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Dronning Maud Land Jurassic volcanism: Volcanology and petrology

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Abstract: The Jurassic igneous rocks of Dronning Maud Land represent Karoo flood basalt magmatism in Antarctica. Fifty years of research has documented systematic differences between magmas associated with the Karoo rift zone (Vestfjella and Ahlmannryggen) and the rift shoulder (Sembberget, Kirwanveggen) settings. The 182–189 Ma rift zone tholeiites were chemically diverse and mainly formed compound-braided flow fields which record several magnetic polarity reversals. In contrast, the ~181 Ma rift shoulder tholeiites were chemically uniform and formed thick tabular sheet lavas within a single normal polarity period. The volcanic architecture records a long initial phase of slow eruptions from shield volcanoes in the initial rift and a brief phase of voluminous fissure eruptions flooding the rift shoulder. All of the major magma types in the rift zone and rift shoulder settings belong to a Nb-depleted category of Karoo flood basalts and were mainly derived from depleted convective upper mantle by magmatic differentiation. Pyroxenite-rich mantle components may have been significant sources for the most enriched magma types. Geochemical fingerprints of recycled crustal material imply that the Nb-depleted Karoo tholeiites may have been derived from mildly subduction-modified parts of the same overall upper mantle reservoir which has been associated with the Ferrar tholeiites.

Supplementary material: Supplementary geochronological (Table S1) and geochemical data (Table S2) are available at <https://doi.org/10.6084/m9.figshare.c.5196613>.

Jurassic mafic volcanic and intrusive rocks are widespread in southern Africa and across the Transantarctic Mountains and have been designated respectively as the Karoo and Ferrar continental flood basalt (CFB) provinces. The formation of both provinces at $\sim 182 \pm 2$ Ma (e.g. Encarnación *et al.* 1996; Jourdan *et al.* 2007a, 2008; Svensen *et al.* 2012; Burgess *et al.* 2015) and the occurrences of contemporaneous flood basalt lavas and intrusions in New Zealand, Australia, Falkland, as well as in Coats Land and western Dronning Maud Land (DML), Antarctica, indicate a great magnitude of igneous activity and a more or less continuous volcanic plateau along the palaeo-Pacific margin of Gondwana before the breakup of the supercontinent (Rex 1967; Hergt *et al.* 1991; Brewer *et al.* 1992; Mortimer *et al.* 1995; Cox 1992; Hole *et al.* 2015). Such large igneous provinces (LIPs) constitute perplexing key events of Earth history (e.g. Bryan *et al.* 2010). Characterizing the chemical and physical variability and emplacement mechanisms of magmas and the timescales of the processes involved is critical for understanding the origin and evolution of LIPs and their environmental impacts.

Geochemical mapping has been utilized to define the compositional characteristics of the Ferrar and Karoo CFBs. Generalizing, the widespread igneous rock types are mainly composed of broadly similar tholeiitic basalt and basaltic andesite (Furnes *et al.* 1987; Cox 1988; Harris *et al.* 1990; Elliot *et al.* 1999) and collectively comprise the Gondwana LIP (Elliot & Fleming 2000). The diversity of isotopic and trace element compositions are indicative of variable magma sources, differentiation histories, and plumbing systems across the vast volcanic province, however (e.g. Jourdan *et al.* 2007b; Marsh *et al.* 1997; Galerne *et al.* 2008; Neumann *et al.* 2011). For instance, the prevalence of different silica contents and initial strontium isotopic ratios in the Karoo and Ferrar tholeiites, first discovered by Faure & Elliot (1971), has been widely interpreted to stem from different principal magma sources in the mantle (e.g. Hergt 2000; Riley *et al.* 2006). Accordingly, flood basalts and associated intrusions in western DML that were initially included in the Ferrar province were subsequently recognized as Karoo CFBs based on their Sr isotopic composition (Faure *et al.*

1979). Furthermore, the dykes in Kwa Zulu, southeastern Africa (Riley *et al.* 2006), the Falkland Islands (Hole *et al.* 2015), and the Theron Mountains, Coats Land (Leat *et al.* 2006), and some lavas in Lesotho (Elliot & Fleming 2000) arguably record intercalation of the Karoo and Ferrar province magma types (Fig. 1).

Fig. 1. Distribution of geochemically distinctive North Karoo (red), South Karoo (blue), and Ferrar (green) flood basalts and related intrusive rocks in a schematic Jurassic reconstruction between Africa and Antarctica at ~180 Ma. The seaward-dipping lava successions (Sabi, Lebombo, Vestfjella) and radiating dyke swarms (Okavango, Sabi, Ahlmannryggen, Vestfjella, Lebombo) define a triple rift structure (Burke & Dewey 1973). Karoo Basin CFBs include the Lesotho lava succession and a large dolerite sill complex (e.g. Marsh *et al.* 1997; Neumann *et al.* 2011). The division into North Karoo and South Karoo is after Luttinen (2018) and the reconstruction is modified after Lawver *et al.* (1998). The inset shows the extent of Karoo and Ferrar CFBs (Gondwana LIP) and an active subduction zone along Gondwana margin (Rapela *et al.* 2005). The area of Fig. 3 is indicated.

Detailed geochemical research has shown that while the Ferrar magmas were in many respects remarkably uniform low-Ti tholeiites (Elliot *et al.* 1999; Elliot & Fleming 2018), the Karoo magmas were notably variable low-Ti and high-Ti tholeiites (e.g. Duncan *et al.* 1984). Advances in geochemical mapping of the Karoo province has led to a plethora of geochemical provincial scenarios and related terminology as the geographical distribution of low-Ti and high-Ti tholeiites has been defined in increasing detail and as the discovery of transitional-Ti tholeiites has led to modified classification schemes (e.g. Erlank *et al.* 1988; Hergt *et al.* 1989; Sweeney & Watkeys 1990; Riley *et al.* 2005; Jourdan *et al.* 2007b; Luttinen *et al.* 2010). The presently available data reveal that the Karoo CFBs comprise two contrasting sub-provinces: a structurally complex and geochemically very heterogeneous assemblage of low-Ti and high-Ti tholeiites related to a large triple rift structure and a contiguous plateau of relatively uniform low-Ti tholeiitic lavas and sills related to major sedimentary basins (Luttinen *et al.* 2015) (Fig. 1).

Luttinen (2018) recently pointed out that the various low-Ti and high-Ti tholeiites of the Karoo triple rift are characterized by Nb depletion relative to Zr and Y, whereas the monotonous low-Ti tholeiites of the ‘plateau association’ do not show such a Nb depletion. The

abundance of Nb relative to Zr and Y can be readily examined using a logarithmic plot of Zr/Y v. Nb/Y and is quantified by the ΔNb parameter ($\Delta Nb = 1.73 + \log(Nb/Y) - 1.94\log(Zr/Y)$; Fitton *et al.* 1997). In the classification of Luttinen (2018), the relatively Nb-depleted low-Ti and high-Ti tholeiites associated with the Karoo triple rift constitute South Karoo and the Nb-undepleted low-Ti tholeiites of the Karoo, Kalahari, and Zambezi basins make up North Karoo (Figs 1–2). It is important to notice that the new classification into North Karoo and South Karoo illustrated in figure 1 refers to the Jurassic plate configuration and is based on the distribution of low- ΔNb and high- ΔNb tholeiites. It is not based on the conventional low-Ti vs high-Ti classification and does not refer to the original provincial scheme proposed by Cox *et al.* (1967) for African Karoo.

Overall, the presently available geochemical, geochronological, and palaeomagnetic data support the view that the Jurassic Gondwana tholeiites may be best understood using a division into three principal magmatic clans: (1) Ferrar, (2) North Karoo, and (3) South Karoo (Table 1). These geographically distinctive subsystems can be geochemically distinguished using strontium isotopic ratios and ΔNb (Fig. 2) and they can be viewed as sub-provinces of the greater Gondwana LIP. Importantly, the three sub-provinces show affinities to contrasting geochemical reservoirs; depleted mantle and continental lithospheric mantle (South Karoo), primitive mantle (North Karoo), and upper continental crust (Ferrar) (Fig. 2).

Fig. 2. Geochemical grouping of the Gondwana LIP into three principal clans, i.e. North Karoo (red), South Karoo (Africa, open blue; DML filled blue), and Ferrar (green) sub-provinces, based on variations in $^{87}Sr/^{86}Sr$ and ΔNb values ($\Delta Nb = 1.74 + \log(Nb/Y) - 1.92\log(Zr/Y)$; Fitton *et al.* 1997). The fields of typical compositions in each sub-province and plausible geochemical major reservoirs are indicated: DM is depleted MORB mantle (Workman & Hart 2005), PM is primitive mantle (McDonough & Sun 1995; Zindler & Hart 1986), CLM is assumed continental lithospheric mantle (Luttinen 2018), UCC is upper continental crust based on Karoo sandstone (Neumann *et al.* 2011). Geochemical data and references for Karoo are listed in the compilation of Luttinen (2018) and data for Ferrar are from Siders & Elliot (1985), Hergt *et al.* (1989), Fleming *et al.* (1992, 1995), Elliot *et al.* (1995, 1999), Wilhelm *et al.* (1996), Antonini *et al.* (1999), and Hanemann *et al.* (2004). Samples from section 82.3 in Mesa Range (Elliot *et al.* 1995) have anomalous high Nb contents and were excluded from Ferrar data due to probable analytical error.

This paper presents a synthesis of geological research on flood basalt magmatism in DML during the past five decades. Geochemically, the Jurassic extrusions and intrusions of DML belong to South Karoo (Luttinen 2018) (Figs 1–2), and tectonically, the tholeiites of Vestfjella and Ahlmannryggen are associated with the Karoo triple rift, whereas those of Björnnutane, Sembberget, and Kirwanveggen can be regarded to represent rift-shoulder setting (Luttinen *et al.* 2015) (Figs 1 and 3). Geochemical data from DML manifest profound compositional variability in the Jurassic magmas, but, on the other hand, the data also constrain the range of primitive magma compositions and mantle sources involved. Overall, flow-by-flow mapping and sampling of lavas and comprehensive mapping and sampling of intrusions record contrasting styles of emplacement and melting conditions for rift and rift shoulder volcanism and arguably provide the most detailed volcanological and petrological portrait of the southern arm of the Karoo rift zone.

Geological setting

A considerable period of Earth history is recorded in the scattered bedrock exposures of western DML. Over large areas between the Ahlmannryggen–H.U. Sverdrupfjella and Mannefallknausane the bedrock mainly consists of Precambrian basement, which ranges in age from Archaean to Mesoproterozoic (Fig. 3).

Archaean basement is exposed only on a small outcrop at Annandagstoppane (Fig. 3) (Halpern 1970; Barton *et al.* 1987), where a leucocratic granite has yielded a crystallization age of 3076 Ma (Marschall *et al.* 2010). Aeromagnetic data indicate that the Archaean crustal domain underlies the sedimentary and volcanogenic sequences of the Mesoproterozoic (~1080 Ma) Ritscherflya Supergroup (Wolmarans & Kent 1982) as well as mafic 800–1000 Ma Borgmassivet intrusions (Krynauw *et al.* 1988, 1991; Moyes *et al.* 1995) in the Ahlmannryggen region and its southwestern boundary is estimated to be located under the ice sheet close to northern Vestfjella (Corner 1994) (Fig. 3). The Archaean basement and the overlying supracrustal rocks comprise the Grunehogna craton (Krynauw *et al.* 1991) which is bounded in the south by the Mesoproterozoic Maud belt (Groenewald *et al.* 1995) (Fig. 3). Several lines of evidence indicate that, prior to Jurassic Africa–Antarctica rifting, the Grunehogna craton was juxtaposed to the Zimbabwe–Kaapvaal craton of southern Africa and these Archaean blocks together formed the Proto-Kalahari craton (Jacobs *et al.* 2008).

The Maud belt and the coeval Namaqua–Natal mobile belt of Africa formed the southern-eastern accretionary rim of the Kalahari craton (e.g. Jacobs *et al.* 1993, 2008). The Maud belt is principally the product of high-grade metamorphism, folding and thrusting of supracrustal successions and syn- to post-tectonic plutonism during the accretion of relatively juvenile crust in the period 1100 – 1040 Ma (Grantham *et al.* 1988; Arndt *et al.* 1991; Moyes *et al.* 1993; Jacobs 2009). Detailed mapping of the Heimefrontfjella area suggests generation of juvenile crust in volcanic arc and associated back-arc setting at 1180 – 1100 Ma, followed by metamorphism, folding, and syn-tectonic granitic plutonism during amalgamation of supercontinent Rodinia (Hoffman 1991; Groenewald *et al.* 1995) at 1100 – 1060 Ma, and subsequent late- and post-tectonic bimodal plutonism at 1050 – 1040 Ma (Jacobs 2009).

As in southern Africa, the Precambrian basement is overlain by Palaeozoic sedimentary rocks at many localities at Heimefrontfjella and Kirwanveggen (Fig. 3). Most of the outcrops of the sedimentary sequence are small outliers capping the much larger exposures of the basement complex with an angular unconformity (e.g. Juckes 1972). In the Vestfjella region, the basement is unexposed and Palaeozoic sedimentary rocks are confined to Fossilryggen ridge (Hjelle & Winsnes 1972).

Fig. 3. Distribution of Jurassic flood basalts in western Dronning Maud Land. Exposures of Archaeon and Proterozoic bedrock and the subglacial extent of the Archaeon Grunehogna craton and the Proterozoic Maud Belt are indicated.

The sedimentary rocks and the basement complex are overlain by Jurassic flood lavas and cut by associated sills and dykes. The main exposures of flood lavas are at Vestfjella, north Heimefrontfjella, and southern Kirwanveggen (Fig. 3). Intrusive equivalents of the flood basalts are abundant in Vestfjella (Furnes & Mitchell 1978; Luttinen *et al.* 2015) and quite common in Ahlmannryggen (Harris *et al.* 1991; Riley *et al.* 2005), H.U. Sverdrupfjella (Grantham 1996), and Mannefallknausane, but rare in Heimefrontfjella (Jukes 1972) and Kirwanveggen (Harris *et al.* 1990; Riley *et al.* 2005). Possible correlates of the intrusions have been reported in the Theron Mountains (Coats Land; Leat *et al.* 2006) and Schirmacher Oasis (central Dronning Maud Land; Suschevskaya *et al.* 2009) (Fig. 1). Moreover, small nepheline-syenite alkaline plutons and correlative dykes at Straumsvola, Tvora, and Sistenup nunataks, Jutulstraumen area, record silicic Jurassic magmatism in DML (Harris *et al.* 1993, 2002; Riley *et al.* 2009). All of the Jurassic flood basalts and most of the intrusions are found within the area of Proterozoic basement and only the Ahlmannryggen intrusions occur within the Archaeon craton (Fig. 3).

Petrography

Extrusive rocks

The Jurassic volcanic rocks have rather uniform petrographic features across western DML (Jukes 1972; Faure *et al.* 1979; Furnes *et al.* 1987; Harris *et al.* 1990; Luttinen & Furnes 2000; Luttinen *et al.* 2010): Most of the lavas are porphyritic. Plagioclase is the predominant phenocryst phase and occurs frequently with clinopyroxene or olivine or both. Combined geochemical and petrographic evidence indicates successive crystallization of (i) olivine and Cr-spinel, (ii) plagioclase and olivine, and (iii) plagioclase, olivine, and clinopyroxene. Phenocrysts are frequently euhedral, but aggregates of subhedral grains are also common and may represent gabbroic autoliths. Typically, olivine is strongly altered to greenish or reddish secondary micaceous material. Plagioclase is rarely unaltered, typically shows alteration to sericite along fractures, and the strongly altered samples record pervasive alteration to saussurite, chlorite, carbonate, and/or epidote. In contrast, clinopyroxene is fresh even in strongly altered samples.

The groundmass consists of plagioclase laths and interstitial clinopyroxene and Fe-Ti oxides. Depending on the relative size of plagioclase and clinopyroxene, the texture varies from ophitic to mesophitic, but subophitic textures are predominant. Opaque Fe-Ti oxide grains typically show skeletal, acicular, or dendritic quench textures. Most of the lavas contain interstitial greenish, brownish, or reddish patches of mesostasis which represent altered or devitrified volcanic glass. The contents of mesostasis are suggestive of intergranular, intersertal, and hyalophitic primary textures, and reflect variable crystallinity of the igneous rocks. Most of the samples have been collected from relatively massive parts of the lavas and intrusions, but many contain at least a few vesicles or dictyotaxitic voids filled with secondary minerals. Groundmass olivine has been positively identified in some samples, but it is often difficult to reliably discern totally pseudomorphed olivine from mesostasis or filled vesicles. Apatite needles are present in most samples.

Intrusive rocks

Overall, the intrusive rocks have similar textural and mineralogical characteristics as the lavas (Jukes 1968, 1972; Furnes *et al.* 1982; Grantham 1996; Riley *et al.* 2005; Heinonen & Luttinen 2008; Luttinen *et al.* 2015): Picritic (olivine-phyric) dykes and sills are common in many localities, whereas rare picritic lavas are confined to Vestfjella. Most of the intergranular samples are intrusive rocks which typically are also less altered than the volcanic rocks due to higher crystallinity and lower porosity. A few coarse-grained intrusive rock types contain interstitial quartz-feldspathic segregation patches. Two larger intrusions in Vestfjella record differentiation of the phenocryst minerals and formation of variable gabbroic rock types most of which display cumulate textures (Vuori & Luttinen 2003; Vuori 2004).

Building blocks of the volcanic edifice

The exposed volcanic and intrusive suites exhibit textural and structural variability indicative of different magma compositions and styles and rates of eruption, and emplacement under a variable crustal stress field. The architecture of the lava successions has not been previously reported in detail. In addition to published papers, the following description utilizes the author's field notes and photographs from Vestfjella, Björnnutane, Sembberget, and Kirwanveggen from the period 1989–2018 and field notes provided by Henrik Grind (Vestfjella dykes), Harald Furnes (Vestfjella lavas), and Phil Leat (Sembberget, Kirwanveggen).

Lava flow units, flow fields, feeder fissures

Flow units. Individual cooling units of stalled lava are referred to as flow units. Most of the well-exposed flow units in DML have relatively smooth, billowy, or ropy surfaces typical of pahoehoe (Macdonald 1953) (Fig. 4). Brecciated flow surfaces have been noted in many localities (e.g. Hjelle & Winsnes 1972; Harris *et al.* 1990; Luttinen *et al.* 2010) and some units have brecciated base, but 'a' units have not been positively identified. The brecciated material commonly shows characteristic features of pahoehoe lava and the lack of clinkery levees and other indications of open channel flows suggests that flow units with brecciated crust and/or base can be regarded as rubbly pahoehoe (Rowland & Walker 1990; Cashman *et al.* 1999; Bondre *et al.* 2004; Keszthelyi *et al.* 2006).

The flow units typically have a vesicle-rich base and upper crust. The vesicles are mainly <1 cm in diameter and are invariably at least partially filled with secondary minerals. The vesicular base is commonly <0.5 m thick and frequently contains 20–30 cm long pipe vesicles

(Fig. 4c). The thickness of the vesicular upper crust is varied and typically ~30–50% of the total thickness of the flow unit. In many flow units that are several meters thick, the vesicular upper crust contains alternating vesicle-rich and vesicle-poor bands that are broadly parallel with the lava surface. The vesicular bands can be referred to as vesicular zones using the terminology of Self *et al.* (1996). These units may also contain flattened or bell-shaped geoids with diameters up to ~0.5 m. The core of the flow units is nearly vesicle-free, but in thick units distinctive (segregation) vesicle cylinders in the core frequently connect the vesicular base and upper crust and form distinctive segregation vesicle sheets (Fig. 5a). Overall, the internal structure of the lava flow units, including those with rubbly surface or base, shows characteristic features of *inflated* pahoehoe (Hon *et al.* 1994; Self *et al.* 1996; Keszthelyi *et al.* 2006).

The flow units exhibit a continuum of size and aspect ratios. Relatively small units are lava lobes which range from decimetre-scale toes to sheets several meters thick. Judging from well-exposed locations, juxtaposed flow units are frequently interconnected and represent parts of more extensive branched tongues formed due to successive lava breakouts during active inflation (Hon *et al.* 1994). Lateral correlation of the flow units is generally difficult. On cliff faces, the width of the units is from a few meters up to several hundred meters, depending on the cross-section (Fig. 6a). The largest flow units are laterally extensive tabular sheets which are up to several tens or even >100 meters thick and up to tens of kilometres wide (Fig. 6b).

Fig. 4. Structures of Jurassic lavas and intrusions in DML. (a) Hummocky surface of pahoehoe, Basen (unit #4 in figure 8; 73.0402° S, 13.3893° W). (b) Ropy pahoehoe at Basen (73.0426° S, 13.4069° W). (c) Cross-section of small inflated pahoehoe flow units belonging to compound-braided flow facies, Basen (73.0224° S, 13.3611° W). (d) Ropy structure within a megavesicle underneath the upper margin of Schievestulen sill, Heimefrontfjella (74.3310° S, 9.7643° W). The hammer in (a) is 70 cm long, the scale bar in (b) and (d) is 15 cm long, and the scale bar in (c) is 50 cm long. Photos Arto Luttinen.

Fig. 5. Lava flow contacts at (a) Basen, Vestfjella (73.0385° S, 13.4572° W), and (b) Tunga (Urfjell), Kirwanveggen (73.9192° S, 5.3200° W). In (a), the lava overlies a ~5 m thick sandstone (sub-horizontally banded top is visible) and shows typical features of inflated pahoehoe, including inclined pipe vesicles in the lower crust, vesicle cylinders and horizontal vesicle sheets in the massive lava core (unit #2 in Figure 8). In (b), the lower unit has a flow-top breccia typical of rubbly pahoehoe with sandstone filling the lava fragments. The upper unit is notably poor in vesicles. The scale bar is 50 cm long. Photos Arto Luttinen.

Fig. 6. Schematic representations of two principal lava flow stacking patterns typical of (a) compound-braided facies and (b) tabular-type facies of Jerram (2002). Some tabular-type lavas have a brecciated crust and represent rubbly pahoehoe. Modified after Jerram (2002).

Flow fields. Lava flow units that have been emplaced during the same overall eruptive cycle form lava flow fields. They are variably identified based on (i) clastic interbeds or otherwise well-defined contacts, (ii) predominant type of flow units, (iii) characteristic colour, and (iv) geochemical compositions. Variable vesicularity, jointing, crystallinity, grain size, mineral composition, and the overall lava stacking pattern have a controlling influence on the degree

of alteration, the secondary mineral assemblage (e.g. Bevins *et al.* 1991), and the colour variations. Flow fields that represent or have a field appearance of a single tabular lava sheet are *simple flow fields*, whereas *compound flow fields* are made of several intimately overlapping units (Walker 1971). Compound flow fields can be further classified based on the characteristic aspect ratios of the flow units. Apart from a few examples of *tabular-type* compound flow fields made of stacked tabular lava sheets, the compound flow fields are made of intertwining pahoehoe lobes and represent the *compound-braided* type of Jerram (2002) (Fig. 6).

Intrusive sub-volcanic feeders. Most of the intrusive rock types are sub-vertical dykes. The width of the dykes varies from ~0.2 m up to 500 m, but the great majority are 1–3 m wide (Furnes *et al.* 1982; Grind *et al.* 1991; Harris *et al.* 1991; Grantham 1996; Riley *et al.* 2005; Curtis *et al.* 2008; Heinonen & Luttinen 2008; Luttinen *et al.* 2015). Sub-horizontal sills 0.2 to 20 m in thickness have been observed in Vestfjella, Mannefallknausane and Heimefrontfjella (Juckes 1968; Hjelle & Winsnes 1972; Luttinen *et al.* 2015). The dykes and sills exhibit variably developed columnar jointing, many have well-defined chilled margins, and some of them contain vesicles indicative of emplacement relatively close to Earth's surface. Judging from geochemical compositions, most of the Vestfjella dykes represent sub-volcanic feeders of lava flows that have been removed by erosion (see section Intrusive magma types). The predominant dyke strike directions are broadly coast-parallel (NNE-SSW in Vestfjella and ENE-WSW in Ahlmannryggen and H.U. Sverdrupfjella), but SSE-NNW trending dykes are also abundant especially in western parts of H.U. Sverdrupfjella. The overall radiating pattern of dyke intrusions in DML and the conjugate African margin is consistent with a major igneous centre in the Karoo triple junction and studies of anisotropic magnetic susceptibility indicate lateral transport of magmas away from this region (Curtis *et al.* 2008; Hastie *et al.* 2014). The roles of mantle plume activity and pre-existing lithospheric structures in the genesis of the radiating dyke swarms are contested (Jourdan *et al.* 2004; Curtis *et al.* 2008; Hastie *et al.* 2014).

Clastic intercalations

Clastic interbeds are relatively common within the lava successions of DML, but the reports are relatively superficial (Hjelle & Winsnes 1978; Harris *et al.* 1990; Luttinen & Furnes 2000). Some of the interbeds have been regarded to be pyroclastic and volcanoclastic (Furnes & Mitchell 1978; Peters 1989), but they have not been described in sufficient detail for reliable identification. A report of thick mafic crystal tuffs in Plogen (Peters 1989) has turned out to be misinterpretation. Detailed mapping of the 400 m thick succession of lavas at Basen revealed four horizons of clastic intercalations (Luttinen 1994). In most places, these are made of fine-grained (clay-size) material and can be referred to as red boles. Some of the fine-grained intercalations are green or yellowish-green or grey-green. The two lower horizons include poorly sorted, but mineralogically mature sandstone deposits interpreted as redeposited Permian sedimentary strata (Luttinen 1994). The lowermost sandstone attains a maximum thickness of ~5 m in the SW corner of the nunatak. Similar sandstone interbeds are visible on the NE cliff face of the nearby Plogen nunatak. Occurrences of red and greenish yellow clastic intercalations have been observed at every major nunatak in Vestfjella, but they have not been mapped or sampled in detail. The clastic interbeds in southern Vestfjella are invariably thin (<1 m ?) and appear to be laterally discontinuous lenses.

Red bole intercalations are common in flood basalt successions worldwide and are considered to represent autochthonous or allochthonous weathering deposits (Shrivastava *et al.* 2012), or pyroclastic material (Bell *et al.* 1996). The red boles of DML have not been studied in sufficient detail to draw conclusions concerning possible involvement of pyroclastic material.

The report of Jukes (1972) and a visual survey of thin sections representing clastic interbeds at Basen (n=15), Plogen (n=1), and Sembberget (n=1) suggest most red boles in DML include a significant allochthonous component revealed by angular quartz and microcline clasts. A single geochemical analysis supports a predominantly allochthonous origin ($\text{SiO}_2 \sim 71$ wt.%, $\text{K}_2\text{O}/\text{Na}_2\text{O} \sim 10$, MgO/CaO and $\text{Al}_2\text{O}_3/(\text{CaO} + \text{K}_2\text{O} + \text{Na}_2\text{O}) \sim 1.3$; Luttinen 1994). The samples typically contain glassy fragments which probably record entrainment of melt from the overlying lava into unconsolidated sedimentary material. Generalising, the clastic interbeds in DML appear to indicate pauses in eruptive activity, but the length of dormancy has not been defined.

Volcanic architecture – lava successions and intrusive suites

This section summarises the physical features and ages of the Jurassic lavas and associated intrusions in western DML. Evidence of excess Ar, Ar-loss, recoil, the lack of plateau ages, or insufficient documentation render many of the published dating results doubtful (Zhang *et al.* 2003; Luttinen *et al.* 2015). The most reliable U–Pb and ^{40}Ar – ^{39}Ar mineral plateau ages are listed in Table 2. The ^{40}Ar – ^{39}Ar ages are reported relative to FCs monitor age (28.29 Ma) and ^{40}K decay constants of Renne *et al.* (2011).

Vestfjella extrusive-intrusive suite

Volcanic stratigraphy. Vestfjella is a ~120 km long range of toothed ridges, clusters of pointed nunataks, and isolated small exposures adjacent to the continental margin of East Antarctica (Fig. 3). The Vestfjella range is almost entirely made of Jurassic lavas and intrusions and minor (<5 m thick) clastic interbeds (Hjelle & Winsnes 1972; Luttinen & Furnes 2000). Fossilryggen represents a unique exposure of Permian sedimentary bedrock that may underlie the lavas in Vestfjella, but the base of the volcanic succession is not exposed (Hjelle & Winsnes 1972; McLoughlin *et al.* 2005). The lowermost exposures are at ~200 m elevation (a.s.l.). The relatively smooth profile of the slopes and ridges and the flatness of cliff faces reflect the fact that the Vestfjella succession is mainly composed of relatively thin, superimposed pahoehoe flow lobes. The thickness of individual flow units is mainly <5 m and the units appear to thin out over distances of <100 m in vertical cross sections. The thickness of the lava pile exceeds 700 m at Plogen, north Vestfjella (Fig. 7a). The emplacement of the lavas has not been reliably dated due to alteration (Zhang *et al.* 2003), but the southern exposures are at least 182 Ma and possibly up to 189 Ma old based on U–Pb zircon and ^{40}Ar – ^{39}Ar plagioclase dating of crosscutting intrusions (Luttinen *et al.* 2015; Table 2).

The Vestfjella CFB succession is predominantly made of overlapping thin pahoehoe lobes which show characteristic features of inflated pahoehoe and comprise compound-braided flow fields. The succession is particularly well exposed on large cliff faces at Basen and Plogen, where different flow fields can be mainly distinguished based on their characteristic colouring (Fig. 7a). Colour variations are quite hard to depict when walking along accessible ridges and the limited lateral dimension of the flow units also complicates detailed correlation between geochemical samples and the succession of flow fields observed on the cliff faces. Clastic intercalations sporadically sandwiched between flow fields and geochemical variations also help define several flow fields.

In comparison, laterally extensive, simple sheet lavas are quite rare. The thickness of the sheet lavas range from ~5 to 20 m and they can be followed laterally up to ~5 km in some locations. Some of the simple lavas have a rubbly flow top breccia (Fig. 5b). The lava fragments typically have oxidized, red surfaces and the interstitial spaces between scoriaous blocks are

variably filled with clastic material. Some of the relatively thick sheet lavas have poorly developed vertical jointing in the massive lava core, whereas the vesicular upper crust exhibits sub-horizontal jointing also in small pahoehoe lobes. Only a few lava flow units have been tentatively classified as 'a' lava (Hjelle & Winsnes 1972). Pipe vesicles, round vesicles, geoids, and other voids are filled mainly with secondary quartz, calcite, chlorite, prehnite, and epidote. Secondary microcline has yielded alteration ^{40}Ar – ^{39}Ar ages of 140 Ma and 152 Ma (Zhang *et al.* 2003). In Vestfjella, subsolidus alteration of the lavas and intrusions renders dating of the magmatic events problematic. Notably variable Cl/K and Ca/K spectra indicate that ^{40}Ar – ^{39}Ar plagioclase plateau ages of ~150–173 Ma are more likely to date secondary resetting of the K–Ar isotopic systematics than magma emplacement even if plagioclase appears to be unaltered in thin sections (Zhang *et al.* 2003; Luttinen *et al.* 2015). Lamproite dykes with ^{40}Ar – ^{39}Ar phlogopite age of 162 Ma record the youngest magmatic event in Vestfjella (Luttinen *et al.* 2002; Table 2) during the purported onset of seafloor spreading between Africa and Antarctica (Jokat *et al.* 2003).

Two nunataks have been mapped in sufficient detail to determine the number of flow fields with reasonable confidence. Colour variations, clastic interbeds, and geochemical variations indicate that the >700 m thick Plogen succession records at least 25 flow fields most of which belong to the compound-braided type (Fig. 8). The compound-braided lavas generally lack indications of significant breaks in effusive activity and individual compound flow fields may be up to 200 m thick, although most are less than 50 m thick (Fig. 7a). The nearby Basen succession is estimated to be made of nine compound-braided and three simple flow fields and up to 5 m thick clastic interbeds (Luttinen & Furnes 2000) (Fig. 8).

Fig. 7. Occurrences of Jurassic flood basalt lavas and intrusions in (a) Vestfjella (Plogen), (b) Björnnutane, (c) Kirwanveggen (Lagfjella), and (d) Heimefrontfjella (Schievestulen) (for localities see Fig. 3). The height of the cliff in (a) is ~400 m. It shows numerous flow fields with variable structures and colours, including possible tumuli. A crosscutting inclined dyke is ~20 m thick. The sandstone in (b) is ~1 m thick. The lower part of the Björnnutane lava succession is made of compound-braided flow fields and simple tabular-type units can be seen in the upper part of the photo. The thick tabular lava sheets in (c) produce a classic trap topography at Kirwanveggen. The 5 m thick Schievestulen sill (d) is underlain by ~20 m of Palaeozoic sedimentary strata. Photos Arto Luttinen.

Fig. 8. Stratigraphic columns illustrating the volcanic architecture of Vestfjella (Basen, Plogen), Björnnutane, Sembberget, and Kirwanveggen (nunatak B, Lagfjella). For chemical compositions see section Extrusive magma types. Numbers indicate interpreted lava flow fields and dashed lines show possible correlations between different localities. The contact between units #4 and #5 of Kirwanveggen is not exposed and chemical data for unit #14 of Sembberget is lacking.

A distinctive plagioclase porphyritic lava at nunatak Basen (flow #3) has been correlated with a tabular-type compound flow field of two similarly plagioclase porphyritic overlapping sheets at nunatak Plogen ~25 km away based on exceptional high-Ti compositions (lava #6) (Luttinen & Furnes 2000). The lava succession dips gently (3–10°) towards W–SW and is cut by abundant dykes and faults. On a regional scale, the tilting and faulting of the lavas lead to uncertainty with respect to the total stratigraphic thickness which has been estimated to be 1000–2500 m (Hjelle & Winsnes 1972; Furnes *et al.* 1987; Peters 1989; Luttinen & Furnes 2000). Flow direction measurements from inclined pipe vesicles (Fig. 5a) show notable variability (Luttinen & Furnes 2000; Furnes & Mitchell 1978, Hjelle & Winsnes 1972), which documents that the tilting is post-volcanic. Chemically different lavas show broadly consistent flow directions (Fig. 8; see section Extrusive magma types).

Dolerite dykes and sills. The dykes and less abundant sills are here referred to as dolerites regardless of textural and mineralogical variability. Most of the dolerites are sub-vertical and have a broadly coast-parallel NNE–SSW strike (Furnes *et al.* 1982; Peters 1989; Grind *et al.* 1991; Luttinen *et al.* 2015). Subordinate N–S, NW–SSE, and E–W strike directions have been interpreted to be successively younger (Grind *et al.* 1991), but the age relationships have not been confirmed by detailed studies. Plagioclase ^{40}Ar – ^{39}Ar dating indicates emplacement of the crosscutting dolerites in southern Vestfjella during the interval 186–189 Ma (Luttinen *et al.* 2015; Table 2). The dykes and sills are relatively narrow, typically 1–3 m wide, although some attain width of several tens of metres (Furnes & Mitchell 1978; Furnes *et al.* 1982; Grind *et al.* 1991; Luttinen *et al.* 2015) (Fig. 4a). Judging from crosscutting relationships, some of the dykes are multiple intrusions generated by successive magma injections. The succession shows normal faulting from cm scale to several tens of meters, but the vertical movements appear to have been typically less than 10 m. The main fault direction coincides with the predominant NNE–SSW dyke strike direction and some of the dykes have slickensides at the dyke-wallrock contact, but also within multiple dykes. Some of the dykes record shearing into lensoid bodies (Grind *et al.* 1991).

Gabbroic intrusions. In southern Vestfjella, the lavas are cut by gabbroic intrusive bodies. Two bodies of gabbroic rock types have been interpreted to represent ~500 m wide dyke-like intrusions at Muren, southern Vestfjella (Luttinen & Vuori 2004). The dykes have indistinguishable U–Pb zircon ages of 182 Ma (Luttinen *et al.* 2015; Table 2). The East Muren dyke is made of relatively homogeneous gabbro, whereas the West Muren dyke is differentiated and is dominated by olivine cumulates which are overlain by leucogabbros and a capping felsic unit (Vuori & Luttinen 2004; Luttinen & Vuori 2006; Luttinen *et al.* 2015). The Utpostane intrusion was first reported by Jukes (1968) and has been subsequently briefly studied by Hjelle & Winsnes (1972). Plagioclase ^{40}Ar – ^{39}Ar dating indicates emplacement of the gabbro at 181 Ma (Zhang *et al.* 2003; Table 2). Detailed geological mapping has shown that Utpostane is a layered intrusion composed mainly of various gabbroic cumulates (Vuori & Luttinen 2004; Luttinen & Vuori 2006). The lithological variations and layer structures are suggestive of >3 km thickness for the exposed part of the Utpostane intrusion (Vuori & Luttinen 2006; Vuori 2004).

Björnnutane extrusive suite

Björnnutane is a group of three small nunataks in northern Heimefrontjella (Fig. 3). The bedrock is principally composed of a lava succession that has a maximum stratigraphic thickness of ~200 m and records at least eight lava flow fields (Jukes 1972; Luttinen *et al.* 2010) (Fig. 8). The base of the lava pile is exposed at two localities, at ~2400 m elevation (a.s.l.), where a ~1 m layer of sandstone is sandwiched between the volcanic succession and the Mesoproterozoic basement (Fig. 7b). The lava succession starts with a ~35 m thick

compound-braided flow field of lobes that vary in thickness from ~1 to 10 m and are mainly 2–4 m thick. Measurements of pipe amygdules in the basal crust indicate flow direction to NE. The basal lava is overlain by a discontinuous and thin (< 1 m) layer of sandstone that fills cracks in the underlying lava crust. The sandstone is succeeded by a ~10 m thick, distinctly light-coloured simple flow fields with pipe amygdules indicating flow direction to NNW. The next unit is a ~30 m thick compound-braided flow field consisting of pahoehoe lava lobes of up to a few metres thick. The upper part of the succession consists of five relatively thick simple flow fields which range in thickness from ~10 to 35 m. The contacts between lavas are poorly exposed, probably due to preferable weathering of vesiculated and brecciated lava tops. Vesicles and other cavities typically contain secondary quartz, agate, calcite, scolecite, stilbite, and apophyllite (Juckes 1972). Summarising, the Björnnutane lava succession records a transition from predominantly compound-braided to tabular-type flow fields (Fig. 8).

Kirwanveggen extrusive suite

The nunataks of southern Kirwanveggen are largely composed of lavas (Fig. 3) and exhibit a terraced appearance, trap topography, typical of many flood basalts (Fig. 7c). Plagioclase ^{40}Ar – ^{39}Ar dating has yielded plateau ages of 182–185 Ma (Duncan *et al.* 1997) for samples from the same stratigraphic level (unit #10 in Fig. 8). The reported data do not allow critical evaluation of the ages and the older ages may result from excess Ar (Zhang *et al.* 2003). The volcanic succession is underlain by Palaeozoic sedimentary rocks and Precambrian basement (Aucamp *et al.* 1972; Wolmarans & Kent 1982) (Fig. 8). The base of the lavas is typically at ~2100 m elevation (a.s.l.). The greatest stratigraphic section is made of 420 m of basalt at ‘nunatak B’ in the Lagfjella area (Faure *et al.* 1979; Harris *et al.* 1990). Field observations are suggestive of shallow (~1–3°), generally SE dipping of the strata (Faure *et al.* 1979; Harris *et al.* 1990), but the irregular lava surfaces render determination of the dip angle and direction difficult.

The Kirwanveggen lava succession is composed almost entirely of simple flow fields that vary in thickness from ~6 m up to >100 m (Faure *et al.* 1979; Harris *et al.* 1990). The lava succession at ‘nunatak B’ is made of 10–11 lava lobes and sheets (Fig. 8). Lava contacts are seldom exposed. Generalizing, the lava units which underlie a distinctive intensively jointed sheet lava are relatively thin (<50 m, frequently ~6–14 m; Faure *et al.* 1979), whereas the jointed flow and those atop of it are notably thick (80–100 m). Detailed descriptions of the lavas are lacking, but the lava tops typically are vesicular (Faure *et al.* 1979) and at least some units have rubbly crust (Fig. 5b). Pipe amygdules at the base are rare, but invariably indicate flow towards the east (Harris *et al.* 1990). The vesicles and voids are filled mainly with quartz, calcite, agate, and zeolite group minerals.

Overall, the Kirwanveggen succession is made of notably thick tabular-type lavas many of which may be rubbly pahoehoe. Sandstone intercalations (Aucamp *et al.* 1972; Harris *et al.* 1990) and thin clastic interbeds interpreted to represent pyroclastic material (‘ash bands’) have been reported in the succession (Harris *et al.* 1990), but the clastic intercalations have not been described in any detail. According to Harris *et al.* (1990), sparse sandstone intercalations are confined to the lower third of the stratigraphic column and one of such deposits infiltrates a flow-top breccia at the Tunga section, in the northernmost part of the basalt exposure of Kirwanveggen (Fig. 5b). Sparse, intrusive Jurassic rocks cut the basement in northern Kirwanveggen (Wolmarans & Kent 1982) and a single dolerite in southern Kirwanveggen, dated at 181 Ma (Zhang *et al.* 2003; Table 2), shows a chemical affinity to Ahlmannryggen intrusions (Riley *et al.* 2005).

Table 1. Characteristics features of the North Karoo, South Karoo, and Ferrar subprovinces of Gondwana LIP

Subprovince	age (Ma) ¹	polarity ²	⁸⁷ Sr/ ⁸⁶ Sr (180 Ma) ³	ϵ_{Nd} (180 Ma) ³	ΔNb ³	MgO (wt.%) ³	TiO ₂ (wt.%) ³	Zr/Y ³
South Karoo	174 – 189	R–N–R–N–R–N–R	0.703 – 0.709	–18 to +9	–	2 – 25	1 – 5	3 – 19
North Karoo	182 – 183	R–N	0.704 – 0.708	–5 to +4	+	3 – 8	1 – 2	3 – 6
Ferrar	182 – 183	N	0.709 – 0.712	–6 to –2	–	2 – 10	0.5 – 2	3 – 5

¹ Age data for North Karoo are U–Pb zircon and baddeleyite ages from Svensen *et al.* (2012), data for South Karoo are ⁴⁰Ar–³⁹Ar plagioclase ages from Duncan *et al.* (1997), Jourdan *et al.* (2004, 2005, 2008), and Luttinen *et al.* (2015) and U–Pb zircon ages from Luttinen *et al.* (2015), and data for Ferrar are U–Pb zircon ages from Burgess *et al.* (2015).

² Magnetic polarity data for Karoo are from Hargraves *et al.* (1997) and Moulin *et al.* (2011), and data for Ferrar are from McIntosh *et al.* (1982). R and N indicate reverse and normal polarity, respectively.

³ Geochemical data for Karoo are from the compilation of Luttinen (2018) and data for Ferrar are from Siders & Elliot (1985), Hergt *et al.* (1989), Fleming *et al.* (1992, 1995), Elliot *et al.* (1995, 1999), Wilhelm *et al.* (1996), Antonini *et al.* (1999), and Hanemann *et al.* (2004). Notice that data for the Dufek intrusion has not been used due to strong influence of accumulation processes on geochemical compositions. $\Delta\text{Nb} = 1.74 + \log (\text{Nb}/\text{Y}) - 1.92\log (\text{Zr}/\text{Y})$ as defined by Fitton *et al.* (1997).

Sembberget extrusive suite

Sembberget is an isolated small exposure of basalt lavas between Heimefrontfjella and Kirwanveggen (Fig. 3) and shows a similar trap topography to nunataks in southern Kirwanveggen (Jukes 1972). The lowermost lava unit is at ~2500 m elevation (a.s.l.) and the base of the ~250 m thick lava succession is not exposed. The volcanic rocks comprise 12–19 flow fields (Luttinen *et al.* 2010); the stratigraphic interpretation presented in figure 8 includes 18 flow fields identified using field observations and geochemical data. Generalising, the succession is dominated by thick tabular-type simple lavas. The basal lava is only partly exposed, but, based on compositional similarity, it may represent a similar massive simple inflated pahoehoe lava as the overlying ~30 m thick unit which contains vesicular zones and upper crust. It is overlain by a ~50 m thick series of six relatively thin (4–14 m) lava sheets which are interpreted to represent discrete eruptions. The overlying ~16 m thick compound-braided flow field has a complex, rubbly base and is covered with a thin layer of cross-bedded, red sandstone. The upper part is almost exclusively made of seven massive 18–20 m thick simple flow fields notably similar to those of Kirwanveggen. The first one directly above the sandstone has a distinct 4 m thick rubbly base and the lava contacts, when exposed, show vesicular and variably rubbly upper crusts. A thin compound flow field of strongly altered lobes is sandwiched between massive lava sheets. The capping lava is only partly exposed and is underlain by a red bole. Lava unit #17 has yielded a plagioclase ⁴⁰Ar–³⁹Ar plateau age of 181 Ma (Fig. 8; Table 2; Supplementary Table S1). Flow direction observations are lacking.

Ahlmannryggen-Sverdrupfjella intrusive suite

Flood basalt lavas are not exposed in Ahlmannryggen and H.U. Sverdrupfjella (Fig. 3), but a large number (>500) of mafic and ultramafic dykes and sills have been mapped in the region (Harris *et al.* 1991; Grantham 1996; Curtis *et al.* 2008). A significant portion of the dykes may be Proterozoic, however, and the subset of 47 dykes reported by Riley *et al.* (2005) provide the most reliable insight into the Karoo-age intrusions in the area. Imprecise whole-rock and groundmass ⁴⁰Ar–³⁹Ar ages point to emplacement at 180–190 Ma (Riley *et al.* 2005). Most of the dykes have been emplaced along pre-existing joints within the Proterozoic Borgmassivet intrusive suite in northern Ahlmannryggen. The predominant strike directions for the dykes and joints are NNE–SSW and ENE–WSW. Oblique jointing has resulted in offsetting segments and en echelon geometries in the Mesozoic dykes. The dykes are generally <5 m wide, but dykes up to 80 m wide have been reported by Riley *et al.* (2005). Dykes that are over 5 m wide are members of a geochemically distinctive subset (Group 2 of

Riley *et al.* 2005; see section Intrusive magma types below). Dykes which were emplaced in the ENE-WSW direction have been interpreted to be the oldest Jurassic intrusions in the area (Riley *et al.* 2005).

Associated intrusive suites

Schievestolen sill. A single Jurassic intrusion has been reported in the northernmost Heimefrontfjella (Fig. 3). The Schievestolen dolerite sill intrudes Permian sedimentary rocks and is exposed over ~2 km distance (Juckes 1972). An ^{40}Ar – ^{39}Ar plagioclase correlation age of ~184 Ma has been provided by Brewer *et al.* (1996), but the result is likely affected by excess Ar. The sill is mostly concordant and has fairly constant thickness of ~10 m about 30 m above the base of the sediments, but, in places, the intrusion transgresses the stratification (Fig. 7d). The sill is further typified by columnar jointing, a vesicular upper part, and development of ropy structures within large, flattened megavesicles (Fig. 4d; cf. Liss *et al.* 2002). Close to the base, the dolerite contains xenolithic quartz grains and small vesicles.

Mannefallknausane intrusions. Numerous mafic intrusions crosscut the 1.1 Ga granitoid basement of Mannefallknausane (Fig. 3) (Juckes 1968; Arndt *et al.* 1991). Most of the intrusions are <5 m thick sub-horizontal sills (dip angles mainly <15°) and usually follow the prominent sub-horizontal jointing of the basement, but are sometimes deflected by other joints (Juckes 1968). One sill is 12–20 m thick. Two ~2 m wide dykes strike ENE-WSW. None of the intrusions has been dated, but one has an ^{40}Ar – ^{39}Ar plagioclase spectrum suggestive of Middle Jurassic emplacement (Zhang *et al.* 2003) and the pristine magmatic mineralogy and geochemical similarities to Vestfjella flood basalts (Heinonen *et al.* 2010; Luttinen *et al.* 2015) also lend support for a Jurassic origin.

Table 2. Representative age data for Jurassic mafic rocks in Dronning Maud Land

Location	Rock type*	Method†	Age ($\pm 2\sigma$)‡	Reference
<i>Vestfjella</i>				
Muren West 73°43.8' S 15°06.3' W	VF1 gabbro	^{206}Pb – ^{238}U zrc. ID-TIMS	182 $\pm$ 1 Ma	Luttinen <i>et al.</i> 2015
Muren East 73°43.5' S 15°03.0' W	VF1 gabbro	^{206}Pb – ^{238}U zrc.+ bad. ID-TIMS	182 $\pm$ 1 Ma	Luttinen <i>et al.</i> 2015
Pagodromen 73°46.3' S 14°57.5' W	VF1 dolerite	^{40}Ar – ^{39}Ar plg. plateau	189 $\pm$ 2 Ma	Luttinen <i>et al.</i> 2015
Utpostane 73°55.2' S 15°35.6' W	VF3 dolerite	^{40}Ar – ^{39}Ar plg. mini-plateau	187 $\pm$ 3 Ma	Luttinen <i>et al.</i> 2015
Kjakebeinet 73°47.5' S 14°50.5' W	VFD dolerite	^{40}Ar – ^{39}Ar plg. plateau	186 $\pm$ 2 Ma	Luttinen <i>et al.</i> 2015
Utpostane 73°53.3' S 15°40.9' W	KW gabbro	^{40}Ar – ^{39}Ar plg. plateau	181 $\pm$ 1 Ma	Zhang <i>et al.</i> 2003
Kjakebeinet 73°46.9' S 14°52.6' W	Lamproite	^{40}Ar – ^{39}Ar phl. plateau	162 $\pm$ 2 Ma	Luttinen <i>et al.</i> 2002
<i>Kirwanveggen</i>				
Lagfjella 74°05.9' S 6°15.3' W	ARE dolerite	^{40}Ar – ^{39}Ar plg. plateau	181 $\pm$ 1 Ma	Zhang <i>et al.</i> 2003
<i>Semlberget</i>				
Nunatak 74°29.4' S 8°11.6' W	KW basalt	^{40}Ar – ^{39}Ar plg. plateau	181 $\pm$ 1 Ma	this study**

* VF1, VF3, VFD, KW, and ARE refer to chemically different magma types (see text)

† Mineral abbreviations: zrc. =zircon; bad. =baddeleyite; plg. =plagioclase; phl. =phlogopite

‡ $^{40}\text{Ar}/^{39}\text{Ar}$ ages are reported relative to FCTs monitor (28.29 Ma) and ^{40}K decay constants of Renne *et al.* (2011).

** Supplementary Table S2.

Geochemical characteristics

Geochemical data for representative samples of Karoo CFBs in DML are listed in Table 3 and the compiled dataset used in this study is given in supplementary Table S2. For analytical methods, the reader is referred to the original publications.

General features

The flood lavas and related intrusions of DML are subalkaline quartz or olivine normative tholeiites (Harris *et al.* 1990; Luttinen & Furnes 2000; Riley *et al.* 2005; Heinonen & Luttinen 2008; Luttinen *et al.* 2010, 2015). The great majority of them exhibits low-Mg basalt or basaltic andesite compositions. Olivine-rich, high-Mg picrite lavas are sporadically intercalated with basaltic lavas in Vestfjella. Picritic intrusions are relatively common in the dyke swarms at Vestfjella and Ahlmannryggen and also occur at Mannefallknausane (Luttinen *et al.* 2015; Riley *et al.* 2005). The Utpostane layered intrusion is mainly composed of high-Mg cumulate rock types (Vuori & Luttinen 2004).

The extrusive and intrusive rocks are characterized by notably variable compositions (Fig. 9). For instance, MgO ranges from 3 to 28 wt.%, SiO₂ from 44 to 57 wt.% and, TiO₂ from 0.3 to 5.5 wt.%. Generalising, concentrations of most major and minor elements (e.g. TiO₂ and FeO^T) and gabbro-incompatible trace elements (e.g. Zr and Y) correlate negatively with Mg-number (molar MgO/(MgO+0.9FeO^T)), whereas compatible elements (e.g. Ni) correlate positively and the trend of Al₂O₃ shows maximum values at Mg-number of ~0.55 (Fig. 9). While most of the analysed samples comprise broadly uniform trends, many of the intrusive rocks from Ahlmannryggen and Vestfjella have distinctively high contents of FeO^T and incompatible elements (TiO₂, Zr, and Y) and low Al₂O₃ at a given Mg-number (Fig. 9).

The initial isotopic compositions have been calculated at 180 Ma. The Nd and Sr isotopic ratios show remarkable variation from depleted compositions, indistinguishable from depleted upper mantle ($\epsilon_{\text{Nd}} +9$, $^{87}\text{Sr}/^{86}\text{Sr}$ 0.7035), to variably enriched compositions similar to Precambrian silicic crust (ϵ_{Nd} down to -18 , $^{87}\text{Sr}/^{86}\text{Sr}$ up to >0.710 ; Fig. 10a). In general, the isotopic ranges of the lavas and intrusions are similar, but the most isotopically depleted samples represent intrusive rock types. Data on Pb and Os isotopic compositions are limited to rare picritic rocks (Heinonen *et al.* 2010, 2014). The initial $^{187}\text{Os}/^{188}\text{Os}$ values vary from 0.124 to 0.143, but mainly record low values typical of primitive and depleted mantle reservoirs (Fig. 10b). The Pb isotopic data are characterized by variable $^{206}\text{Pb}/^{204}\text{Pb}$ (17.0–18.4), $^{208}\text{Pb}/^{204}\text{Pb}$ (37.0–38.3), variable $^{207}\text{Pb}/^{204}\text{Pb}$ (15.3–15.6) (Fig. 10c,d).

As in African Karoo, the Karoo tholeiites in DML have been divided into normal (low-Ti) and enriched (high-Ti) types based on incompatible element contents. Overall, ~30% of the analysed rock samples can be described as high-Ti types based on TiO₂ > 2 and Zr >200 ppm (Fig. 9), but the enriched types are overrepresented due to duplicate analyses of the same intrusive units (e.g. Riley *et al.* 2005; Heinonen *et al.* 2008). The high-Ti types are effectively limited to coastal areas at Vestfjella and Ahlmannryggen, whereas the low-Ti types are found at all localities. Both categories show pronounced variations in mantle-incompatible element and isotopic ratios which facilitates division of the igneous rocks into compositionally different groups often referred to as magma types. The following section summarizes the geochemical key features of the magma types using a uniform modified nomenclature. The petrological basis for the grouping is that fractional crystallization of tholeiitic basalt and picrite magmas has only a mild influence on incompatible element ratios such as Ti/Zr, Ti/P, Nb/La, Nb/Zr, and Zr/Y, so that different ratios are likely to indicate different magma plumbing systems.

Table 3. Representative elemental and isotopic compositions of Jurassic tholeiites in Dronning Maud Land

Sample	Z.1801.1 ¹	Z.1814.4 ¹	Z.1805.1 ¹	Z.1810.1 ¹	Z.1803.1 ^{1,2}	Z.1816.1 ^{1,2}	Z.1826.1 ^{1,9}
Magma type ¹⁰	AR1	AR1	AR2	AR2	ARD	ARD	ARE
Locality	Ahlmann ¹¹	Ahlmann ¹¹	Ahlmann ¹¹	Ahlmann ¹¹	Ahlmann ¹¹	Ahlmann ¹¹	Ahlmann ¹¹
	73°09.43' S	72°02.20' S	72°13.31' S	72°16.65' S	72°08.13' S	72°03.27' S	71°59.54' S
	2°08.18' W	2°47.80' W	3°25.02' W	3°25.43' W	3°18.25' W	2°42.74' W	3°21.64' W
SiO ₂ (wt.%)	52,43	55,53	51,95	50,47	49,15	48,66	49,33
TiO ₂	1,58	2,25	2,26	2,34	4,06	3,34	4,39
Al ₂ O ₃	12,15	14,59	14,43	14,11	12,02	9,38	8,81
FeO ^T	11,33	10,06	12,40	13,57	12,96	12,87	11,93
MnO	0,20	0,16	0,21	0,21	0,17	0,16	0,15
MgO	8,86	5,45	5,59	6,21	8,66	14,73	14,41
CaO	10,34	8,66	10,14	9,96	10,46	8,99	8,74
Na ₂ O	2,12	1,92	2,43	2,55	1,84	1,43	1,47
K ₂ O	0,80	1,27	0,36	0,35	0,44	0,21	0,43
P ₂ O ₅	0,19	0,12	0,25	0,24	0,24	0,23	0,34
LOI	1,67	0,56	1,30	0,50	0,69	1,89	2,05
Cr (ppm)	668	76	84	84	479	803	834
Ni	294	83	64	66	390	500	666
Sc	24	30	32	33	30	37	34
V	258	425	327	336	345	375	319
Cu	95	206	100	97	146	146	140
Zn	93	124	119	118	144	147	141
Ga	18	23	20	20	21	20	17
Ta	0,5	0,6	0,8	0,8	0,7	0,6	1,5
Nb	7,2	9,4	11,9	11,9	10,0	8,4	22,0
Hf	3,1	4,4	4,1	3,9	7,4	8,1	10,8
Zr	122,0	163,0	159,0	153,0	275,0	295,0	413,0
Y	27,2	30,1	34,4	34,3	43,7	43,9	38,6
Ba	310,0	314,0	115,0	100,0	112,0	38,0	337,0
Rb	14,1	12,9	6,5	6,9	11,6	2,4	21,9
Sr	248,0	356,0	181,0	213,0	257,0	246,0	584,0
U	0,6	0,5	0,5	0,4	0,3	0,2	0,5
Th	1,9	2,4	1,4	1,2	1,2	0,4	2,1
Pb	4,2	4,2	11,5	2,0	2,1	0,8	3,0
La	14,7	17,5	12,8	12,3	11,0	7,5	27,7
Ce	31,8	38,6	30,6	29,9	30,8	24,8	71,2
Pr	4,4	5,5	4,6	4,5	5,4	5,0	11,7
Nd	18,9	24,5	21,4	21,0	29,3	29,6	55,6
Sm	4,5	5,9	5,5	5,5	9,4	9,9	13,0
Eu	1,4	1,9	1,8	1,8	3,2	3,4	3,9
Gd	5,2	6,4	6,5	6,4	11,0	11,4	12,1
Tb	0,9	1,0	1,0	1,0	1,7	1,7	1,7
Dy	4,9	5,6	6,0	6,0	8,9	9,1	8,4
Ho	1,0	1,1	1,2	1,2	1,6	1,7	1,5
Er	2,5	2,8	3,3	3,2	3,9	3,9	3,3
Tm	0,4	0,4	0,5	0,5	0,6	0,6	0,5
Yb	2,2	2,4	3,1	3,0	3,0	3,0	2,5
Lu	0,3	0,4	0,5	0,5	0,4	0,4	0,4
⁸⁷ Rb/ ⁸⁶ Sr	0,1637	0,1047	0,1038	0,0936	0,1302	0,0284	0,1084
⁸⁷ Sr/ ⁸⁶ Sr	0,707608	0,70881	0,704604	0,704802	0,705842	0,703647	0,705652
⁸⁷ Sr/ ⁸⁶ Sr (180 Ma)	0,707189	0,708542	0,704338	0,704563	0,705509	0,703574	0,705374
¹⁴⁷ Sm/ ¹⁴⁴ Nd	0,1514	0,1479	0,1588	0,1605	0,2019	0,209	0,1481
¹⁴³ Nd/ ¹⁴⁴ Nd	0,512271	0,512283	0,512631	0,512682	0,512902	0,513113	0,51266
εNd(180 Ma)	-6,1	-5,8	0,8	1,7	5,1	9,0	1,6
²³⁸ U/ ²⁰⁴ Pb	na	na	na	na	9,90	11,91	10,62
²³² Th/ ²⁰⁴ Pb	na	na	na	na	34,84	34,71	45,07
²⁰⁶ Pb/ ²⁰⁴ Pb	na	na	na	na	18,03	18,57	17,61
²⁰⁷ Pb/ ²⁰⁴ Pb	na	na	na	na	15,43	15,51	15,38
²⁰⁸ Pb/ ²⁰⁴ Pb	na	na	na	na	37,80	38,03	37,84
²⁰⁶ Pb/ ²⁰⁴ Pb (180 Ma)	na	na	na	na	17,75	18,24	17,31
²⁰⁷ Pb/ ²⁰⁴ Pb (180 Ma)	na	na	na	na	15,41	15,49	15,36
²⁰⁸ Pb/ ²⁰⁴ Pb (180 Ma)	na	na	na	na	37,49	37,72	37,44
Re	na	na	na	na	0,36	0,83	0,28
Os	na	na	na	na	0,63	1,31	0,71
¹⁸⁷ Re/ ¹⁸⁸ Os	na	na	na	na	2,759	3,078	1,936
¹⁸⁷ Os/ ¹⁸⁸ Os	na	na	na	na	0,135	0,134	0,144
¹⁸⁷ Os/ ¹⁸⁸ Os (180 Ma)	na	na	na	na	0,127	0,125	0,138

Data sources: ¹ Riley *et al.* (2005); ² Heinonen *et al.* 2014; ³ Heinonen & Luttinen (2008); ⁴ Heinonen *et al.* (2010); ⁵ Luttinen & Furnes (2000); ⁶ Luttinen¹⁰ See text for definition of magma types; ¹¹ Ahlmann = Ahlmannryggen; ¹² Kirwan = Kirwanveggen

Z.1833.2 ^{1,9}	AL/B7-03 ^{3,4}	AL/WM1e-98 ^{3,4}	AL/B7-98 ^{3,4}	JSH/B006 ⁴	307-AVL ⁴	VF57-85 ⁵	B16-AVL ⁶
ARE	VFD	VFD	VFE	VFE	VF1	VF1	VF2
Ahlmann ¹¹	Vestfjella	Vestfjella	Vestfjella	Vestfjella	Vestfjella	Vestfjella	Vestfjella
72°02.21' S	73°02.50' S	73°43.82' S	73°01.30' S	73°01.77' S	73°12.17' S	73°01.68' S	73°01.23' S
3°30.34' W	13°24.00' W	15°06.17' W	13°23.93' W	13°25.17' W	13°49.55' W	13°25.40' W	13°21.73' W
47,71	47,05	43,65	49,07	44,86	47,50	53,36	50,79
4,24	1,70	2,07	3,16	3,01	0,50	1,38	1,59
8,42	8,59	8,85	11,29	8,19	7,71	14,97	11,16
12,37	12,87	15,10	13,69	16,19	12,42	9,71	12,36
0,17	0,20	0,20	0,18	0,21	0,18	0,17	0,18
15,23	18,57	18,88	10,49	15,54	26,22	5,99	11,67
8,83	9,24	9,02	9,37	9,02	4,64	10,50	9,87
1,91	1,41	1,53	1,76	1,75	0,66	2,58	1,90
0,75	0,23	0,50	0,59	0,87	0,13	1,07	0,22
0,38	0,13	0,19	0,39	0,36	0,06	0,27	0,12
3,33	1,23	1,58	3,86	2,42	na	1,77	4,22
918	1132	1022	357	579	1195	234	702
789	807	880	370	660	1321	65	328
28	28	28	21	19	17	28	29
283	321	364	258	285	144	277	308
133	139	171	80	116	na	95	150
101	95	100	132	152	na	95	116
17	15	17	25	20	na	20	na
1,8	0,4	0,4	1,2	1,2	0,1	0,4	0,2
27,5	5,5	6,0	17,1	18,5	1,5	8,1	3,5
12,0	2,2	2,7	4,1	4,0	0,9	3,5	2,6
477,0	80,0	104,0	160,0	151,0	41,0	137,0	92,0
34,8	15,1	16,6	28,2	23,7	9,5	28,7	27,0
702,0	55,8	90,5	164,8	225,0	60,0	508,0	79,0
33,4	6,7	8,4	7,9	20,8	10,5	17,0	5,0
1005,0	242,2	302,8	415,0	520,0	76,0	349,0	244,0
0,9	0,1	0,1	0,5	0,5	0,1	0,4	0,2
4,5	0,5	0,5	1,9	1,7	0,5	1,6	0,6
5,6	1,1	1,3	2,2	2,2	na	4,3	1,6
59,8	7,5	7,8	17,9	18,9	3,8	20,4	7,0
137,9	20,0	19,8	38,2	43,7	8,5	41,8	16,5
20,3	3,0	2,9	5,0	6,1	na	5,0	na
84,5	13,8	14,5	23,5	27,4	5,1	22,0	11,2
15,4	3,6	4,3	7,1	7,1	1,5	5,4	3,7
4,2	1,3	1,5	2,6	2,5	0,6	1,8	1,4
11,7	3,7	4,5	7,5	7,2	1,8	5,6	4,3
1,6	0,6	0,7	1,2	1,1	na	0,9	0,8
7,6	3,4	3,8	6,5	5,9	1,9	5,6	na
1,3	0,6	0,7	1,1	1,0	0,4	1,1	na
3,0	1,6	1,5	2,5	2,3	na	2,8	na
0,4	0,2	0,2	0,3	0,3	na	0,4	na
2,2	1,1	1,1	1,6	1,4	0,8	2,2	2,0
0,3	0,2	0,2	0,2	0,2	0,1	0,3	0,3
0,0961	0,06763	0,07992	0,05472	0,11394	0,41641	0,14700	0,05346
0,705188	0,703302	0,70320	0,70518	0,70457	0,70804	0,70703	0,70634
0,704942	0,703128917	0,70300	0,70504	0,70428	0,70697	0,70665	0,70621
0,1167	0,1482	0,16330	0,16150	0,14830	0,16684	0,13770	0,17730
0,512321	0,513004	0,51301	0,51269	0,51276	0,51206	0,51200	0,51263
-4,3	8,3	8,0	1,8	3,5	-10,7	-11,1	0,3
9,28	10,75	7,28	13,85	12,30	6,74	na	na
51,13	28,11	24,76	58,28	48,51	45,25	na	na
17,46	18,12	17,83	18,26	18,26	17,20	na	na
15,43	15,50	15,49	15,60	15,54	15,44	na	na
37,86	37,73	37,52	38,28	38,26	37,93	na	na
17,20	17,82	17,62	17,87	17,91	17,01	na	na
15,42	15,49	15,48	15,58	15,53	15,43	na	na
37,40	37,48	37,30	37,76	37,82	37,53	na	na
0,82	0,74	0,79	0,44	0,55	0,07	na	na
1,80	1,22	0,90	0,26	0,15	3,02	na	na
2,207	2,910	4,271	8,299	17,290	0,106	na	na
0,137	0,134	0,141	0,167	0,192	0,131	na	na
0,130	0,126	0,128	0,143	0,140	0,130	na	na

¹ *et al.* (1998); ⁷ Luttinen *et al.* (2010); ⁸ Harris *et al.* (1990); ⁹ Heinonen (unpublished data)

VF72-85 ⁵	sk229-AVL ^{4,5}	VF126-85 ⁵	Z.1610.14 ⁷	Z.1610.7 ⁷	255-AVL-92 ⁷	Z.1610.9 ⁷	Z.1609.2 ⁷
VF2	VF3	VF3	VF3	VF3	VF1	VF1	KW
Vestfjella	Vestfjella	Vestfjella	Björnnutane	Björnnutane	Björnnutane	Björnnutane	Sembberget
73°01.68' S	73°46.40' S	73°44.65' S	74°37.40' S	74°37.40' S	74°37.10' S	74°37.40' S	74°28.60' S
13°25.40' W	14°56.53' W	14°47.42' W	9°59.00' W	9°59.00' W	10°03.60' W	9°59.00' W	8°08.30' W
50,49	48,14	49,51	50,04	47,61	52,28	51,70	51,93
3,08	1,00	1,50	1,70	1,93	1,26	1,44	1,59
13,06	9,49	15,14	14,60	14,92	15,98	15,55	13,95
14,77	13,10	10,72	11,38	12,80	10,14	11,09	12,55
0,17	0,20	0,17	0,17	0,21	0,16	0,17	0,19
5,29	19,13	7,92	7,40	7,53	5,47	5,83	6,24
9,61	7,68	12,57	11,56	12,28	11,81	9,98	10,37
2,39	1,02	2,12	2,48	2,31	2,43	3,25	2,55
0,89	0,10	0,17	0,53	0,16	0,30	0,80	0,47
0,26	0,14	0,19	0,14	0,25	0,17	0,19	0,15
3,00	4,00	2,29	0,72	2,07	4,79	3,56	0,58
115	1413	546	255	318	157	175	146
110	642	170	95	139	77	73	68
26	25	34	29	31	27	28	36
383	223	295	321	324	232	266	288
146	66	95	135	150	74	106	135
140	91	78	88	101	94	94	95
28	15	16	22	20	19	22	21
0,5	0,2	0,4	0,2	0,2	0,2	0,3	0,3
6,7	3,1	4,9	3,0	4,0	8,0	4,0	4,0
5,1	1,5	2,0	2,7	2,5	2,4	2,8	3,1
173,0	56,0	80,0	101,0	100,0	86,0	110,0	117,0
43,0	15,0	17,0	23,0	24,0	20,0	22,0	29,0
239,0	71,0	140,0	175,0	219,0	282,0	344,0	210,0
18,0	3,0	2,0	12,0	6,0	11,0	20,0	11,0
357,0	125,0	320,0	234,0	330,0	308,0	323,0	188,0
0,7	0,1	0,1	0,2	0,1	0,3	0,4	0,2
1,5	0,2	0,2	0,8	0,3	1,4	1,7	1,4
3,5	1,4	0,9	2,1	1,7	3,8	4,1	2,9
14,9	5,2	5,7	7,3	7,9	10,6	12,6	9,9
33,8	11,4	13,8	17,8	19,8	23,7	27,7	22,5
4,7	1,6	2,0	2,8	3,1	3,3	3,9	3,3
22,8	7,8	10,2	14,0	16,0	15,3	17,6	15,7
7,3	2,4	3,2	3,9	4,2	3,7	4,3	4,3
2,5	0,9	1,3	1,4	1,6	1,3	1,4	1,4
8,7	2,8	3,9	4,8	5,0	4,1	4,7	5,2
1,5	0,5	0,6	0,8	0,8	0,7	0,7	0,9
9,2	3,0	3,7	4,5	4,5	3,8	4,3	5,2
1,8	0,6	0,7	0,9	0,9	0,7	0,8	1,1
4,3	1,6	1,8	2,2	2,2	1,9	2,2	2,8
0,6	0,2	0,2	0,3	0,3	0,3	0,3	0,4
3,3	1,3	1,4	1,8	1,9	1,7	2,0	2,6
0,5	0,2	0,2	0,3	0,3	0,3	0,3	0,4
0,15130	0,06101	0,00900	0,07992	0,00337	0,07805	0,14429	0,087790849
0,70657	0,70509	0,70366	0,70426	0,70409	0,70663	0,70620	0,705677
0,70619	0,70493	0,70363	0,70405	0,70408	0,70643	0,70583	0,70545232
0,19330	0,16229	0,19000	0,17834	0,17018	0,15342	0,15097	0,164476116
0,51252	0,51252	0,51273	0,51278	0,51268	0,51234	0,51232	0,512509822
-2,1	-1,4	2,0	3,2	1,4	-4,9	-5,3	-1,8
na	3,14	na	na	na	na	na	na
na	10,71	na	na	na	na	na	na
na	17,37	na	na	na	na	na	na
na	15,54	na	na	na	na	na	na
na	37,16	na	na	na	na	na	na
na	17,28	na	na	na	na	na	na
na	15,54	na	na	na	na	na	na
na	37,06	na	na	na	na	na	na
na	0,23	na	na	na	na	na	na
na	2,02	na	na	na	na	na	na
na	0,545	na	na	na	na	na	na
na	0,131	na	na	na	na	na	na
na	0,130	na	na	na	na	na	na

[illegible]

Vestfjella type 1 (VF1). The northern part of Vestfjella is dominated by low-Ti picrite and basalt (Mg-number 0.4–0.8) lavas which are typified by low Ti/Zr (mainly <80), Ti/P (mainly <14), Nb/La (mainly <0.6), and Zr/Y (mainly 4–6) and high La/Sm (<2) (CT1 of Luttinen & Siivola 1997) (Figs 8 and 11). Compared to other Vestfjella lavas, VF1 lavas have low TiO₂ and FeO^T, but high Zr at a given Mg-number (Fig. 9). Initial Nd and Sr isotopic compositions are enriched (ϵ_{Nd} –2 to –18, $^{87}\text{Sr}/^{86}\text{Sr}$ 0.705–0.711) (Fig. 10a). A single picrite lava has initial $^{187}\text{Os}/^{188}\text{Os}$ (0.130) akin to primitive mantle, notably low $^{206}\text{Pb}/^{204}\text{Pb}$ (17.0), and low $^{207}\text{Pb}/^{204}\text{Pb}$ (15.4) and $^{208}\text{Pb}/^{204}\text{Pb}$ (37.5) (Fig. 10b–d). Several of the Vestfjella intrusions belong to VF1 (Luttinen *et al.* 2015) and geochemically resembling lavas of Björnnutane (BN2 of Luttinen *et al.* 2010) can be correlated with this category (Figs 8–11). Some dykes at Ahlmannryggen (AR1; Group1 of Riley *et al.* 2005) show broad similarity to VF1.

Vestfjella type 2 (VF2). The Basen section, northernmost Vestfjella, is dominated by basalt and rare picrite lavas (Mg-number 0.4–0.7) that are transitional between low-Ti and high-Ti compositions judging from their TiO₂ (mainly >2 wt.%) and Zr (<200 ppm) (CT2 of Luttinen & Siivola 1997) (Figs 8 and 9). Type VF2 is distinguished from other Vestfjella lavas by its combination of high Ti/Zr (80–120) and Ti/P (mainly 15–20), and low Nb/La (<0.5) (Fig. 11). Concentrations of TiO₂ and FeO^T are higher than in type VF1 at a given Mg-number. Initial Nd and Sr isotopic compositions are variably enriched (ϵ_{Nd} +1 to –8, $^{87}\text{Sr}/^{86}\text{Sr}$ 0.706–0.708) (Fig. 10a). Isotopic data on Os and Pb for VF2 are lacking.

Vestfjella type 3 (VF3). The exposed volcanic bedrock of southern Vestfjella is dominated by VF3 type of low-Ti lavas that effectively lack the strong geochemical crustal signature which typifies other low-Ti lavas of DML (CT3 of Luttinen & Siivola 1997). The VF3 lavas range from picrite to basalt (Mg-number 0.4–0.8) and have low Ti/P (mainly <14) combined with high Ti/Zr (80–150) and low Zr/Y (<5), whereas Nb/La is relatively high (mainly 0.5–0.7) and La/Sm low (<2.5) compared to other Vestfjella lavas (Fig. 11). Concentrations of TiO₂ and FeO^T are higher and those of Zr lower than in VF1 at the same Mg-numbers (Fig. 9). Isotopic compositions vary from mildly depleted to mildly enriched (ϵ_{Nd} +4 to –2, $^{87}\text{Sr}/^{86}\text{Sr}$ 0.7035–0.7050) (Fig. 10a). Two VF3 picrites have initial $^{187}\text{Os}/^{188}\text{Os}$ (~0.130) and $^{206}\text{Pb}/^{204}\text{Pb}$ (~17.3) quite similar to those of VF1, but $^{207}\text{Pb}/^{204}\text{Pb}$ (~15.5) and $^{208}\text{Pb}/^{204}\text{Pb}$ (~37.1) are dissimilar (Fig. 10b–d). The Vestfjella dyke swarm is mainly composed of VF3 (Luttinen *et al.* 2015) and geochemically similar lavas dominate the Björnnutane succession (BN1 of Luttinen *et al.* 2010) (Figs 8–11).

Kirwanveggen type (KW). The lava successions of Kirwanveggen and Sembberget are composed of geochemically notably uniform basalts (Mg-number 0.4–0.6) typified by low TiO₂ and Zr, but high FeO^T at a given Mg-number (Harris *et al.* 1990; Luttinen *et al.* 2010) (Fig. 9). Their compositions are in many respects intermediate between those of the Vestfjella types VF1–3; Ti/Zr are mainly within 70–100, Ti/P is 9–15, La/Sm is 2–3, and Nb/La is mainly <0.6 (Fig. 11). The Kirwanveggen type is readily distinguished from the Vestfjella types due to coupling of low Ti/Zr and Zr/Y (Fig. 11c). In the case of Kirwanveggen lavas, the initial Nd isotopic compositions are chondritic or mildly depleted (ϵ_{Nd} +3 to 0), but the Sembberget lavas also include mildly enriched compositions (ϵ_{Nd} +2 to –5) (Fig. 10a). The initial Sr isotopic compositions are mostly mildly enriched, but the Sembberget lavas range to strongly enriched compositions ($^{87}\text{Sr}/^{86}\text{Sr}$ 0.7045–0.7055) (Fig. 10a). Isotopic data on Os and Pb for KW are lacking. In Figure 8, the enriched subtype has been distinguished from the main group as Kirwanveggen type E. One simple flow in the Björnnutane section has been correlated with the enriched subtype (Luttinen *et al.* 2010).

Fig. 9. Variations in (a) TiO_2 (wt.%), (b) Al_2O_3 (wt.%), (c) FeO^T (wt.%), (d) Ni (ppm), (e) Zr (ppm), and (f) Y (ppm) v. Mg-number (molar $\text{MgO}/(\text{MgO} + 0.9\text{FeO}^T)$) in the Karoo CFBs of DML. Compositions of different volcanic (Vol) and intrusive (Int) magma types of Vestfjella (VF), Björnnutane (BN), Kirwanveggen and Sembberget (KW), and Ahlmannryggen (AR) are shown with filled and open symbols, respectively (exception Utpostane, UP) (see text for explanation of magma types). The conventional low-Ti v. high-Ti compositional boundary is shown in (a) and (e) (Erlank *et al.* 1988). Compositions of Björnnutane lavas (BN1 and BN2) are circled in (c). Geochemical data are from Supplementary Table S2.

Intrusive magma types

At Vestfjella, the majority of the intrusive, sub-volcanic dykes and sills can be correlated with the volcanic magma types (Figs 9–11). Importantly, sampling of the Vestfjella dyke swarm and intrusions in Mannefallkanusane and Ahlmannryggen has also revealed compositional types that lack extrusive equivalents. The geochemical assessment of the Karoo-related intrusions in Ahlmannryggen and H.U. Sverdrupfjella is based on data reported by Riley *et al.* (2005) and Heinonen *et al.* (2013, 2014), because the datasets of Harris *et al.* (1991) and Grantham (1996) lack precise trace element and isotopic data and also may include Proterozoic dykes (Riley *et al.* 2005). The intrusive rock types of Ahlmannryggen probably represent feeder fissures of now eroded lavas.

Vestfjella depleted type (VFD). A suite of geochemically quite variable dyke rocks can be collectively designated as Vestfjella depleted type (VFD) based on their depleted Nd isotopic compositions (depleted ferropicrites and low-Nb of Heinonen *et al.* 2010; CT3-E of Luttinen *et al.* 2015). Three of the intrusions are found in Mannefallkanusane. This magma type shows a notably wide range of basalt and picrite compositions (Mg-numbers 0.3–0.8). The VFD dykes exhibit low-Ti to high-Ti compositions with TiO_2 of 1–5 wt.%, Zr of 50–300 ppm, and Zr/Y of 4–7 and are typified by high Ti/Zr (90–150), Ti/P (13–18), and Nb/La (0.6–0.9) as well as high FeO^T at given Mg-number (Figs 9 and 11). The initial Nd isotopic compositions vary from strongly to mildly depleted ($\epsilon_{\text{Nd}} +8$ to $+2$) and initial Sr isotopic ratios from depleted to mildly enriched ($^{87}\text{Sr}/^{86}\text{Sr}$ 0.7035–0.7055) (Fig. 10a). The initial Os isotopic ratios

are low ($^{187}\text{Os}/^{188}\text{Os}$ 0.126–0.129; Fig. 10b). Apart from two crustally contaminated samples that have exceptionally high and low Pb isotopic ratios (Heinonen *et al.* 2010), the VFD dykes are typified by rather uniform $^{206}\text{Pb}/^{204}\text{Pb}$ (17.6–17.9), $^{207}\text{Pb}/^{204}\text{Pb}$ (~15.5), and $^{208}\text{Pb}/^{204}\text{Pb}$ (37.4–37.5) (Fig. 10c-d).

Vestfjella enriched type (VFE). A small number of dykes show broad geochemical similarities to ocean island basalts (OIB) and are referred here collectively as Vestfjella enriched type (VFE) (enriched ferropicrites of Heinonen & Luttinen 2008; high-Nb basalts of Luttinen *et al.* 2015). The VFE dykes have high-Ti basalt and picrite compositions (Mg-number 0.4–0.7) with TiO_2 of 2–3 and Zr/Y of ~6 (Figs 9 and 11). They show overlap with VF3 in Ti/Zr v. Ti/P plot, but are readily distinguished from all other Vestfjella magma types by their relative enrichment of Nb, with notably high Nb/La at given Ti/Zr and high Nb/Zr (Fig. 11). The initial Nd and Sr isotopic compositions are mainly mildly depleted and cluster close to primitive mantle ($\epsilon\text{Nd} +4$ to -1 , $^{87}\text{Sr}/^{86}\text{Sr}$ 0.7035–0.7055) (Fig. 10a). The Pb isotopic ratios are somewhat higher than in most VFD ($^{206}\text{Pb}/^{204}\text{Pb}$ ~17.9, $^{207}\text{Pb}/^{204}\text{Pb}$ ~15.6, and $^{208}\text{Pb}/^{204}\text{Pb}$ ~37.8), but $^{187}\text{Os}/^{188}\text{Os}$ values are much higher (0.140–0.143) and record the most radiogenic compositions in the Jurassic CFBs of DML (Fig 10b-d).

Utpostane type (UP). The geochemical compositions of the gabbroic rocks of Utpostane layered intrusion are mainly controlled by accumulation processes (Vuori & Luttinen 2004). Compositions of samples from the capping Zone 1 and a gabbroic apophysis are likely to be least-affected by accumulation and provide the best proxy for parental magma compositions (Luttinen & Vuori 2006). Detailed comparison reveals that UP type magmas are geochemically different from the other magma types of Vestfjella and show many similarities to the Kirwanveggen magma type (Luttinen *et al.* 2010) with, for example, low Zr/Y (~4), intermediate Ti/Zr (~90), and enriched Nd and Sr isotopic compositions ($\epsilon\text{Nd} -2$, $^{87}\text{Sr}/^{86}\text{Sr}$ ~0.7055) (Figs 10a and 11). Isotopic data on Os and Pb for UP are lacking.

Ahlmannryggen type 1 (AR1). A small set of dykes in Ahlmannryggen (Group 1 of Riley *et al.* 2005) shows affinity to VF1 lavas and dykes of Vestfjella, although TiO_2 (1.5–2.3 wt.%) contents are somewhat higher at given Mg-number (0.4–0.6) and straddle the low-Ti v. high-Ti boundary (Fig. 9). Similar to VF1, AR1 is typified by relatively low Ti/Zr (80–90), Ti/P (~15), Nb/La (~0.6) and Zr/Y (4–5) (Fig. 11), as well as enriched initial Nd and Sr isotopic compositions ($\epsilon\text{Nd} -6$, $^{87}\text{Sr}/^{86}\text{Sr}$ 0.706–0.709) (Fig. 10a). Isotopic data on Os and Pb for AR1 are lacking.

Ahlmannryggen type 2 (AR2). Another group of dykes in Ahlmannryggen can be distinguished from other magma types by combined high Nb/La (~0.9) and low Zr/Y (~5) (Group 2 of Riley *et al.* 2005). Overall, Ahlmannryggen type AR2 is geochemically quite uniform with low Mg-number (0.4–0.5), intermediate TiO_2 (~2 wt.%), Zr (~150 ppm), Ti/Zr (90–100), and Ti/P (12–15) (Figs 9 and 11). Isotopically, these dykes are typified by mildly depleted compositions ($\epsilon\text{Nd} +1$, $^{87}\text{Sr}/^{86}\text{Sr}$ ~0.704) (Fig. 11). The exceptionally wide dykes (5–80 m) in Ahlmannryggen belong to type AR2 (Riley *et al.* 2005). Isotopic data on Os and Pb for AR2 are lacking.

Ahlmannryggen depleted type (ARD). A group of high-Ti basalt and picrite dykes in Ahlmannryggen can be distinguished from other magma types in DML by their high Ti/P (20–25) and Nb/La (>1) at intermediate Ti/Zr (60–110) (Fig. 11) (Group 3 of Riley *et al.* 2005). The ARD dykes are further characterized by notably high TiO_2 (3–5 wt.%), FeO^{T} (12–14 wt.%), Zr (200–300 ppm), and Y (35–45 ppm) at a given Mg-number (0.5–0.8) (Fig. 9). High Zr/Y (6–7) underline the enriched incompatible element compositions of these dykes, but the strongly incompatible elements are relatively with, for example, La/Sm and Nb/Zr

below primitive mantle values (Fig. 11). The ARD dykes include the isotopically most depleted samples of DML (ϵ_{Nd} 5–9, $^{87}\text{Sr}/^{86}\text{Sr}$ 0.704–0.706) (Fig. 10a). The initial $^{187}\text{Os}/^{188}\text{Os}$ values are invariably low (0.124–0.128), $^{206}\text{Pb}/^{204}\text{Pb}$ (17.4–18.4), $^{208}\text{Pb}/^{204}\text{Pb}$ (37.0–37.9), $^{207}\text{Pb}/^{204}\text{Pb}$ (15.3–15.5) show notable variability (Fig. 10b–d).

Ahlmannryggen enriched type (ARE). Another high-Ti magma type in Ahlmannryggen is distinguished by its very high Zr (>300 ppm) (Group 4 of Riley *et al.* 2005). The ARE dykes resemble the ARD dykes in having exceptionally high TiO_2 (4–5 wt.%) and Y (35–45) at a given Mg-number (0.45–0.75) (Fig. 9) and plots apart from other magma types at low Ti/Zr (40–70) because of high Ti/P (14–22), Nb/La (0.5–0.9), and Zr/Y (7–16) (Fig. 11). The initial Nd compositions cluster around primitive mantle (ϵ_{Nd} +2 to –5) and those of Sr are mildly enriched ($^{87}\text{Sr}/^{86}\text{Sr}$ 0.705–0.706) (Fig. 10a). The initial $^{187}\text{Os}/^{188}\text{Os}$ (0.122–0.138), $^{206}\text{Pb}/^{204}\text{Pb}$ (17.2–17.9), $^{207}\text{Pb}/^{204}\text{Pb}$ (15.4–15.5), and $^{208}\text{Pb}/^{204}\text{Pb}$ (37.4–38.1) show notable variability (Fig. 10b–d).

Fig. 10. Variations in initial (a) ϵ_{Nd} v. $^{87}\text{Sr}/^{86}\text{Sr}$, (b) ϵ_{Nd} v. $^{187}\text{Os}/^{188}\text{Os}$, (c) $^{207}\text{Pb}/^{204}\text{Pb}$ v. $^{206}\text{Pb}/^{204}\text{Pb}$, and (d) $^{208}\text{Pb}/^{204}\text{Pb}$ v. $^{206}\text{Pb}/^{204}\text{Pb}$ in the Karoo CFBs of DML calculated at 180 Ma. Compositions of different volcanic (Vol) and intrusive (Int) magma types are shown with filled and open symbols, respectively (exception Utpostane). Compositions of Southwest Indian Ridge (SWIR) MORB (le Roex *et al.* 1983, 1992; Mahoney *et al.* 1992) are shown for comparison in (a), (d), and (e). PM is chondritic primitive mantle (Zindler & Hart 1986; Meisel *et al.* 2001). Geochemical and isotopic data sources and magma type abbreviations as in figure 9.

Fig. 11. Geochemical grouping of Karoo CFBs of DML into magma types in (a) Ti/P v. Ti/Zr, (b) Nb/La v. Ti/Zr, (c) Zr/Y v. Ti/Zr, and (d) La/Sm v. Nb/Zr diagrams. Compositions of different volcanic (Vol) and intrusive (Int) magma types are shown with filled and open symbols, respectively (exception Utpostane). The conventional low-Ti v. high-Ti compositional boundary is shown in (c) (Erlank *et al.* 1988). PM is primitive mantle (McDonough & Sun 1995). Geochemical data sources and magma type abbreviations as in figure 9.

Petrology – mantle sources and differentiation

Some of the intrusive rock types lack geochemical indications of crustal contamination and, therefore, provide the best source of information on the mantle sources (Luttinen *et al.* 1998; Luttinen & Furnes 2000; Riley *et al.* 2005; Heinonen & Luttinen 2008, 2010; Heinonen *et al.* 2010, 2013, 2014, 2015, 2018; Heinonen & Kurz 2015). Detailed isotopic (Nd, Sr, Pb, Os) and chemical studies of picrite samples of VFD, VFE, ARD, and ARE type dykes have defined four mantle components that fall into depleted and enriched categories. Tholeiitic compositions indicate a relatively high degree of melting, which means that the ratios of highly incompatible elements in the nearly undifferentiated picrites closely correspond to those of their respective mantle sources.

Mantle sources

Depleted mantle sources. The picrite samples of VFD type dykes exhibit Nd, Sr, Pb, Os, and He isotopic and chemical characteristics indicative of a depleted upper mantle peridotite source (DM in Fig. 12) notably similar to that of modern Southwest Indian Ocean MORB

(e.g. $\epsilon\text{Nd} +8$; $\text{La}/\text{Sm} \sim 0.8$ and $\text{Nb}/\text{Zr} \sim 0.5$ relative to primitive mantle) (Figs 10–12) (Heinonen & Luttinen 2008, 2010; Heinonen *et al.* 2010, 2018; Heinonen & Kurz 2015). Variable contents of fluid-mobile Ba and Sr in the picrites and O isotopic data on olivine phenocrysts point to mild heterogeneity which has been interpreted to result from addition of subduction-related fluids into sub-Gondwanan convective upper mantle (Heinonen *et al.* 2018). The ARD picrite dykes reveal another kind of Nd and Sr isotopically (e.g. $\epsilon\text{Nd} +9$) depleted mantle source that shows strong relative depletion of highly incompatible elements (La/Sm and $\text{Nb}/\text{Zr} \sim 0.5$ relative to primitive mantle; Fig. 11) but has notably high concentrations of incompatible elements in general (Fig. 9). Their Sr and Os isotopic compositions and whole-rock and olivine chemical characteristics point to derivation from pyroxenite-rich mantle (PX1 in Fig. 12) that may contain recycled altered oceanic crust (Riley *et al.* 2005; Heinonen *et al.* 2013, 2014).

Enriched mantle sources. The OIB-like high-Ti VFE and ARE dykes record enriched mantle sources. Both types have a chemical signature of pyroxenite-rich sources with broadly similar mildly depleted Nd and Sr isotopic compositions ($\epsilon\text{Nd} +4$) (Riley *et al.* 2005; Heinonen & Luttinen 2008; Heinonen *et al.* 2010, 2013). Detailed geochemical comparison (e.g. Fig. 11) indicates differences that require generation of the VFE and ARE dykes from distinctive reservoirs, however. Most notably, VFE has unusually high (i.e. primitive mantle-like) ΔNb and represents the only Nb-undepleted magma type of DML and reveal an enriched (Nb/Zr 0.10–0.15, La/Sm 2–4, $^{187}\text{Os}/^{188}\text{Os}$ 0.14; Figs 11–12) pyroxenite-rich mantle source (PX2 in Fig. 12) (Heinonen *et al.* 2010). In comparison, the ARE dykes show very low ΔNb and extremely high Zr contents. Such a combination of geochemical indications of both depletion and enrichment is common in highly alkaline lamproite magmas which are presumably derived from continental lithospheric mantle (Vollmer *et al.* 1984; Bergman 1987; Luttinen *et al.* 2002). The most enriched samples of the geochemically variable ARE dykes show particularly strong geochemical affinities to lamproite-type magmas and may record a lithospheric mantle source for DML magmas (CLM in Fig. 12). The less enriched ARE dykes may represent hybridization of magmas from convective and lithospheric mantle sources (Fig. 13) (Riley *et al.* 2005). Variations in Os and Pb isotopic compositions point to additional involvement of lower continental crust in the petrogenesis of the ARE dykes (Fig. 12b).

Differentiation

The most recent petrogenetic studies of Jurassic magmatism in DML suggest differentiation is largely responsible for the wide compositional ranges in the flood basalt lavas. Depleted upper mantle is the only plausible mantle source which could explain generation of the predominant flood basalt types by magmatic differentiation processes (Luttinen *et al.* 2015; Heinonen *et al.* 2016). The ΔNb parameter ($= 1.73 + \log(\text{Nb}/\text{Y}) - 1.94 \log(\text{Zr}/\text{Y})$; Fig. 2) is a particularly useful tracer of parent-daughter relations as it is not strongly affected by crustal contamination (Fitton *et al.* 1997; Baksi 2001; Luttinen 2018). For example, the ARD and ARE magma types, both of which have been associated with pyroxenite-rich mantle sources, plot apart from the general compositional trend of DML magmas due to markedly low ΔNb at given ϵNd , whereas exceptionally high ΔNb , TiO_2 , and $^{187}\text{Os}/^{188}\text{Os}$ compositions render the VFE magma type an implausible parental magma type (Figs 12–13).

In contrast, primitive VFD type dykes consistently define an endmember composition in DML and have been postulated to record the mantle source of the various flood basalt magma types. In general, quantitative energy-constrained assimilation-fractional crystallization (EC-AFC; Bohron & Spera 2001) models show that the low-Ti magma types of Vestfjella can be explained quite well by combined fractional crystallization, wall-rock melting, and

contamination of VFD-type low-Ti parental magmas with Archaean (VF1) and Proterozoic (VF2, VF3) crust (Luttinen *et al.* 2015; Heinonen *et al.* 2016) (Fig. 13). An additional lamproite-like contaminant from the continental lithospheric mantle has been associated with some VF3 magmas and the enriched members of VFD dykes. It is worthwhile to note that the VFD dykes record variable degrees of partial melting of depleted mantle and the parental magmas of the flood basalts represent a relatively high degree of melting (Fig. 13) (Heinonen *et al.* 2016).

The origin of the Kirwanveggen magma type has not been modelled quantitatively, but its diagnostic features are compatible with crustal contamination of low-Ti parental magmas that were generated from depleted mantle. Systematically low Zr/Y and Sm/Yb suggest that the parental magmas of the KW lavas required a somewhat higher degree of melting than those of the Vestfjella lavas (Fig. 13).

Fig. 12. Variation in (a) ΔNb v. $\epsilon\text{Nd}(180\text{Ma})$ and (b) $^{187}\text{Os}/^{188}\text{Os}$ v. $^{206}\text{Pb}/^{204}\text{Pb}$ in Karoo CFBs of DML. Compositions of different volcanic (Vol) and intrusive (Int) magma types are shown with filled and open symbols, respectively (exception Utpostane). Plausible mantle sources are indicated: DM is depleted MORB mantle (Shirey & Walker 1998; Workman & Hart 2005), PX1 is assumed pyroxenite source of ARD dykes (Heinonen *et al.* 2013, 2014), PX2 is assumed pyroxenite source of VFE dykes (Heinonen & Luttinen 2010; Heinonen *et al.* 2010), CLM is assumed continental lithospheric mantle with ΔNb and ϵNd values based on 162 Ma Vestfjella lamproites (Luttinen *et al.* 2002) and $^{187}\text{Os}/^{188}\text{Os}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ values based on southern African peridotite xenoliths (Simon *et al.* 2007; Walker *et al.* 1989). Typical compositional range of Archaean and Proterozoic continental upper crustal (UCC) and lower crustal (LCC) rocks (Heinonen *et al.* 2010; Neumann *et al.* 2011) are shown for comparison. Mixing trajectory between DM and altered oceanic crust is based on Heinonen *et al.* (2014). ΔNb values indicate depleted (negative ΔNb) and undepleted (positive ΔNb) Nb contents relative to Zr and Y (Fitton *et al.* 1997) (see caption for Fig. 2). PM is primitive mantle (Zindler & Hart 1986; McDonough & Sun 1995; Meisel *et al.* 2001). Geochemical and isotopic data sources and magma type abbreviations as in figure 9.

Fig. 13. Variation in (a) TiO_2 (wt.%) and (b) $\epsilon\text{Nd}(180\text{Ma})$ v. Sm/Yb in Karoo CFBs of DML. Compositions of different volcanic and intrusive magma types are shown with filled and open symbols, respectively (exception Utpostane). Assumed principal mantle sources are indicated: DM is depleted MORB mantle (Workman & Hart 2005) and CLM ($\text{Sm/Yb} \sim 18$) is assumed continental lithospheric mantle source of 162 Ma Vestfjella lamproites (Luttinen *et al.* 2002). PC and AC illustrate likely compositions of Archaean and Proterozoic upper crustal rock types in DML (Luttinen *et al.* 2010, 2015). Compositions of DM-sourced melts have been modelled using non-modal batch melting equations using a garnet lherzolite source (ol 57%, opx 32%, cpx 6%, grt 5%) and melt mode ol:opx:cpx:grt = 1:1:4:4. The geochemical effect of fractional crystallization and crustal contamination is schematically indicated by the arrow and a binary mixing model illustrates hybridisation between ARD-type magmas (sample Z1816.1; Riley *et al.* 2005) and CLM-sourced lamproite-like melts. Geochemical and isotopic data sources and magma type abbreviations as in figure 9.

Reconstruction of DML volcanic system

Reconstruction of volcanic systems requires a detailed understanding of the chemical and physical features of the structural components and timing of the endogenic and exogenic processes involved. In the case of Jurassic Karoo volcanism, it is crucial to bear in mind that the igneous system is composed of two compositionally different subprovinces, North Karoo and South Karoo (Figs 1 and 2) and that the origin of the two subprovinces may have been fundamentally different with regard to the principal mantle sources and timing of magmatism (Luttinen 2018). Chemical variability within both provinces has been mapped in some detail, whereas the physical volcanological data are rather patchy and the temporal constraints are strongly biased to North Karoo. The high-precision mineral age data (e.g. Zhang *et al.* 2003; Jourdan *et al.* 2007a, 2008; Svensen *et al.* 2012; Luttinen *et al.* 2015) and palaeomagnetic record (Løvlie 1979; Peters 1989; Hargraves *et al.* 1997) manifest (1) rapid province-wide emplacement of the main volume of lavas, possibly within ~ 0.5 Ma, and (2) continued magmatism in the Karoo triple rift after the province-wide peak, and (3) also raise the question whether significant volcanism within South Karoo predated the main stage (Table 1). The Jurassic flood basalt exposures of DML are relatively small but provide detailed snapshots of a rift and rift shoulder volcanic system relevant to the origin and evolution of the compositionally and structurally complex South Karoo CFB succession.

The lava flow facies concept of Jerram and co-workers (e.g. Jerram 2002; Single & Jerram 2004; Jerram & Widdowson 2005) provides a useful conceptual framework for assessing the variable lava stacking patterns and geochemical compositions which typify the Jurassic volcanism in DML (Figs 8–13).

Structural analysis of the volcanic edifice of three CFB provinces (the Deccan Traps, Paraná-Etendeka, and Northern Atlantic Igneous Province) led Jerram and Widdowson (2005) to propose three characteristic phases of flood basalt volcanism: Initial, relatively low-volume eruptions are confined by pre-existing lithospheric structures and related topography and typically produce compound-braided type stacking. The main phase represents a rapid culmination of province-wide igneous activity and is typified by repeated emplacement of large tabular-type flows during episodes of voluminous eruptions. The waning phase characteristically involves localized eruptions and is commonly associated with increasing silica contents. The lava stacking pattern of the Tertiary flood basalt succession of Skye has been studied in great detail (Single & Jerram 2004) and may exemplify the transition from initial to main phase flood basalt magmatism in the Northern Atlantic Igneous Province (Jerram & Widdowson 2005).

Volcanic architecture of DML flood basalts

It is proposed that the volcanic exposures of DML comprise a flood basalt succession that is structurally notably similar to that described for the Skye flood basalts: The thick accumulation of compound-braided facies flow fields in Vestfjella represent an early phase of prolonged, but relatively slow effusion of magmas within an incipient rift zone. In contrast, the thick simple flow fields of Kirwanveggen belong to the tabular-type facies and are related to main phase magmatism that led to flooding of the rift and rift shoulders by episodic, voluminous eruptions. The Björnnutane succession and possibly the Sembberget succession represent a transitional phase when eruptive volumes (rapidly?) increased. Such a scheme helps evaluation of the available physical, chemical, geochronological and palaeomagnetic observational evidence for DML flood basalts. The following synthesis is limited to the Vestfjella, Björnnutane, Sembberget, and Kirwanveggen exposures, because the dykes in the Ahlmannryggen area seem to represent a geochemically distinctive segment of the laterally heterogeneous Karoo central rift.

Skye stratigraphy	Dronning Maud Land stratigraphy	
		Kirwanveggen Sembberget Tabular-type simple lavas up to <100 m Rubbly pahoehoe Uniform low-Ti and -Mg compositions No garnet signature (low Sm/Yb) -high% melting Narrow age range (~181 Ma) Uniform polarity (N)
		Björnnutane Compound-braided flow fields at the base Tabular-type simple flows at the top Magma types correlate with Vestfjella and Kirwanveggen Garnet signature (high Sm/Yb) dominates -relatively small% melting
		Vestfjella Predominantly compound-braided flow fields Several low-Ti and high-Ti magma types Garnet signature (high Sm/Yb) -relatively small% melting Wide age range (189-181 Ma) Polarity reversals (R-N-R)

Fig. 14. Comparison between the schematic volcanic stratigraphy of Skye, Northern Atlantic Volcanic Province, and DML, Karoo province. The Skye lava succession has been divided into (i) initial phase, (ii) transitional phase, and (iii) main phase of eruptive activity (Single & Jerram 2004). The Vestfjella, Björnnutane, and Kirwanveggen–Sembberget lava outcrops are ascribed to a similar evolutionary sequence (colours illustrate chemical variations as in Figure 8). Age data are from Table 2. Palaeomagnetic polarity data are from Løvlie (1979), Peters (1989), and Hargraves *et al.* (1997). The Skye stratigraphy is modified after Single & Jerram (2004).

Age relations. The age constraints from limited high-precision results of ^{40}Ar – ^{39}Ar plagioclase and U–Pb zircon dating and the available palaeomagnetic data are compatible with a view that Vestfjella represents relatively old and that Sembberget and Kirwanveggen represent younger stratigraphical levels of the Jurassic volcanic edifice (Fig. 14; Table 2). Specifically, the age data for Vestfjella are exclusively from the southern exposures which appear to record the deepest section in DML: The 185–189 Ma ages of the VF1 and VF3 type dolerites are likely to correspond to the age of the lava pile and most of the geochemically similar crosscutting dykes. The younger ages represent two ~500 m wide 182 Ma gabbroic dykes and a 181 Ma layered intrusion which intruded a thick accumulated lava pile. Crucially, the Utpostane layered intrusion and the coeval 181 Ma Sembberget lava (Table 2) are geochemically indistinguishable from the Kirwanveggen lavas (Figs 9–13), which suggests rapid emplacement of the KW type magmas at ~181 Ma (Fig. 14). The palaeomagnetic record of R-N(-R?) polarity reversals in Vestfjella and a consistent N polarity in Kirwanveggen are compatible with the purported age relations (Fig. 14).

Eruptive styles, rates, and vent systems. The formation of compound-braided lava flow fields has been ascribed to lava breakouts along flow fronts of voluminous sheets (Self *et al.* 1998) or proximity of vents in shield volcanoes (Walker 1973; Rowland & Walker 1990; Passey & Bell 2007). The Vestfjella succession is almost exclusively made of compound-braided pahoehoe flow fields, which points to relatively short lava flow distances (e.g. Walker, 1973) and the volcanic pile most likely formed by accumulation of low-viscosity lava during prolonged, slow effusion relatively close to eruptive vents (cf. Self & Jerram 2004; Passey & Bell 2007). The predominance of VF1 and VF2 in north Vestfjella and the associated flow directions (Fig. 8) support location of the eruptive vents of VF1 and VF2 to the north and east of Basen and Plogen, respectively. The southern (and possibly central) Vestfjella is principally composed of VF3 (Luttinen & Furnes 2000). The flow directions for VF3 are quite variable, mainly from broadly SW in the southernmost Vestfjella and from east in northern and central Vestfjella (Hjelle & Winsnes 1972; Furnes *et al.* 1987; Luttinen & Furnes 2000; Fig. 8), and are suggestive of vent systems within the west-south-east sector. The intercalated flow fields of VF1–3 lavas may record lavas emplaced between three shield volcanoes. In contrast, the notably thick simple flow fields of the tabular-type facies at Kirwanveggen point to high effusion rates (Self *et al.* 1998; Harris & Rowland 2009) and successive flooding of the rift shoulders by large inflated pahoehoe units from fissure eruptions. The occurrences of rubbly flow top breccias lends support to high effusion rates (Keszthelyi *et al.* 2006). Evidence of voluminous outpouring of melt and consistent flow direction towards the east (Harris *et al.* 1990; Fig. 8) can be associated with opening of major fissure vents to the west of Kirwanveggen, i.e. in the general direction of the rift axis (Fig. 3).

Tectonic setting. The supracrustal strata from the African rifted margin indicate that incipient Jurassic volcanism along the southern arm of the Karoo triple rift occurred in a pre-existing basin (Watkeys 2002) and evidence from the triple junction area suggest emplacement of the Jurassic dykes may have been controlled by Precambrian structures (Jourdan *et al.* 2004; Riley *et al.* 2005). Detailed mapping of the African rifted margin in the central Lebombo area led Klausen (2009) to propose that the Karoo rift zone magmatism was associated with rapid crustal extension which is also supported by up to 14% dilation recorded by dolerite dykes in southern Vestfjella (Luttinen *et al.* 2015). Consequently, the Vestfjella lavas probably erupted within an actively developing rift system. The lack of intrusions in the Kirwanveggen area is consistent with drowning of the rift shoulder only during the main phase when voluminous inflated pahoehoe units were able to flow far from the fissure vents (Walker 1973).

Magma compositions. The geochemical compositions are compatible with physical implications for different eruption rates. Most importantly, the Kirwanveggen type lavas have

low incompatible element contents at given Mg-number and are distinguished by their low Sm/Yb. Relative depletion of the heavy rare earth elements (REE) has been frequently used as a proxy for mantle melting conditions (e.g. Tegner *et al.* 1998). Specifically, a garnet-bearing mantle source produces relatively high Sm/Yb because residual garnet is a sink for the heavy REE. The low Sm/Yb values thus suggest that the mantle source of the Kirwanveggen lavas was poor in garnet either because the melting took place at relatively low pressures where garnet is not stable, or because a high degree of melting led to efficient consumption of garnet. Given the low abundances of incompatible elements and the tholeiitic compositions, the degree of melting must have been relatively high. The melting model in Figure 13 suggests ~12% partial melting of depleted mantle would produce parental magmas with low Sm/Yb typical of Kirwanveggen lavas. Overall, the geochemical features of the Kirwanveggen type thus imply high melt productivity, which is compatible with high eruption rates indicated by the physical dimensions of the lavas. The homogeneity of Kirwanveggen lavas, their low Mg-numbers, and high volumes point to tapping of the magmas from a large magma chamber in which efficient homogenisation was possible.

In comparison, the Vestfjella magma types are compositionally quite variable. Some of the magma types have high Sm/Yb due to hybridization with lithospheric mantle material, but the predominant crustally contaminated magma types have probably preserved mantle-derived Sm/Yb quite well. Accordingly, systematically high Sm/Yb values in Vestfjella are compatible with a relatively low degree of melting (Fig. 13). The succession appears to be fed by several plumbing systems typified by long-lived but rather slow-rate eruptions and intercalation of flows from closely-spaced vents, possibly in juxtaposed shields. Thick tabular-type VF3 lava flows at Björnnutane and wide VF1 gabbro dykes in Vestfjella suggest that the eruption rates may have been increased at the onset of the main phase of magmatism at ~182 Ma (Table 2).

Flood basalts of DML and the Gondwana LIP

Summarizing, geological mapping of the scattered outcrops of western DML has defined the overall compositional structure of the Antarctic portion of the Karoo CFB province. The DML system is clearly genetically related to geochemically similar basalts and picrites of the Lebombo Monocline at the African rifted margin (Faure *et al.* 1979; Harris *et al.* 1990; Luttinen & Furnes 2000). The compositionally diverse Vestfjella suite probably represents a conjugate margin of the southernmost Lebombo (Luttinen & Furnes 2000; Luttinen *et al.* 2010, 2015), whereas the Jurassic dykes of Ahlmannryggen – H.U.Sverdrupfjella region show compositional affinities to magma types of the Mwenezi area at the triple junction (Riley *et al.* 2005) (Fig. 1). The compositionally uniform lava suites of Kirwanveggen and Sembberget probably represent a rift shoulder setting and, apart from the Utpostane layered intrusion, they lack geochemical equivalents elsewhere in the Karoo province.

Geochemical models support the view that the low-Ti flood basalt magmas of DML were mainly generated from depleted upper mantle and were differentiated into numerous compositional types in physically distinctive plumbing systems largely due to interaction with different kinds of Archaean and Proterozoic crustal wall-rocks (Luttinen *et al.* 2015; Heinonen *et al.* 2016). Subordinate high-Ti magma types are confined to the rifted margin, mainly show indications of pyroxenite-rich sources, and are likely to record tapping of enriched components in convective and lithospheric mantle (Luttinen *et al.* 2015; Heinonen *et al.* 2010, 2013, 2014). Recent studies have proposed similar models for the high-Ti magma types at the African rifted margin (Harris *et al.* 2015; Kamenetsky *et al.* 2017).

The general physical architecture of the Jurassic volcanic edifice reveals contrasting lava flow stacking patterns, and, consequently, different eruption rates and flow distances for the rift and rift-shoulder settings. The age relationships are still ambiguous, but the available geochemical, palaeomagnetic, and geochronological data, and the physical architecture of the lava successions are compatible with progressively increased eruption volumes and filling of the Jurassic rift by flood basalts (Fig. 14). Two rift zone gabbro dykes have been dated at 182 Ma using the U–Pb zircon method (Luttinen *et al.* 2015), whereas most of the published ^{40}Ar – ^{39}Ar age data suffer from Ar-loss, excess argon, recoil, use of whole-rock samples, or insufficient documentation, and do not yield reliable plateau ages (e.g. Brewer *et al.* 1996; Duncan *et al.*, 1997; Zhang *et al.* 2003; Riley *et al.* 2005; Curtis *et al.* 2008; Luttinen *et al.* 2015). Sparse reliable ^{40}Ar – ^{39}Ar age data are suggestive of early onset (possibly at ~189 Ma) and a long duration of magmatic-tectonic activity in the rift environment and relatively rapid emplacement of lavas on the rift shoulder (Table 2). Obviously, further geochronological research is required to establish the absolute ages of the different structural components of the DML volcanic system and their relationships to African Karoo. Combined flow-by-flow palaeomagnetic and geochemical sampling and detailed structural analysis has potential to decipher the evolutionary stages of the DML igneous system (e.g. magma chamber processes, fluctuating magma production rates and eruption volumes, duration of emplacement and cooling of lavas), many of which may have occurred rapidly in time scales unresolvable using radiometric dating.

The Jurassic flood basalt system of western DML represents a small part of the greater Gondwana LIP, but the lessons learned have province-wide implications. The VFD dykes have provided a detailed insight into a depleted upper mantle source which may have been the predominant mantle source of the South Karoo subprovince as a whole (Figs 1–2) (Ellam & Cox 1991; Luttinen 2018). Importantly, the depleted source was probably variably modified by subducted crustal material: Selective enrichment of LILE in the picrites and elevated oxygen isotopic ratios in the olivine phenocrysts indicate the source material of the low-Ti flood basalts was mildly affected by subduction-related fluids (Heinonen *et al.* 2018), whereas the various high-Ti compositions may record recycled oceanic crustal components (Heinonen *et al.* 2010, 2014). The geochemical traces of subduction in the Nb-depleted South Karoo subprovince could stem from long-distance transportation of subducted material from the coeval subduction zone along the Gondwana margin (Rapela *et al.* 2005; Wang *et al.* 2015; inset in Fig. 1), or preservation of an ancient subduction signature generated in Palaeozoic or even Proterozoic time (Choi *et al.* 2019).

Overall, the boundary between the low- ΔNb and high- ΔNb tholeiites (Fig. 1) is likely to reflect plume- and subduction-related large-scale mantle provinciality. The Nb-undepleted North Karoo subprovince, which dominates the African part of the Gondwana LIP, was formed directly above the sub-African large low shear-velocity anomaly of deep mantle (Torsvik *et al.* 2010) and its rapid emplacement (Svensen *et al.* 2012) and geochemical features are compatible with a mantle plume source (Luttinen 2018). In contrast, the Nb-depleted South Karoo and Ferrar subprovinces (Figs 1–2) were probably generated from upper mantle sources and largely outside the limits of the deep mantle anomaly. However, the South Karoo tholeiites in DML and Africa were formed close to the purported sub-African mantle plume convection pattern and the early onset and exceptionally high mantle potential temperatures suggested for magmatism in DML (Luttinen *et al.* 2015; Heinonen *et al.* 2015) could stem from the arrival of a mantle plume underneath North Karoo. The voluminous main phase may have been triggered by further plume-related heating of the ambient upper mantle and rapid lithospheric extension.

Despite their different silica contents and Sr isotopic compositions (Faure & Elliot, 1971), the Nb-depleted South Karoo and Ferrar subprovinces (Figs 1–2) could have been derived from parts of the same overall upper mantle reservoir that were mildly (South Karoo) and strongly (Ferrar) modified by subducted crustal material (e.g. Hergt *et al.* 1991; Luttinen 2018). Interestingly, the fundamental petrological boundary in the Gondwana LIP appears to coincide remarkably well with the boundary between East and West Gondwana.

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