indicate that the Straumsvola – Tvora plutons were still magmatically and hydrothermally active up to 8 Myr after emplacement.

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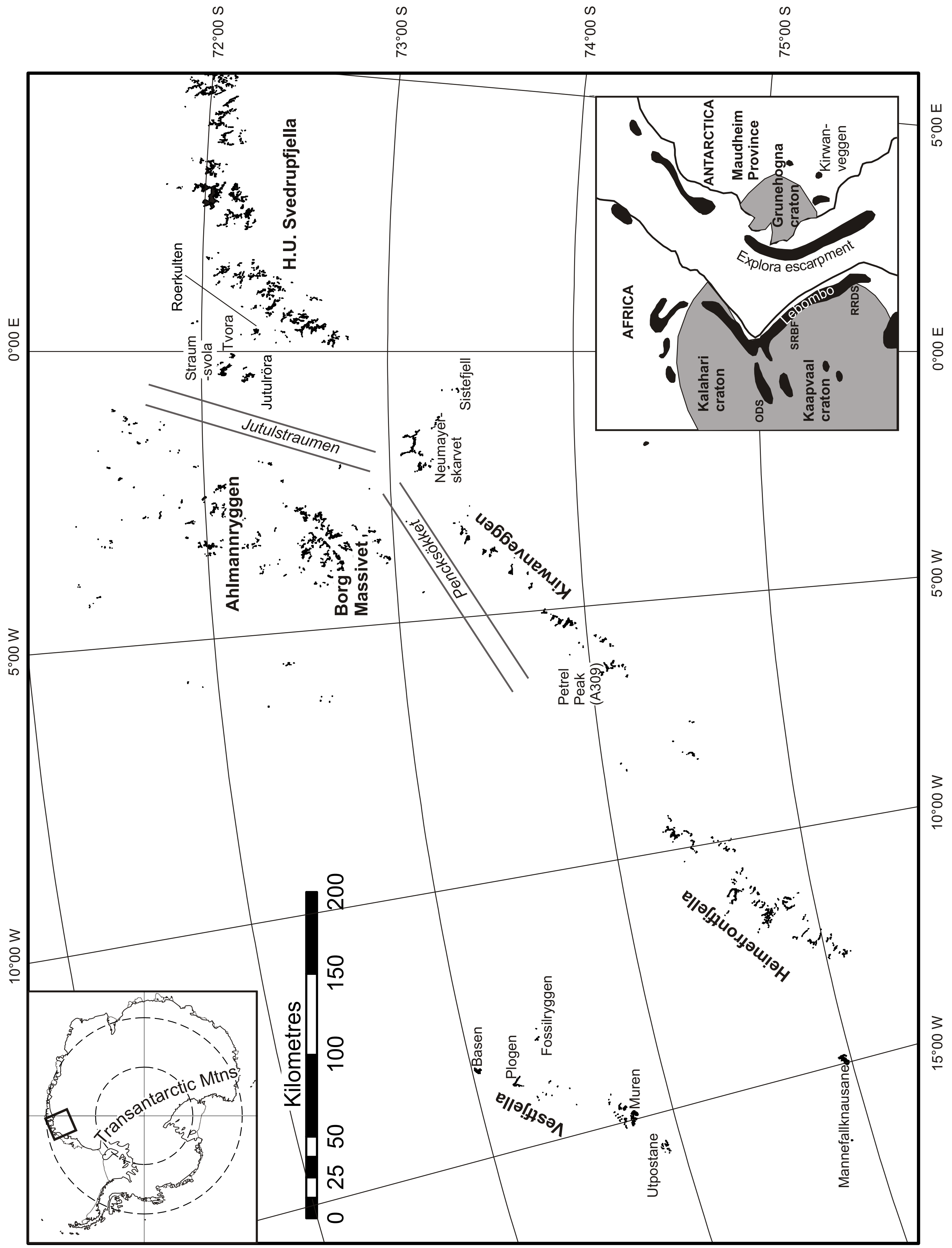
List of Figures

1. Location map of rock outcrops in western Dronning Maud Land (Antarctica) from Vestfjella to H.U. Svedrupfjella, including the location of the Jutustraumen and Pencksökket subglacial troughs. The inset is a pre-break-up Gondwana reconstruction of Africa and Antarctica showing the extent of the Kaapvaal-Grunehogna craton and the outcrop of Early – Middle Jurassic age Karoo igneous rocks (after Luttinen & Furnes, 2000). ODS, Okavango dyke swarm; SRBF, Sabi River Basalt Formation; RRDS, Rooi Rand dyke swarm. After Riley et al. (2005). The region of western Dronning Muad Land shown is situated on the boundary between the Grunehogna craton and the Maud Province in the reconstruction.
2. Total Magnetic Intensity map for the Jutulstraumen Rift region (Ferraccioli et al., 2005b). The Jutustraumen Rift is marked by a prominent linear aeromagnetic low. In contrast, both rift flanks feature magnetic highs. High-frequency aeromagnetic patterns on the western flank relate mainly to the Borgmassivet Intrusives, while the longer wavelength Sverdrupfjella aeromagnetic anomaly on the eastern flank may relate to buried Grenvillian-age arc crust. Discrete anomalies overlie the Jurassic alkaline intrusions of Straumsvola and Tvora. A high amplitude anomaly over Straumsnutane delineates a major intrusion of unknown age (possibly Jurassic). Similar features are not detected beneath the Jutulstraumen rift axis. White lines are major aeromagnetic lineaments interpreted as delineating sub-ice faults.
3. Geometry of dykes intruding a) the nepheline syenite pluton at Straumsvola, b) the country rock surrounding the Straumsvola pluton, c) Tvora quartz syenite and immediate country rocks, d) Jutulrøra nunataks. The dyke population in each sub area are represented by frequency vs. orientation (rose) diagrams.

4. ^{39}Ar release spectra for samples Z.1904.3, Z.1911.4, Z.1911.7, Z.1919.5, Z.1926.6, Z.1933.3, Z.1928.3 and Z.1902.7 (Curtis et al., 2008). Seven samples generated a plateau that satisfied the key criteria for reliable age data, (1) multiple (3 or more) concordant step ages comprising >50% of the total gas released, (2) concordant plateau and isochron ages, (3) low MSWDs (<3) for plateau and isochron ages. Sample Z.1902.7 failed to satisfy these criteria.
5. Geochronology summary of selected dyke suites from the Karoo Volcanic Province. Data from Riley et al. (2005, 2006); Le Gall et al. (2002); Jourdan et al. (2004); Zhang et al. (2003); this study.
6. Total alkali vs. SiO_2 diagram (wt%) for the Svedrupfjella dyke suite. Classification boundaries are from Le Bas et al. (1986).
7. Variations in Al_2O_3, TiO_2, Ni, Y and Zr vs. MgO for the Svedrupfjella dyke swarm.
8. $Na_2O + K_2O$ vs. Zr for dyke populations from Straumsvola (inside and outside pluton), Tvora and Jutulrøra.
9. Chondrite (Nakamura, 1974) normalized REE diagrams for Svedrupfjella dykes.
10. Initial εNd and $^{87}Sr/^{86}Sr$ for Svedrupfjella dykes relative to fields from elsewhere in western Dronning Maud Land. Data sources: Harris *et al*. (1990); Riley *et al*. (2005). Data are normalised to an initial value at 178 or 204 Ma. Groups 1 – 4, Dronning Maud Land geochemical groups 1 – 4 (Riley et al., 2005). The model curve is derived using the EC-RAFC model of Spera & Bohrson (2004) employing a syenitic contaminant (phonolite) as an end member (Table 2).
11. Zr/Hf vs. Zr diagram for dykes from Straumsvola, Tvora and Jutulrøra. The chondritic value of Zr/Hf is shown as ~35 (Eggins et al., 1997). The depleted (sub chondritic) values are mostly outside pluton dykes from Straumsvola.



Riley et al.
Fig. 1

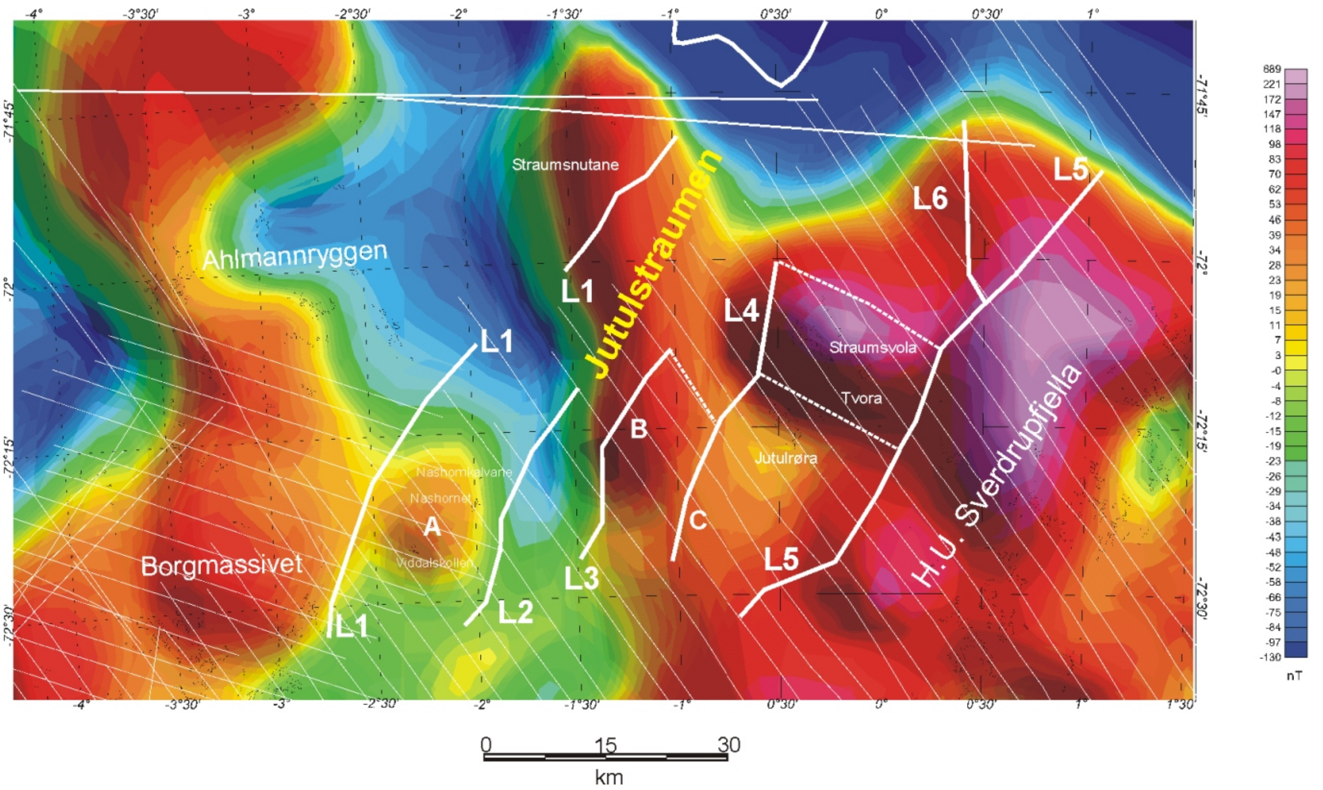


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Fig. 2

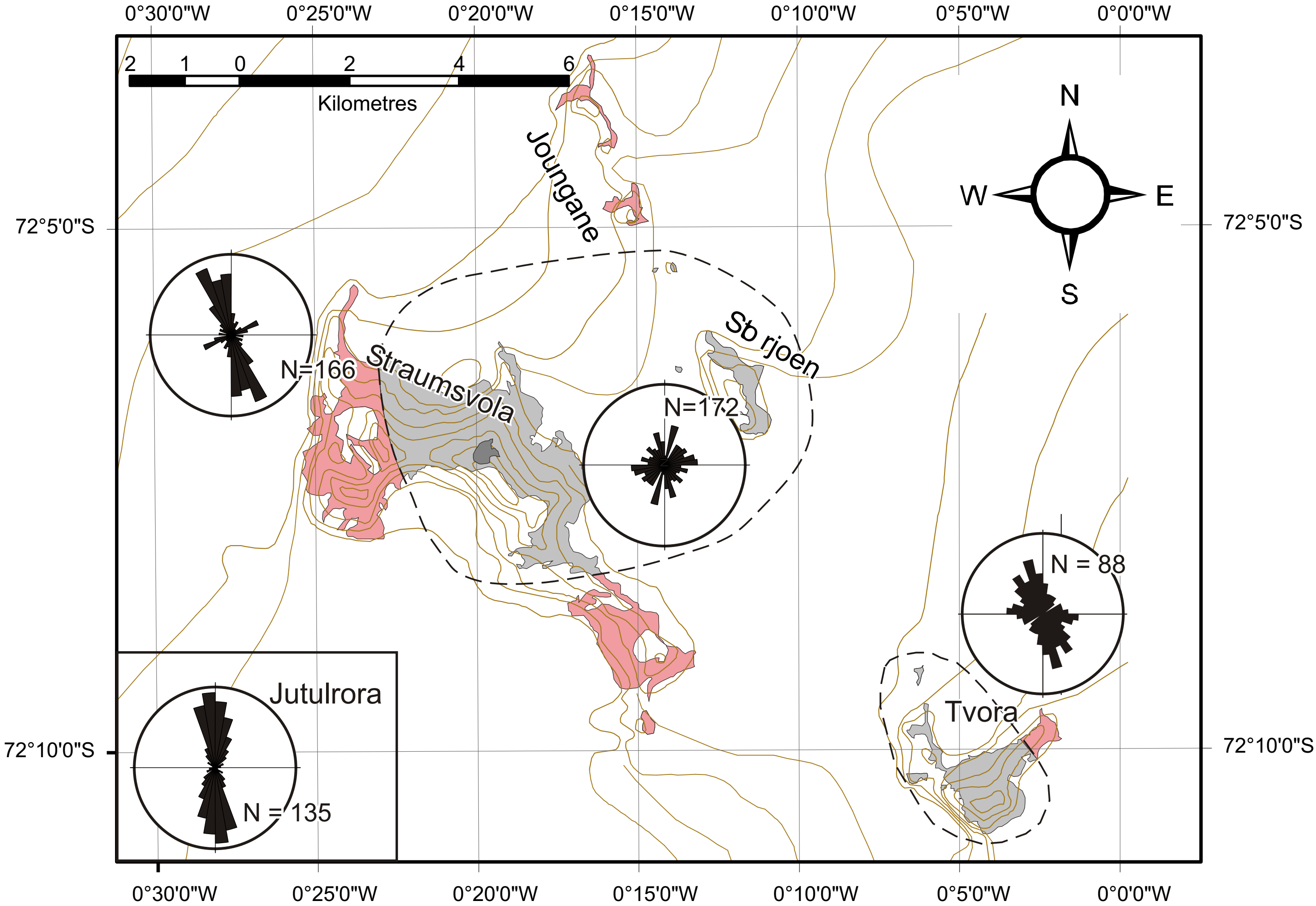

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Fig. 3

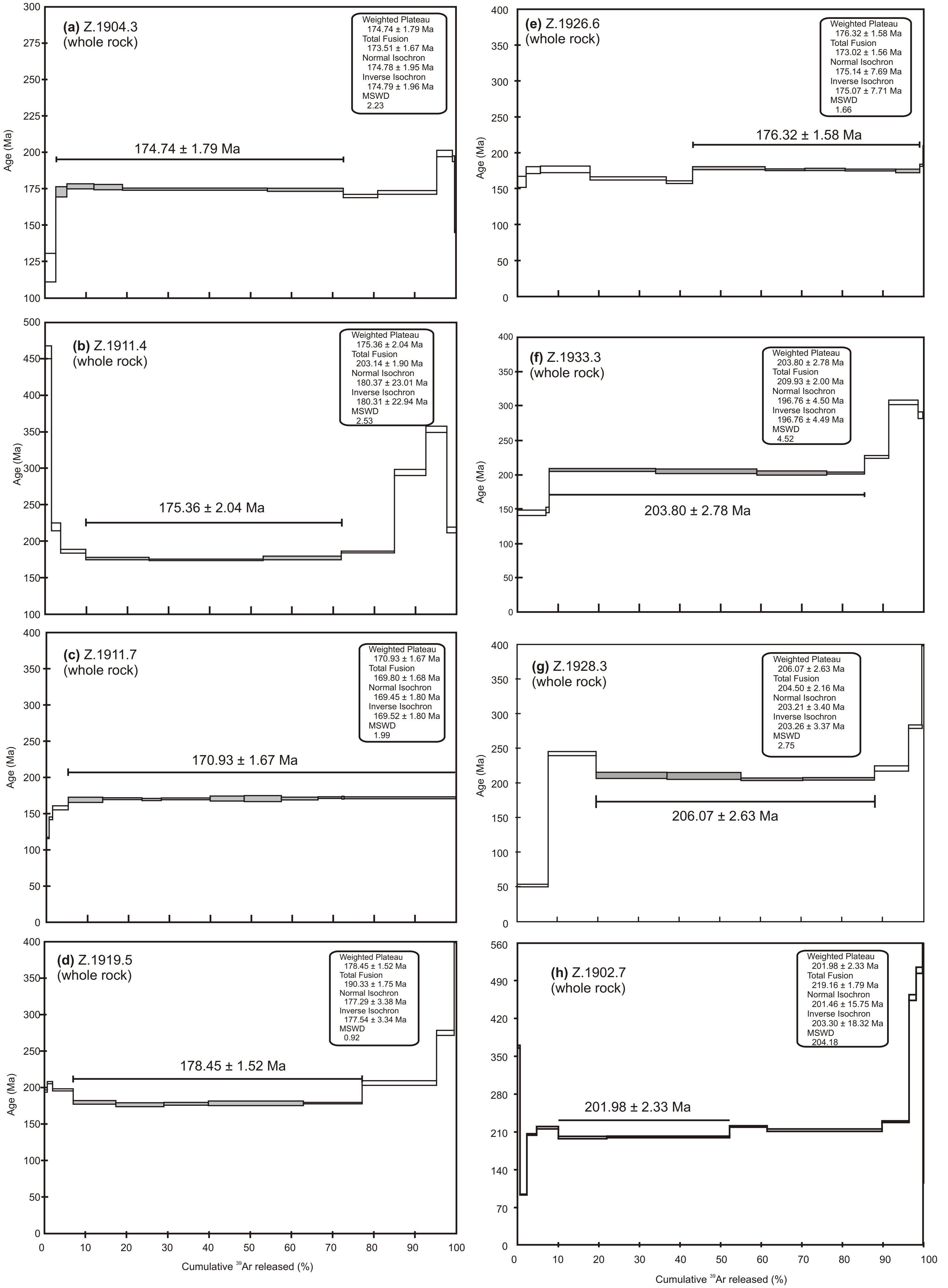

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Fig. 4

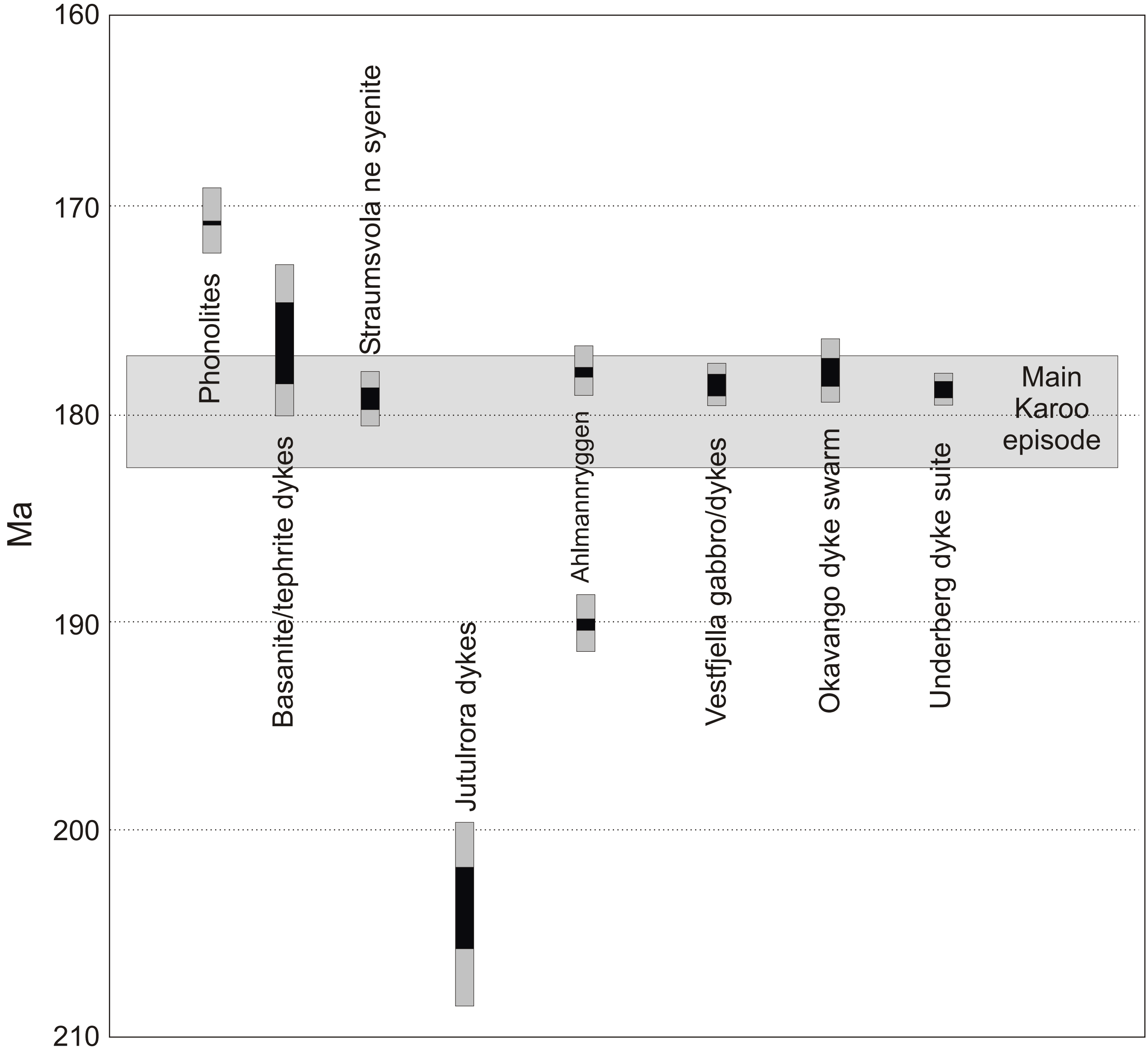

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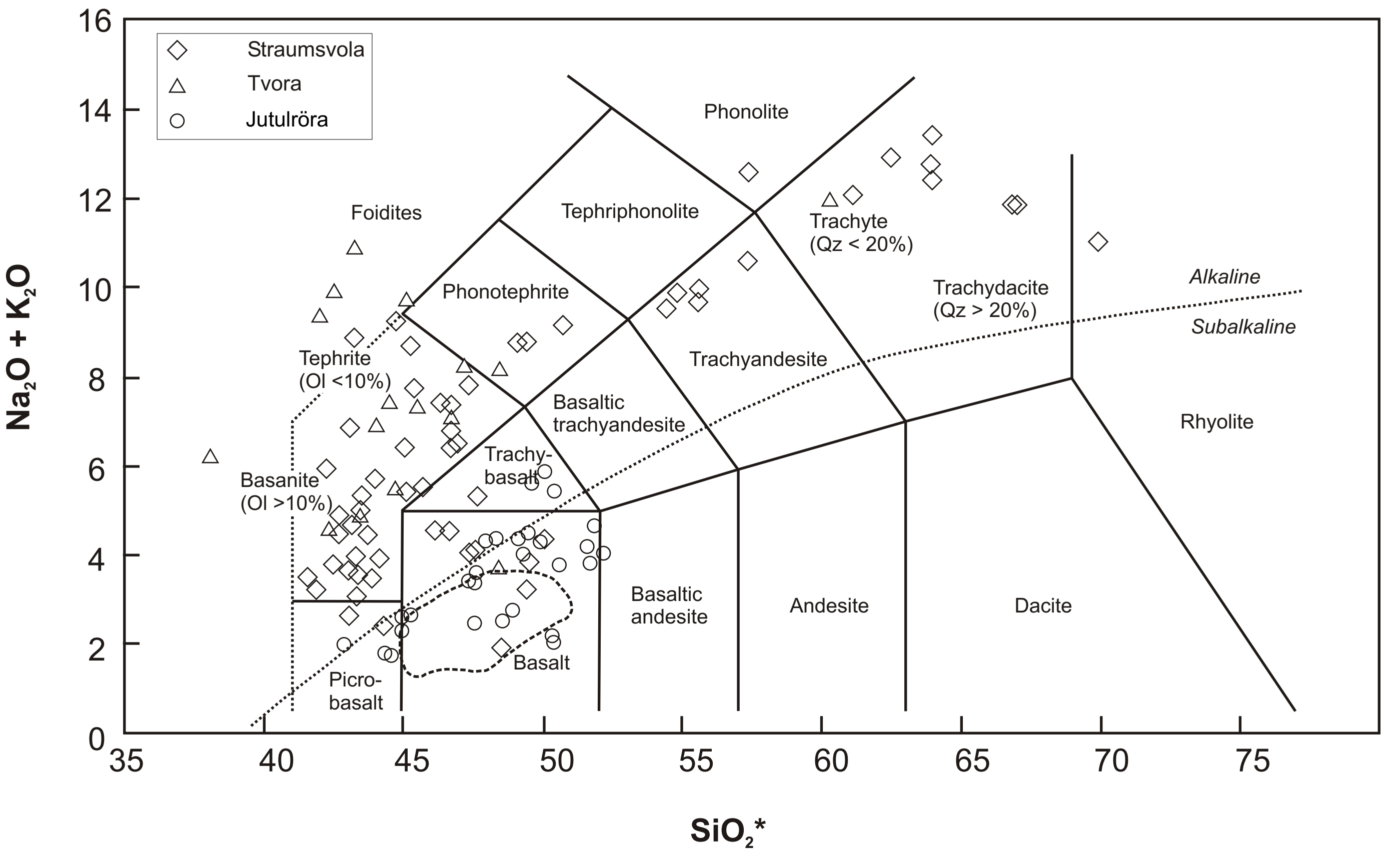
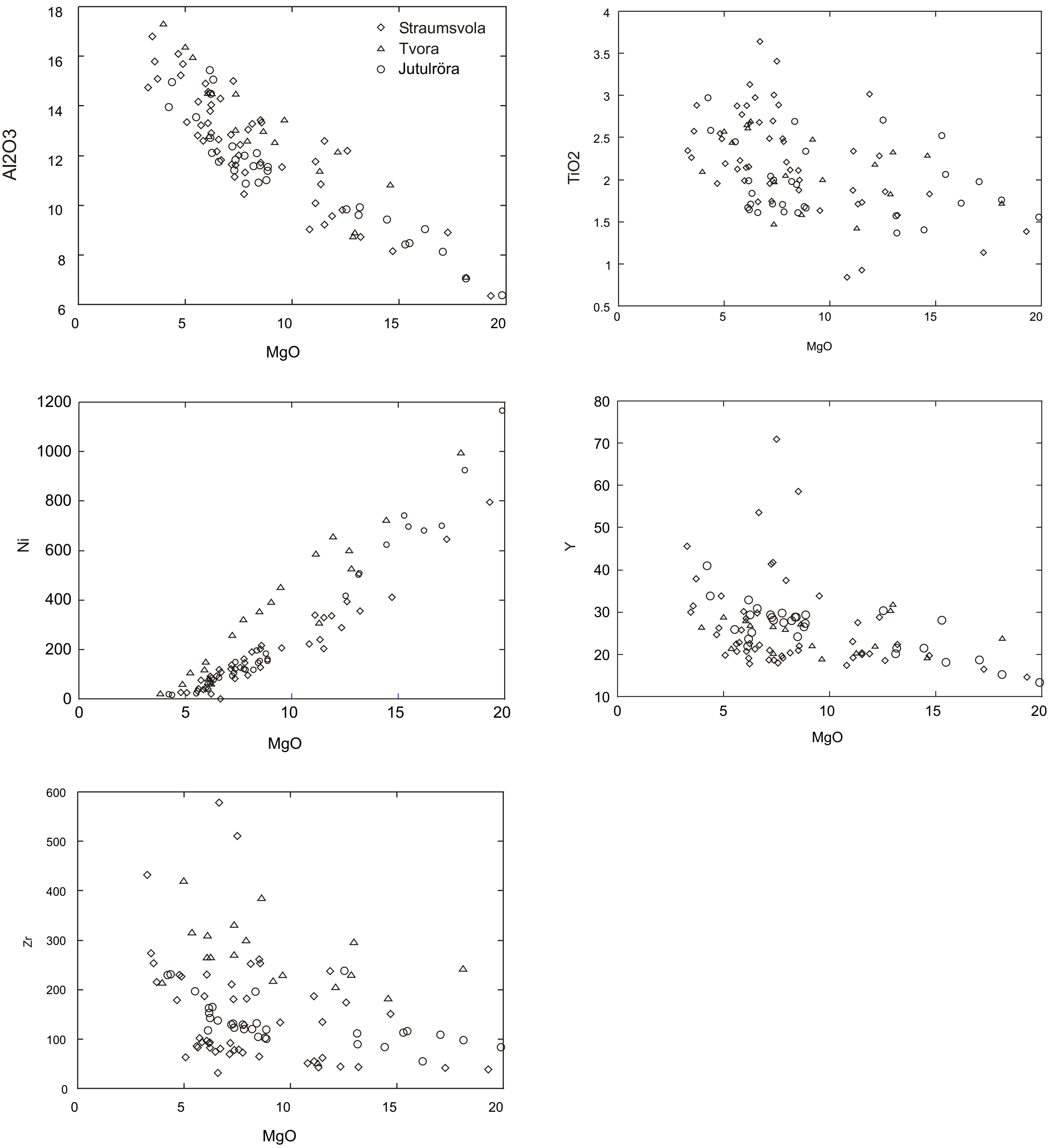
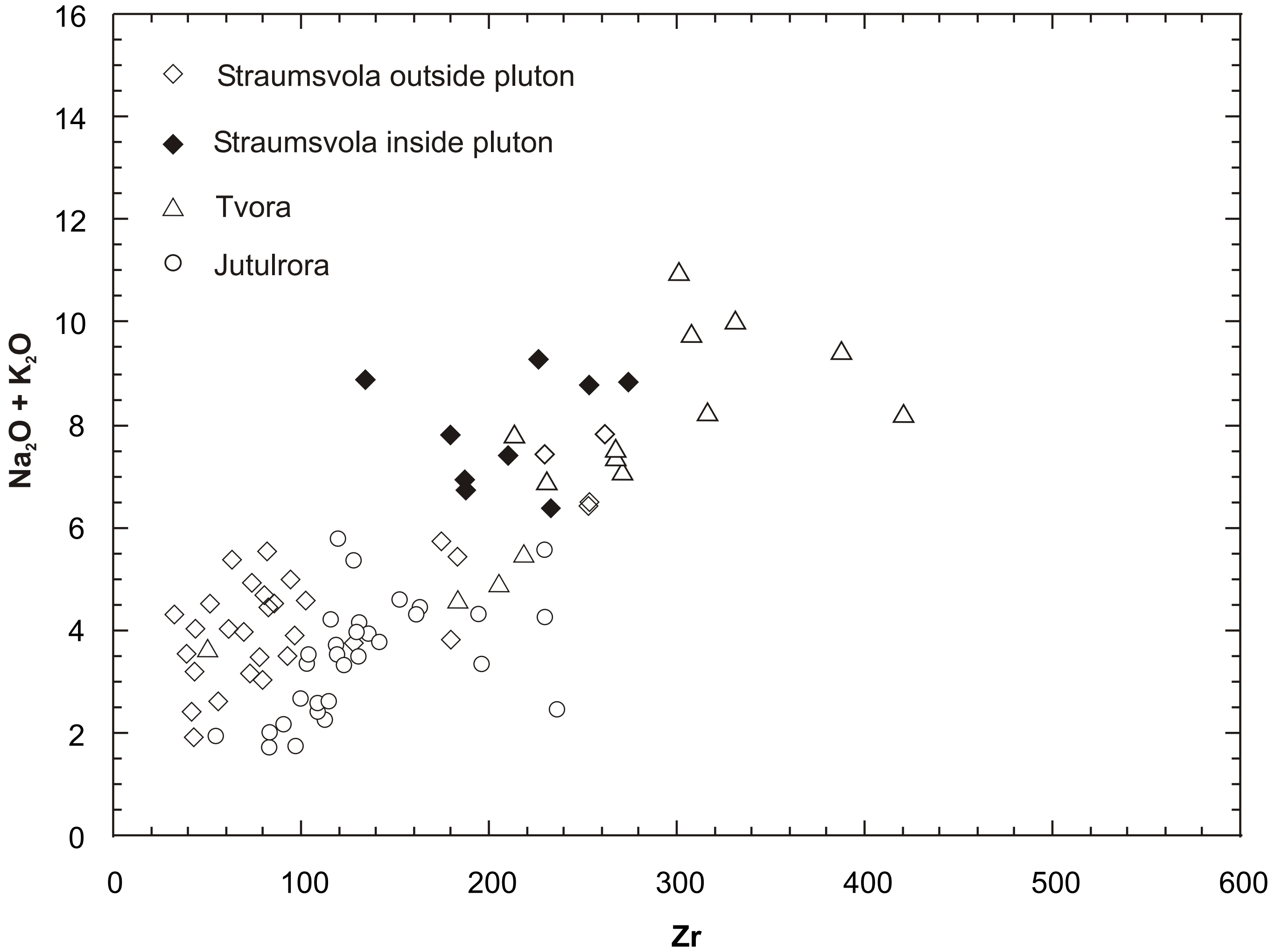
Fig. 5



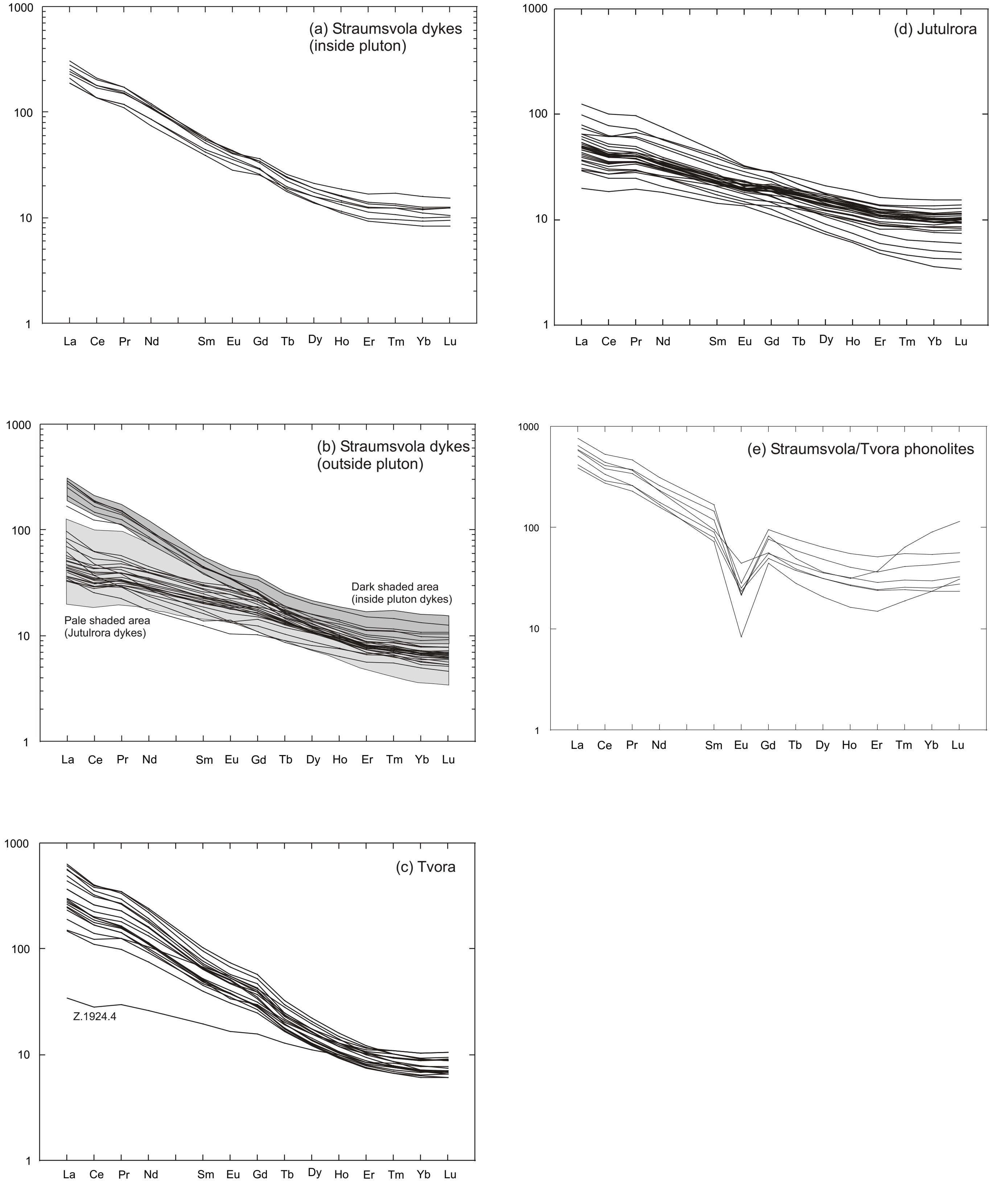
Riley et al.
Fig. 6



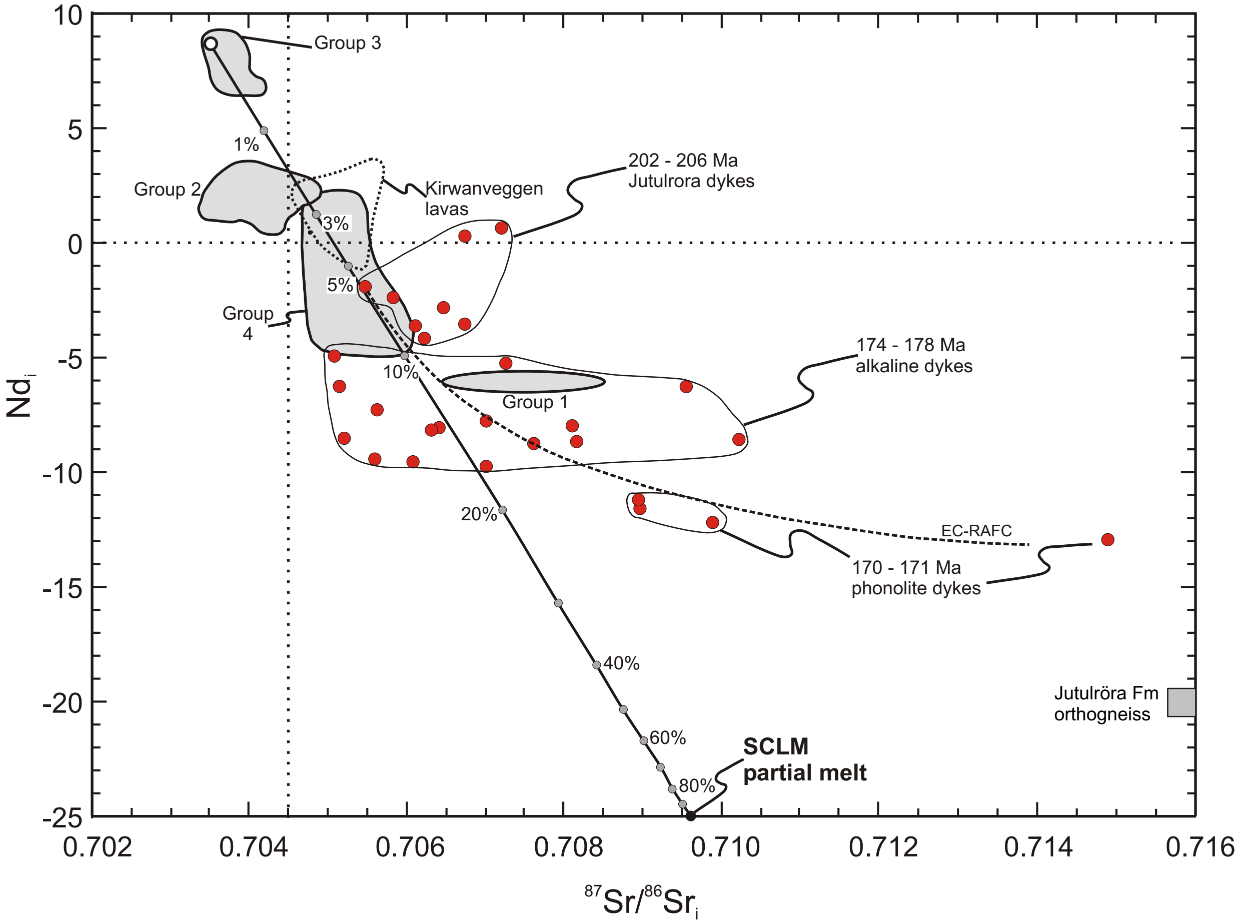
Riley et al.
Fig. 7



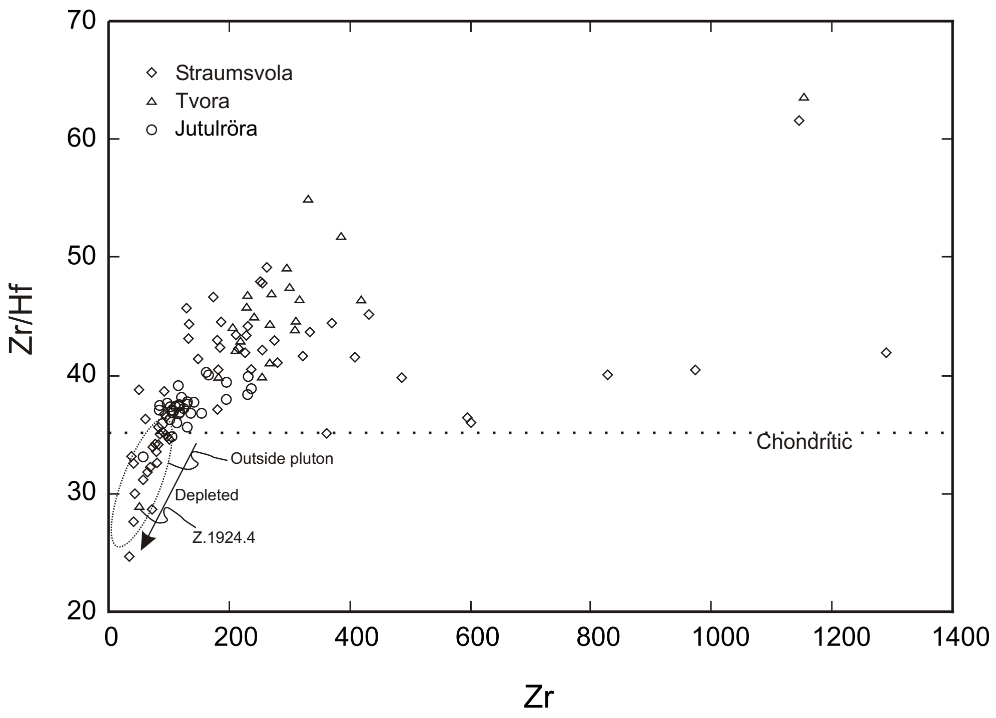
Riley et al.
Fig. 8



Riley et al.
Fig. 9



Riley et al.
Fig. 10



Riley et al.
Fig. 11

Table 1: Selected geochemical and isotopic analyses from the Straumsvola - Tvora - Jutulrora dyke suite

Sample	**Z.1901.3**	**Z.1904.3**	**Z.1904.6**	**Z.1906.4**	**Z.1911.4**	**Z.1911.7**	**Z.1912.1**
	Straumsvola	Straumsvola	Straumsvola	Straumsvola	Straumsvola	Straumsvola	Straumsvola
Latitude	-72.15150	-72.15158	-72.15006	-72.14456	-72.13564	-72.13292	-72.12778
Longitude	-0.22481	-0.23931	-0.24269	-0.25572	-0.29050	-0.29892	-0.30144
Altitude (m)	1183	1309	1300	1261	1296	1347	1487
SiO_2	41.83	43.93	56.90	46.07	44.93	64.09	64.21
TiO_2	2.98	2.12	1.31	0.84	1.99	0.24	0.41
Al_2O_3	12.18	13.29	15.34	9.03	14.91	16.11	15.56
Fe_2O_3T	17.23	12.61	9.50	12.63	13.25	6.02	6.03
MnO	0.21	0.19	0.23	0.22	0.19	0.13	0.21
MgO	6.49	8.12	1.42	10.80	5.95	0.00	0.02
CaO	11.66	10.11	3.56	14.36	7.87	0.09	1.31
Na_2O	3.85	3.26	5.81	2.93	4.66	7.48	7.16
K_2O	0.94	3.01	3.86	1.53	1.87	5.88	5.23
P_2O_5	0.40	0.92	0.49	0.34	0.54	0.03	0.06
LOI	1.84	2.04	1.52	0.80	3.34	0.12	0.13
Total	**99.60**	**99.60**	**99.95**	**99.55**	**99.51**	**100.16**	**100.35**
Cr	112	409	1	780	36	0	0
Ni	77	169	6	192	35	6	5
Cl	408	78	817	953	451	45	84
S	1152	472	116	516	583	71	65
Sc	21.71	15.71	11.59	31.36	14.91	0.19	4.05
V	433.1	204.5	2.4	243.9	216.4	-0.8	-0.7
Co	60.3	41.6	5.0	58.1	48.8	0.1	0.7
Cu	98.7	61.7	7.8	266.2	26.8	4.1	4.2
Zn	123.4	97.2	149.3	122.8	101.6	229.6	118.0
Ga	21.0	19.0	22.4	12.6	17.9	49.9	27.8
Rb	28.82	105.4	104.59	54.82	44.08	370.6	160.33
Sr	675.1	1503.5	657.7	417.4	1129.0	9.1	17.1
Y	21.4	20.3	44.7	17.5	30.2	39.9	56.2
Zr	75	252	370	51	186	596	486
Nb	12.34	96.96	85.88	10.61	46.31	67.51	98.38
Cs	1.34	9.44	2.76	6.81	0.68	2.43	1.03
Ba	373	1584	1848	335	1112	14	205
La	14.8	95.9	95.5	11.7	82.7	168.6	126.6
Ce	32.6	159.9	182.0	22.2	151.4	291.4	235.5
Pr	4.86	18.42	21.92	2.79	17.5	31.95	28.16
Nd	22.3	63.7	79.6	11.2	62.8	105.4	99.4
Sm	5.34	9.07	12.63	2.53	9.57	14.76	16.04
Eu	1.91	2.67	3.41	0.8	2.69	0.64	1.81
Gd	5.54	7.02	10.52	2.83	7.74	12.18	13.68
Tb	0.81	0.86	1.49	0.47	1.03	1.45	1.96
Dy	4.26	4.12	7.84	2.8	5.49	7.11	10.84
Ho	0.79	0.72	1.51	0.58	1.04	1.25	2.08
Er	1.88	1.78	4.01	1.54	2.69	3.36	5.5
Tm	0.26	0.25	0.62	0.24	0.41	0.64	0.87
Yb	1.49	1.44	3.79	1.52	2.5	5.18	5.55
Lu	0.22	0.23	0.62	0.24	0.39	1.04	0.94
Hf	2.2	5.26	8.33	1.32	4.4	16.39	12.19
Ta	0.79	5.58	4.66	0.63	2.39	3.78	5.33
Pb	7.16	11.66	31.92	20.47	22.31	24.01	12.53
Th	1.66	10.89	13.46	1.62	11.78	14.08	19.6
U	0.43	2.29	2.57	0.55	1.22	1.64	3.11
Alkali Index	0.604	0.649	0.895	0.717	0.650	1.159	1.121
$^{87}Sr/^{86}Sr_m$	0.706548	0.707243	0.707559	0.707982	0.705421	1.034743	0.784009
$^{87}Sr/^{86}Sr_i$	0.706235	0.706730	0.706394	0.707020	0.705135	0.727611	0.714964
$^{143}Nd/^{144}Nd_m$	0.512368	0.512326	0.512104	0.512171	0.512190	0.511858	0.511858
eNd_i	-4.2	-3.7	-8.2	-7.8	-6.4	-12.8	-13.0

Z.1923.6	**Z.1925.4**	**Z.1926.6**	**Z.1928.3**	**Z.1932.1**	**Z.1933.3**	**Z.1936.9**	**Z.1937.1**
Tvora	Tvora	Tvora	Jutulrora	Jutulrora	Jutulrora	Jutulrora	Jutulrora
-72.16178	-72.16758	-72.17417	-72.23081	-72.22183	-72.22728	-72.27067	-72.26378
-0.10414	-0.05325	-0.08492	-0.52089	-0.51244	-0.44744	-0.41164	-0.38364
1347	1373	1152	1210	1069	988	1464	1210
53.37	42.91	35.14	47.82	45.27	47.70	48.34	48.55
0.36	2.19	1.83	2.71	2.06	2.34	2.04	1.37
17.95	12.15	8.75	9.84	8.46	11.37	12.36	9.94
5.06	13.02	11.02	13.43	15.85	13.65	12.99	12.59
0.32	0.18	0.21	0.17	0.20	0.18	0.17	0.17
0.01	12.14	12.86	12.53	15.48	8.86	7.21	13.16
2.12	10.53	15.26	9.34	10.05	10.74	10.92	8.40
10.05	2.51	3.08	1.67	1.89	2.22	3.11	1.59
6.16	2.32	2.69	0.79	0.76	0.42	0.82	0.54
0.06	0.82	1.55	0.27	0.23	0.22	0.26	0.15
3.96	1.79	7.88	1.65	0.17	2.31	1.19	2.85
99.40	**100.56**	**100.27**	**100.23**	**100.40**	**100.01**	**99.40**	**99.31**
0	695	640	873	1242	473	230	998
4	330	301	408	690	146	83	551
1178	142	952	34	172	20	70	122
110	617	972	804	476	167	145	657
0.05	20.26	21.42	24.38	23.53	26.87	25.62	23.1
2.5	224.7	217.6	273.7	333.3	336.5	272.2	244.9
1.0	58.2	52.5	60.7	82.7	50.5	47.2	58.2
2.6	79.2	83.9	104.2	150.0	82.2	39.2	83.1
141.9	112.0	87.2	112.2	101.5	109.6	97.1	80.9
34.5	17.5	13.1	16.9	17.7	18.7	18.1	15.4
168.21	58.29	97.63	17.19	23.84	12.02	20.96	14.85
889.6	1427.9	2384.4	370.2	316.3	272.0	310.6	198.7
36.9	22.1	30.3	30.4	18.2	29.4	29.3	21.5
1155	205	230	237	116	101	130	91
482.28	58.3	138.19	14.51	11.72	6.78	8.76	5.36
8.38	1.26	5.72	1.9	1.21	7.34	0.31	0.77
73	1762	2519	242	269	135	385	162
175.4	86.7	202.0	21.5	15.1	10.2	15.9	11.9
321.7	160.5	344.4	53.6	34.3	23.3	35.7	26.3
28.86	19.25	42.44	8.18	4.89	3.43	4.9	3.59
80.2	70.2	147.8	36.7	21.7	16.0	21.8	16.0
9.47	10.26	19.32	8.18	4.84	4.25	5.33	3.78
2.29	2.91	5.22	2.46	1.56	1.54	1.74	1.2
7.54	7.84	14.54	7.83	4.77	5.21	5.79	4.13
1.03	0.93	1.53	1.14	0.7	0.9	0.98	0.71
6	4.43	7.02	5.97	3.68	5.19	5.65	4.14
1.2	0.76	1.14	1.09	0.66	1.02	1.1	0.83
3.62	1.81	2.63	2.65	1.58	2.59	2.83	2.09
0.63	0.24	0.35	0.37	0.22	0.37	0.41	0.3
4.24	1.49	2	2.26	1.32	2.28	2.48	1.85
0.7	0.24	0.3	0.33	0.2	0.35	0.38	0.28
18.14	4.66	4.92	6.09	3.14	2.78	3.66	2.54
26.25	3.14	7.19	0.97	0.75	0.42	0.56	0.35
79.46	13.79	22.32	3.65	2.97	1.82	3.59	2.64
81.39	8.61	24.12	2.23	1.68	1.08	2.12	1.4
15.96	1.54	3.45	0.57	0.36	0.24	0.41	0.24
1.292	0.547	0.912	0.366	0.465	0.361	0.486	0.322
0.709011	0.707296	0.706648	0.707536	0.706661	0.707578	0.708648	0.709508
0.707626	0.706997	0.706308	0.707196	0.706109	0.707254	0.708154	0.708961
0.512041	0.512016	0.512081	0.512603	0.512392	0.512337	0.512141	0.512009
-8.8	-9.8	-8.2	0.6	-3.6	-5.4	-8.7	-11.3

Table 2: EC-AFC parameters

Thermal parameters

Magma liquidus temperature	1210°C
Magma initial temperature	1210°C
Assimilant liquidus temperature	1100°C
Assimilant initial temperature	600°C
Solidus temperature	950°C
Isobaric specific heat of magma (J/kg K)	1484
Fusion enthalpy (J/kg)	354000
Isobaric specific heat of assimilant (J/kg K)	1388
Crystallization enthalpy of recharge magma	396000
Isobaric specific heat of recharge magma (J/kg K)	1500

Compositional parameters

Element	**Sr**	**Nd**
Magma concentration	350	22
Bulk D_0	0.8	0.1
Enthalpy	0	0
Assimilant concentration	300	80
Bulk D_0	0.4	0.5
Enthalpy	0	0
Isotope	$^{87}Sr/^{86}Sr$	εNd
Ratio magma	0.706	-3
Ratio assimilant	0.715	-12