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The composition of the lower oceanic crust in the Wadi Khafifah section of the southern Samail (Oman) ophiolite

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Key Points:

- The intrusive oceanic crust is divided into lower gabbros and upper gabbros on the basis of incompatible trace element concentrations and mineral compositional variability
- The lower oceanic crust is accreted throughout in small sills of primitive melt
- The upper gabbros additionally receive the fractionated melts from the crystallization of the lower gabbros via melt migration.

Plain Language Summary:

The composition and structure of the oceanic crust is traditionally difficult to estimate due to lack of exposure. Using rocks that crystallized from magmas at a submarine spreading center, we present major and trace element geochemical data for the entire lower oceanic crust. Our data shows how the lowermost sections of the oceanic crust are related to the uppermost intrusive and extrusive by crystallization and melt migration before and after eruptions. The bulk composition of our crustal section is in chemical equilibrium with the mantle and therefore represents a plausible primary mantle melt.

Abstract

The composition of the intrusive gabbroic lower oceanic crust remains poorly characterized in comparison to the extrusive portion of the oceanic crust, especially for intermediate-fast spreading mid-ocean ridges. This is a consequence of limited exposures of extant lower oceanic crust or ophiolites similar to mid-ocean ridge crust. One of the best analogues for mid-ocean ridge crust is the southern Samail ophiolite that formed during a period of rapid seafloor spreading above a nascent subduction zone. Here, we focus on the geochemical stratigraphy (whole rock and mineral major and trace element compositions) of the 5200 m-thick, lower crustal, Wadi Khafifah section of the Wadin Tayin massif in the southern Samail (Oman) ophiolite. Gabbros from the lowermost 3700 m of this section (the 'lower gabbros') show no systematic changes in composition with height above the Mantle Transition Zone. In contrast, gabbros from the uppermost 1500 m (the 'upper gabbros') display marked increases in incompatible trace element concentration with increasing height. Liquids in equilibrium with the lower gabbros have major and trace element compositions that overlap with those measured in the upper gabbros and sheeted dikes. Upper gabbros preserve mineral cores with primitive major element compositions that overlap with the range of lower gabbros; however, upper gabbro whole rock compositions are significantly more enriched in incompatible trace elements relative to the lower gabbros. Our data reveal that the upper gabbros are a composite of accumulated minerals derived from primitive melts and a large fraction of evolved melts derived from the fractionation of the lower gabbros. We propose a new "Full Sheeted Sills" model for the lower oceanic crust in which primitive magmas from the mantle are emplaced throughout the lower crust and crystallized *in situ*. After diking events, evolved magmas leave the lower gabbros and replenish the upper gabbros, thereby contributing to the higher incompatible trace element budget in the upper gabbros relative to the lower gabbros. Our reconstructed bulk compositions of the lower plutonic crust and the bulk oceanic crust from the Wadi Khafifah section yield a plausible primary mantle-derived magma composition in equilibrium with depleted MORB mantle.

1 Introduction

It has long been known that mid-ocean ridge basalts (MORB) are not the direct result of mantle melting, but rather have experienced crystal fractionation and magma mixing prior to eruption (see review by Thompson, 1987 and references therein). Yet fundamental questions remain to be answered, notably on where this fractionation occurs within the lower oceanic crust and upper mantle, what degree of fractionation melts undergo, and how melt is extracted to feed the overlying dikes and lavas.

Crust generated at intermediate to fast-spreading mid-ocean ridges, is typically between 5-7 km thick (> 5 cm per year, half-rate); only when spreading rates become ultra-slow (e.g. < 2 cm per year, half-rate) do crustal thicknesses become significantly smaller (White and McKenzie, 1992; Chen, 1992; Forsyth, 1993; Dick et al., 2003). The igneous stratigraphy of oceanic crust formed at intermediate - fast spreading ridges is commonly subdivided into three distinct layers: a ~4km thick gabbroic lower section, overlain by an ~ 1 km thick sheeted dike complex, and then by a ~ 1 km thick section of basaltic lava erupted to the seafloor as pillow basalts and flows (Fig. 1). This type of 'layer-cake' stratigraphy is commonly termed the "Penrose Structure" (Anonymous, 1972).

Although drilling into intact oceanic crust has provided innumerable insights into some portions of the oceanic crust and upper mantle, no stratigraphically continuous core has so-far been recovered from the seafloor to the mantle at an extant, intermediate- to fast-spreading mid-ocean ridge. In order to address questions related to the compositional structure of the entire 5-7 km thick oceanic crust, we must turn to ophiolites, where paleo-oceanic lithosphere has been obducted onto the continental crust. In some cases, such as in the Samail (Oman) ophiolite, continuous exposure of the entire stratigraphic column from the depleted mantle peridotite at the base of the crust to the basalts and marine sediments at the paleo-seafloor is accessible.

Here we document the vertical stratigraphic variation in the composition of the gabbroic portion of the Wadi Khafifah section in the Wadi Tayin massif of the southern Samail (Oman) ophiolite (Pallister & Hopson, 1981; Garrido et al., 2001; VanTongeren et al., 2008; VanTongeren et al., 2015). We present bulk rock major element and trace element compositions together with *in situ* mineral major and trace

element compositions throughout this ~ 7.2 km thick section. The lower oceanic crust can be divided into 'lower gabbro' and 'upper gabbro' sections based on major and trace element geochemistry. The 'lower gabbros' are characterized by cumulate gabbros with low incompatible trace element concentrations, whereas the 'upper gabbros' contain a large proportion of zone crystals and interstitial material with high incompatible trace element concentrations.

2 Background

2.1 Ophiolites and mid-ocean ridge crust

Few, if any, well-preserved ophiolites represent oceanic lithosphere formed at typical mid ocean ridges. Typically, they have geochemical and geological features characteristic of magmas from supra-subduction zone (SSZ) settings (Pearce et al., 1984) formed during the initial stages of subduction when slab rollback creates an extensional tectonic environment inboard of the embryonic ocean trench (Stern and Bloomer, 1992). Recent dredging and drilling in the Western Pacific have provided clues to how rapidly spreading oceanic crust could still form in a subduction initiation setting. There, glasses recovered via drilling and dredging close to a nascent trench have MORB-like compositions, some with no obvious enrichment in fluid-mobile trace elements and their isotopes (Coulthard et al., 2021). With time, and distance from the nascent trench, compositions evolve from MORB to depleted arc tholeiites and boninites, producing oceanic crust and then a protoarc edifice. Dating has revealed that subduction initiation in the Western Pacific was followed by c. 2 Myr. of intermediate-rate sea-floor spreading with the earliest oceanic crust having MORB-like compositions (Reagan et al., 2019). Although the cause of extension is different (local slab rollback rather than distal slab pull), the process of crustal accretion is similar at normal mid-ocean ridges and nascent subduction settings.

Many subduction initiation features are locally present in the Samail ophiolite, notably the boninite and depleted tholeiite magmas that intruded into, and erupted upon, the main 'Penrose' stratigraphy in the northern part of the Samail ophiolite (e.g. Alabaster et al., 1982; Ishikawa et al., 2002).

However, most of these complicating factors are of minor significance in the southern part of the ophiolite, the site of this study. Indeed, the “Penrose model” crustal section is based largely on the equivalence between seismic observations of Pacific crust and geological observations of lithological layering in the Samail ophiolite (e.g., Christensen & Smewing, 1981).

Two tectonically exposed sections of the fast-spreading East Pacific Rise (EPR) gabbroic crust have been studied in detail: Hess Deep and Pito Deep. Pito Deep exposes 300-700 m of upper gabbro (Perk et al., 2007; Brown et al., 2019) and is not directly comparable to the Khafifah section presented here. Hess Deep exposes an extensive section of layered and isotropic gabbro comparable to the Khafifah section, though there are uncertainties associated with the structural integrity of the section that has been drilled (e.g. Ferrini et al., 2013).

At Hess Deep, Natland and Dick (1996), Lissenberg et al. (2013) and Gillis et al. (2014) document the presence of primitive gabbro with similar clinopyroxene Mg# and An content to that observed in the lower gabbros in our samples (Fig. 3). Though Khafifah plagioclase falls among the highest An contents at a given clinopyroxene Mg# in gabbroic samples from Hess Deep (Fig. 3), the broad overlap in range gives further evidence that processes forming the lower crust of the Oman ophiolite were similar to those at modern-day, fast-spreading ridges. Note that both the Khafifah and Hess Deep mineral compositions have higher plagioclase An at a given clinopyroxene Mg# than samples from other mid-ocean ridge sections, including Pito Deep from the EPR. Thus, while all ophiolites (including the Samail) have mineral and lava compositions that differ systematically from mid-ocean ridge samples, with some geochemical characteristics of volcanic arc or supra-subduction zone magmas (Miyashiro, 1975; Pearce et al., 1984; Dilek and Furnes, 2014), samples from the southern massifs of the Samail ophiolite (the Samail Massif and the Wadi Tayin massif; Fig. 2) are more similar to mid-ocean ridge lithologies than samples from any other well-studied ophiolite worldwide (e.g., Macleod et al., 2013).

2.2 The Oman Ophiolite

The Samail ophiolite in Oman and the United Arab Emirates is arguably the largest and best-preserved ophiolite on Earth, formed at a fast-spreading submarine spreading center (Tilton et al., 1981; Rioux et al., 2012; Coleman, 2012; Coleman & Hopson, 1981). The ophiolite is divided into three distinct domains, the northern, central and southern (Nicolas et al., 2000; Fig. 2). Each domain displays a more-or-less continuous Penrose-type stratigraphy of harzburgitic mantle, overlain by gabbros, sheeted dikes, and pillow basalts (Anonymous, 1972). The thicknesses of each unit, however, vary considerably from north to south (Nicolas et al., 2000).

Basalt compositions from the two southernmost massifs of the ophiolite, the Samail and Wadi Tayin blocks (Fig. 2), are from the Geotimes lava unit (Alabaster et al., 1982), also termed V1 (Ernewein et al., 1988), which has major and trace element characteristics that reveal a near MORB-like composition with a minor subduction zone signature (Pearce & Peate, 1995; McLeod et al., 2013). As noted in the previous section, its nearest analogues are the fore-arc basalts (FAB) of the Western Pacific that mark spreading following subduction initiation (Reagan et al., 2010; Shervais et al., 1999). It is more similar to MORB than the Lasail and Alley (V2) lava units that overlie the Geotimes/V1 lavas in the northern ophiolite massifs and include boninites (Alabaster et al., 1982; Pallister & Knight 1981; Godard et al., 2006; Ishikawa et al., 2002). Similarly, lower crustal gabbros in the Wadi Tayin and Samail massifs mostly record crystallization of olivine (ol), plagioclase (plag) and clinopyroxene (cpx), typical of cumulates derived from fractional crystallization of tholeiitic basalts such as MORB magmas, followed by extraction of the remaining evolved melt. These gabbros are unlike abundant low calcium pyroxene (orthopyroxene, opx) bearing cumulates – websterites and gabbro-norites – that form significant proportions of the igneous crust in the northern massifs, although small intrusions of primitive (Mg#, or molar $\text{Mg}/(\text{Mg}+\text{Fe}) > 0.8$), opx-bearing cumulates are present in the Samail and Wadi Tayin mantle sections (e.g., Kelemen et al., 1997; Kelemen et al., 2020; and our unpublished mapping). Primitive opx-bearing cumulates record the initial stages of crystallization of mantle-derived magnesian andesites, such as boninites, which are found within some forearcs, volcanic arcs and upper lavas in the northern massifs, but are not found in the southern massifs. Nonetheless, the higher plagioclase anorthite content at a given

clinopyroxene Mg# in Samail and Wadi Tayin massif gabbros relative to mid-ocean ridges (Fig. 3) may be indicative of stabilization of An-rich feldspar in magmas with water contents at the upper end of the MORB spectrum. Hornblende gabbros are present just below the sheeted dikes in some Wadi Tayin crustal sections (Pallister & Hopson, 1981; Garrido et al., 2001), similar to gabbros from the sheeted dike-gabbro transition in other mid-ocean ridge samples (Alt et al., 2007; Koepke et al., 2011; Gillis et al., 1996).

The mantle section of the Samail and Wadi Tayin massifs records major and trace element mineral compositions (Godard et al., 2000; Monnier et al., 2006; Hanghøj et al., 2010) similar to those of peridotites dredged and drilled at mid-ocean ridges (Johnson et al. 1990; Bodinier & Godard, 2003; Niu, 2004). Spinel Cr# (molar Cr/(Cr+Al)) spans a range from 35 to 70, extending to values that are just slightly higher values than spinels from mid-ocean ridges (10 to 65, with one of ~1100 values at Cr# 70; e.g., Urann et al., 2020). Again, these are unlike spinels from the northern massifs of the Samail ophiolite, which extend to Cr#'s as high as 81 (e.g., Rollinson, 2005), as do chromites from many supra-subduction zone settings, and from many ophiolites worldwide.

2.3 Field work and sampling

All lower crust samples analyzed for this study were collected from the Wadi Khafifah section, first described in detail by Pallister and Hopson (1981), in the Wadi Tayin massif (Fig. 2). The Wadi Khafifah section was selected based on the lack of high-offset faulting or shear zones within the lower crustal section. It is located approximately 10 km to the west of Wadi Gideah, which has been extensively studied by Müller (2016) and is the site of gabbro holes GT1 and GT2 of the Oman Drilling Project (Fig. 2).

Stratigraphic depths for gabbroic samples were determined according to the strike and dip of the rock with the paleo-mantle-crust transition zone (MTZ) as 0 m (see Garrido et al., 2000). The preserved crustal section in this area is 6 km thick, made up of gabbros and sheeted dikes, but excluding the upper pillow basalt layer, which is not preserved. A total crustal thickness of 7.2 km is estimated for the Wadi

187 Khafifah section, which includes an estimated 1.5 km of sheeted dikes (0.8 km of which is preserved), an
 188 estimated 0.5 km of pillow basalt, and 5.2 km of gabbroic lower crust. The 5.2 km gabbroic portion is
 189 further subdivided into an ~4.2 km-thick "layered gabbro" section (see Fig. 4a for photos), a ~0.5 km -
 190 thick "transitional gabbro" section, and finally a ~0.5 km-thick "high-level gabbro" section (Fig. 1; e.g.
 191 Pallister and Hopson, 1981; Pallister and Gregory, 1983). The "transitional gabbro" and "high-level
 192 gabbros" are referred to as 'foliated gabbros' and 'varitextured gabbros' by Macleod and Yaouancq (2000)
 193 in other sections of the ophiolite (see also Koepke et al., 2011, France et al., 2009; France et al., 2013;
 194 Nicolas et al., 2008).

195 In the terminology of Pallister and Hopson (1981), the 'transitional gabbros' are defined as
 196 planar-laminated, but not macroscopically layered, cpx-gabbro and ol-cpx gabbro; whereas the 'high-
 197 level gabbros' are defined as isotropic hornblende-clinopyroxene-gabbros with minor olivine-hornblende-
 198 clinopyroxene-gabbro. The two units commonly grade into one another, and in some cases the
 199 transitional gabbro section is absent entirely. For the Khafifah section, Pallister and Hopson (1981) place
 200 the base of the transitional gabbro section at 4200 m above the Mantle Transition Zone and the base of the
 201 high-level gabbro section at ~4700 m.

202 Our whole rock and mineral incompatible trace element data (see Results below) from Wadi
 203 Khafifah show that there is a distinct compositional break at 3700 m above the MTZ, approximately 500
 204 m *below* the base of the 'transitional gabbro' section of Pallister and Hopson (1981). Furthermore, the
 205 location of this compositional boundary is nearly coincident with a distinctive change in plagioclase
 206 lattice preferred orientation (e.g. VanTongeren et al., 2015). At approximately 3300m-3600 m above the
 207 MTZ, plagioclase b-axis maxima transition from Moho perpendicular in the lower gabbros to nearly
 208 parallel in the upper gabbros (e.g. elongate plagioclase grains align horizontally with long-axis (a-axis)
 209 parallel to the Moho in the lower gabbros vs. vertically in the upper gabbros; VanTongeren et al., 2015).
 210 The stratigraphic coincidence of the major change in the mineral-scale orientation (e.g., VanTongeren et
 211 al., 2015) with the major change in whole rock incompatible trace element concentration (this study),

gives confidence that there is a fundamental shift in the nature of the magmatic system occurring in the lower crust at approximately 3700 m above the MTZ in the Wadi Khafiah section.

We therefore designate two distinct layers in the gabbroic lower crust: (1) the 'lower Gabbros' corresponding to stratigraphic heights from 0-3700 m above the MTZ, and (2) the 'upper gabbros', corresponding to stratigraphic heights from 3700 - 5200 m above the MTZ. Grouping the uppermost 1500 m of the gabbroic section into a single 'upper gabbro' unit is preferable to avoid confusion based on gradual, or sometimes absent, field-based distinctions.

3 Materials and Methods

Outcrops corresponding to the 'lower gabbros' are common and typically very fresh, whereas outcrops of the 'upper gabbros' in this section suffer from pervasive weathering making detailed sampling of these sections impossible. We sampled only exceptionally fresh outcrops, which reduces the total number of samples for the upper gabbros, but allows us to truly evaluate igneous processes from whole rock and mineral compositions. All gabbro samples measured here are exceptionally fresh and largely free of low temperature alteration or metasomatism (Fig. 4).

Sheeted dike samples were collected from a similar location to those studied by Pallister and Hopson (1981)(Table 1b). All 33 sheeted dike samples reported here are slightly to moderately altered at greenschist facies, but preserve chilled margin contacts and provide reliable compositions for comparison here for all but the more fluid-mobile elements.

3.1 Compositional Analyses

We report data from 33 lower crustal samples spaced on average every 50-100 m through the lower crust stratigraphy, except for a stratigraphic sampling gap occurring between 2369 m and 2999 m. Whole rock major element compositions for gabbro and sheeted dikes lithologies were determined by

XRF at the Washington State Geoanalytical Laboratory (Table 2). Trace element concentrations were determined by Inductively Coupled Plasma Mass Spectrometry (ICPMS) at the Université de Montpellier (the gabbros) and Cardiff University (the dikes).

Compositions of the major rock forming minerals were determined by electron microprobe analysis (EPMA) at the Massachusetts Institute of Technology JEOL EPMA facility and the American Museum of Natural History Cameca EPMA facility. Major and minor elements in pyroxenes (Table 3) and olivines (Table 4) were analyzed with 20nA, 15KeV beam, and 30 sec on peak and 15 sec on background. Major and minor elements in plagioclase (Table 5) were analyzed with a 10nA, 15 keV beam with 30 sec on peak and 15 sec on background. Modal abundances of minerals were determined by the least squares method using the major element compositions of the whole rock and its constituent minerals. This method does not distinguish between cumulus and intercumulus mineral abundances.

Trace element concentrations of plagioclase (Table 6) and clinopyroxene (Table 7) were measured by Laser Ablation ICPMS (LA-ICPMS) at Rutgers University. For plagioclase, we used a spot size of 65 microns and a fluence of 5.32 J/cm². For pyroxene, we used a spot size of 40 microns and fluence of 2.95 J/cm². Standards NIST 610, 612, and 614 were used to construct calibration curves, and basalt glasses BCR and BIR were regularly analyzed as unknowns to ensure accuracy. All data presented represent averages of mineral cores. No mineral rims were measured in this study.

4 Results

4.1 Bulk rock compositions

The modal mineralogy for each sample from the Wadi Khafifah lower crustal section is provided in Table 1. In the lowermost portion of the gabbroic section (0-3700 m above the Mantle Transition Zone), hereafter referred to as the 'lower gabbros', there are small-scale changes in modal proportions of minerals due to magmatic layering. However, the typical gabbroic modal abundance of 50-55% plagioclase, 35-40% clinopyroxene, and 5-10% olivine is roughly constant throughout the lower gabbro

section (Table 1). In contrast, the uppermost 1500 m of the gabbro section (3700-5200 m), the 'upper gabbros', lack olivine and instead Fe-Ti oxides and amphibole become more common phases (Table 1).

Whole rock major and trace element compositions for each sample are provided in Table 2. In the lower gabbros, whole rock Mg# is in the range of 80.2 ± 3 and MgO wt% has an average of 11.6 ± 2.3 wt% with no systematic variation with increasing height above the mantle-crust transition zone (MTZ). Above 3700 m, in the upper gabbros, whole rock Mg# decreases from ~82 to 46; and the whole rock MgO content decreases from ~12 wt% to 5 wt% at the top of the section (Fig. 5).

Incompatible (bulk partition coefficient $D < 1$) trace elements show a similar change in character at the lower gabbro-upper gabbro transition, i.e., at 3700 m above the MTZ (Fig. 6). Whole rock Sr, Zr, Y and middle to heavy rare earth element (REE) contents are low and approximately constant through the stratigraphy in the lower gabbros, whereas the upper gabbros show systematic increases in these trace element contents with increasing height above the MTZ. Whole rock P and light REE concentrations show a scattered but significant increase with height in the lower gabbros, followed by a much more marked increase with height in the upper gabbros.

In contrast to the whole rock major elements and incompatible trace elements, compatible (bulk $D > 1$) trace elements show no systematic change with increasing stratigraphic height throughout the entire lower crustal section, including in the upper gabbros (Fig. 6).

The paucity of fresh, unaltered outcrops of pillow lava from the Wadi Tayin massif limits our ability to compare the lower crustal gabbros to the lavas in this section. Lava samples from the massifs further to the north and west have been analyzed by Godard et al. (2003), Godard et al. (2006), and Macleod et al. (2013), but these have experienced extensive prehnite-pumpellyite facies metamorphism and their compositions, particularly of fluid-mobile elements, cannot be reliably related to the gabbro stratigraphy. Sheeted dike samples from Wadi Khafifah, while subject to some greenschist facies metamorphism, have preserved chilled margins and compositions that are less altered. Additionally, Kelemen et al. (2020) showed that the sheeted dikes and V1 lavas from throughout the ophiolite have indistinguishable compositional ranges for fluid immobile elements. Results from IODP drill cores along

the East Pacific Rise also show indistinguishable compositions for the sheeted dikes and pillow lavas (see data from Teagle et al., 2006 and Umino et al., 2008). For this reason, we consider the compositions of sheeted dike samples from Wadi Khafifah presented here to best represent extrusive volcanism for comparison with the lower crustal gabbro section.

The major and trace element compositions of sheeted dikes (and V1 lavas) range from those similar to the upper gabbros to others that are distinctly more evolved. The continuous nature of the compositional evolution from upper gabbros to sheeted dikes suggests that these units are likely related by crystal fractionation (Fig. 5, 6).

4. 2 Mineral major and trace elements

Average major element concentrations for plagioclase, clinopyroxene, and olivine throughout the gabbroic section (Tables 3 – 5) show no systematic trends with stratigraphic height in the gabbros (Fig. 7). Clinopyroxene Mg# varies unsystematically from 88 to 78; plagioclase An content varies from An₈₈ to 72; and olivine varies from Fo₈₅ to 75. Only one sample, near the top of the upper gabbro section, has mineral core compositions significantly more evolved than the majority of the lower crust. Sample OM97-209, approximately 4468 m above the MTZ, has average plagioclase An₄₇ and clinopyroxene Mg# of 73. This sample also contains a large portion of magmatic amphibole (Table 1).

Despite the lack of systematic variation with height, olivine Fo content and clinopyroxene Mg# in the Khafifah data are strongly correlated, while plagioclase An is weakly but significantly correlated with Mg/Fe in both olivine and clinopyroxene.

In situ trace element concentrations for plagioclase and clinopyroxene in the gabbroic samples are presented in Tables 6 and 7, respectively. Average concentrations of compatible trace elements, such as Cr and Sc in clinopyroxene and Sr in plagioclase, do not change systematically with height above the MTZ in the lower gabbros, and do not change appreciably between the lower gabbros and upper gabbros (Fig. 8). Average incompatible trace elements, however, do show systematic increases in concentration

from the lower to the upper gabbros. Zr in clinopyroxene increases from ~4-6 ppm near the base of the crust to ~10 ppm at the lower gabbro-upper gabbro transition, with one outlier at 14 ppm just below this level (Fig. 8), but return to lower values of ~6 ppm in the upper gabbros. In clinopyroxene, Zr concentrations correlate strongly with other highly incompatible elements (including light REE) but not with less incompatible trace elements such as the middle to heavy REE. Clinopyroxene Mg# is weakly but significantly, negatively correlated with clinopyroxene Zr and LREE contents, but not with more mobile trace element concentrations, e.g., Sr and Ba.

Similarly to Zr in clinopyroxene, Ce in plagioclase (chosen due to its relatively high concentration compared with other REE and incompatible trace elements) exhibits a systematic increase with height above the MTZ. Plagioclase in samples from near the base of the crust contains approximately 0.3 ppm Ce. Ce concentration in plagioclase gradually increases to ~0.65 ppm at the top of the lower gabbro section (Fig. 8), before returning to lower values of ~0.38 ppm in the uppermost gabbro sample. Plagioclase and clinopyroxene REE are well-correlated.

These observations for the Wadi Khafifah section are similar to those made by Korenaga and Kelemen (1998) in the Wadi Al Abyad section of the Nakhla massif, about 100 km northeast of the Khafifah section. Using the data of Browning (1982), Korenaga and Kelemen noted a similar lack of correlation between stratigraphic height and olivine Fo or clinopyroxene Mg#. Additionally, despite well-correlated elemental compositions within and between minerals, they did not observe any systematic variation with stratigraphic height in compatible trace element concentrations or elemental ratios.

5 Discussion

5.1 Compositional stratigraphy in the lower oceanic crust

In the lower gabbros, there is a lack of systematic compositional variation with stratigraphic height for most elements and element ratios (Figs. 5-8). While mineral compositions are variable, they

remain in a narrow range throughout the entire 3700 m of the lower gabbroic crust (Fig. 7, 8). Above ~3700 m in our section, a major compositional break marks the geochemical transition to the upper gabbroic section. Olivine no longer appears as a cumulus mineral phase, and instead Fe-Ti oxides and amphibole become more common phases. Whole rock incompatible trace element concentrations increase dramatically above this level (Fig. 6). In the whole rocks, the concentration of trace elements typically compatible in clinopyroxene and olivine (e.g., Cr and Ni) decrease markedly, while concentrations of elements typically compatible in plagioclase (e.g. Sr) increase (Fig. 6). Despite this change in whole rock compositions, mineral cores have major element and compatible trace element compositions that do not appear to change at this level (Fig. 7, 8). The Mg# of clinopyroxene and An content of plagioclase cores stay within the range of the layered gabbros until the uppermost two samples in our section, starting at ~4500 m. This observation is similar to that made by Pallister and Hopson (1981), who showed that the mineral cores stayed the same through the transitional gabbros, but the rims became highly evolved.

The compositional break at approximately 3700 m can be explained by the transition from rocks dominated by cumulate minerals in the lower gabbros, from which melt was efficiently extracted in an open system, to rocks that may have undergone closed system crystallization in the upper gabbros, including solidification of some proportion of low temperature, evolved melt that was never extracted. Closed system crystallization is often described in terms of “trapped melt” (Barnes et al., 1986; Ross and Elthon, 1997; Borghini and Rampone, 2007), however, this concept is somewhat fraught given that there is no melt remaining in the rocks today. Instead, geochemical enrichment likely manifests in the formation of evolved rims in zoned crystals (e.g. Pallister and Hopson, 1981; Lissenberg et al., 2013), or grain boundary material rich in incompatible elements.

To quantify the difference in incompatible element enrichment between the lower gabbros and upper gabbros, we can turn to highly incompatible trace elements (e.g., bulk partition coefficient = $D \ll 1$) such as Zr in the whole rock. An enrichment factor, E , is calculated as:

$$E = Zr_{\text{whole rock}} / Zr_{\text{liquid}}$$

eqn. 1

Because the magma originally in equilibrium with the cumulate assemblage is now gone, we must assume a parent magma composition appropriate for a mid-ocean ridge setting. A regression of Mg# vs ppm Zr in MORB glasses from the EPR (from PetDB; <https://search.earthchem.org/>) yields ~ 40 ppm Zr at an Mg# of 70, appropriate for a primitive, mantle-derived, low fO_2 basalt (for samples from the Mid-Atlantic Ridge, MAR, a simple regression yields slightly higher, 48 ppm, Zr at Mg# 70). Following equation 1, the lower gabbros in our section have an enrichment factor of 5-10; whereas the upper gabbros have significantly higher E, up to 80 (Fig. 9a; Table 2). There is a slight increase in E in the lower gabbros just prior to the transition to the upper gabbros, with some samples reaching 15-20 (Fig. 9a).

While it is impossible to know the precise Zr concentrations in the original Khafifah parent magmas, adjusting this value will not change the observed distinction between the lower gabbros and upper gabbros in our study. For example, slightly higher enrichment factors (10-20 in the lower gabbros and 40-70 in the upper gabbros) are calculated using P_2O_5 as the highly incompatible element in the calculations (regression of Mg# vs wt% P_2O_5 for EPR MORB glasses yields ~ 0.085 wt% P_2O_5 at an Mg# 70 [MAR, 1.0 wt% P_2O_5 at Mg# 70] (Fig. 9b).

Another way to estimate the proportion of incompatible trace element enrichment present along grain boundaries or as thin, evolved rims of crystals is to compare the measured whole rock composition to a reconstructed whole rock composition calculated from modal abundances of minerals and *in situ* mineral compositions (not including rims within 50 microns of grain boundaries, which we did not analyze):

$$Whole\ Rock_{\text{calculated}} = [(X_i^{cpx} \times Mode^{cpx}) + (X_i^{plag} \times Mode^{plag})]/100 \quad \text{eqn. 2}$$

$$Enrichment = \frac{Whole\ Rock_{\text{calculated}} - Whole\ Rock_{\text{measured}}}{Whole\ Rock_{\text{measured}}} \quad \text{eqn. 3}$$

For our calculations, we assume that the incompatible trace element contents of olivine are negligible.

Due to the low incompatible trace element abundances typically measured in olivine and the low modal abundance of olivine in our section, these assumptions do not affect the results for most elements considered here.

The enrichment between measured and calculated whole rock compositions (eqn. 3; Suppl. Table 1) increases from the lower gabbros to the upper gabbros for all incompatible trace elements (Fig. 10). This is consistent with previous observations that mineral core compositions are similar in upper and lower gabbros, while mineral rims are significantly more evolved and compositional zoning becomes more pronounced in the upper gabbros from W. Khafifah (Pallister and Hopson, 1981), Wadi Al Abyad (MacLeod and Yaouancq, 2000; Lissenberg and MacLeod, 2016) and Hess Deep (Lissenberg et al., 2013).

5. 2 Formation of the Upper Gabbros

The lack of systematic variation in major and compatible trace element compositions of minerals and whole rocks (Figs. 5-8) and low extents of core-rim zoning (Fig. 10) over 3700 m of stratigraphy in the lower gabbros from W. Khafifah, provide evidence that the evolved melt was efficiently extracted following initial crystallization of the lower gabbros. To estimate the composition of this extracted liquid, we calculate the REE concentration of liquids in equilibrium with clinopyroxene from the lower gabbros using the mineral-melt partition coefficients of Wood and Blundy (1997)(Table 8) and the Fe/Mg ratio of liquids in equilibrium with lower gabbro olivine using the Fe/Mg $K_D = 0.3$ from Roeder and Emslie (1970). Figure 11 shows that the compositions of calculated liquids in equilibrium with the lower gabbros overlap the whole rock compositions of the upper gabbros and the most depleted sheeted dike compositions in our section. Thus, it is likely that upper gabbros and overlying extrusive upper crust contain the expelled liquid fraction from the lower gabbros.

On the basis of compiled data on whole rock REE concentrations, Kelemen et al. (1997b), proposed that the upper gabbros represent the liquids expelled from the lower gabbros, and represent their

so-called 'compositional conjugate'. Our new dataset, however, shows that this interpretation cannot be entirely correct. The whole rock compositions of the upper gabbros have prominent Eu anomalies (Fig. 12), indicating that they are not themselves "frozen liquids", but instead contain a component of cumulate plagioclase (and clinopyroxene) that crystallized from an evolving melt, some of which was later extracted. Mineral cores in the upper gabbros have major and compatible trace element concentrations similar to their counterparts in the lower gabbros (Fig. 7-8), and requires that they initially crystallized from similar, primitive parent magmas to the lower gabbros. However, four lines of evidence show that, in addition to accumulated plagioclase and clinopyroxene, the upper gabbros host a significant fraction of the evolved melt component expelled after crystallization of the lower gabbros: (1) clear evidence of mineral zoning and grain boundary enrichment in the upper gabbros (Fig. 10), (2) a change in the textural character of the lower gabbros compared with the upper gabbros (e.g., Fig. 4), (2) markedly higher whole rock incompatible trace element concentrations in upper gabbros relative to lower gabbros (Fig. 5, 6), and (3) the similarity in whole rock composition of the upper gabbros to equilibrium liquids from the lower gabbros (Fig. 11, and Kelemen et al. 1997b).

5.3 *How is melt extracted from the lower crust?*

With regards to the mechanism of melt extraction from the lower gabbros to the upper gabbros, three end-member possibilities exist: (1) periodic fracturing and extraction in dikes (e.g. Kelemen and Aharonov, 1998), (2) compaction and porous flow (Quick and Denlinger, 1993; Coogan et al., 2000), or (3) focused, reactive flow in anorthosite channels (Kelemen & Aharonov, 1998; Morales et al., 2011). Variations in, and combinations of, these options are also possible (e.g. Macleod et al., 2007; Lissenberg and Dick, 2008; Lissenberg et al., 2009).

Periodic fracturing and tapping of magma from crustal melt lenses was proposed by Korenaga and Kelemen (1997) and Kelemen et al. (1997) in their studies of gabbro lenses in the Mantle Transition Zone in the Samail ophiolite. These studies showed that MTZ gabbros had similar compositions, layering, and textures to those found in the overlying lower gabbros. They noted that the MTZ gabbros

were near-perfect adcumulates that had lost a significant fraction of evolved melt (e.g. Fig. 4). Moreover, Korenaga & Kelemen (1998) showed that the nature of compositional layering in lower crustal gabbros – poorly correlated with depth in the crust, but with strong element-element and mineral-mineral compositional correlations – is inconsistent with reactive porous flow of the bulk of the crust-forming magma through the crystal matrix near the base of the crust. Thus, most of the melt must be extracted from lower gabbros in focused conduits, rather than by diffuse porous flow. A mechanism of magmatic fracturing and extraction was quantified by Kelemen and Aharonov (1998), who also proposed that periodic pressure changes associated with fracturing might be responsible for some of the characteristic modal layering observed throughout the lower crust and MTZ sills. Nevertheless, melt extraction could also take place in conduits of focused porous flow, possibly represented by cross-cutting anorthosite veins and (transposed?) anorthosite bands (Kelemen & Aharonov 1998; Morales et al., 2011).

In contrast, Lissenberg et al. (2013) examined a suite of samples dredged from the ~4.5 km thick lower crustal section at Hess Deep on the East Pacific Rise and concluded that the major and trace element characteristics of the cumulate minerals require pervasive dissolution-precipitation of the minerals upsection in Hess Deep. Lissenberg et al. (2013) made several fundamental observations that are important to list here in order to compare with our Khafifah data:

(1) Similar to the Khafifah gabbros, Mg# in the cores of clinopyroxene from Hess Deep remains within a narrow range (average of all analyses $\text{Mg\#} = 79 \pm 6$ at Hess Deep compared with $\text{Mg\#} = 83 \pm 2$ in Khafifah (1 sigma, Fig. 13)). Neither section shows systematic variation with height in the lower 3 km of the crust.

(2) However, in contrast to the Khafifah gabbros, there is systematic variation in the An content of plagioclase cores from Hess Deep from 77 at the base of the crust to 52 at the top (Fig. 13). Plagioclase An contents in the first 1000 meters above the MTZ from Khafifah overlap with the range measured in Hess Deep lower gabbros, though the Khafifah compositions fall within the higher end of the Hess Deep range (Fig. 13). From ~1000 meters to the top of the gabbro section, Khafifah plagioclase is systematically more An rich than at Hess Deep. Above a height of 2500

m, plagioclase An from Hess Deep shows more variability, and is nearly 10 An units lower than in Khafifah at the same structural level (Fig. 13).

(3) *in situ* trace element concentrations in clinopyroxene and plagioclase in Hess Deep are generally not in equilibrium with one another at magmatic temperatures. Lissenberg et al. (2013) demonstrated that highly incompatible trace elements measured in plagioclase are depleted with respect to theoretical plagioclase in equilibrium with a MORB parental melt, whereas moderately incompatible trace elements are less depleted. We do not observe this relationship in the Khafifah section.

(4) In Hess Deep and Khafifah, there is an overall increase in incompatible trace element abundance in clinopyroxene and plagioclase from the base of crustal section to the top. Clinopyroxenes in Hess Deep samples have nearly constant Zr contents in the lower 2.5 km of gabbros, and increase 9-fold in the uppermost 1.8 km. In Khafifah, clinopyroxene Zr contents increase systematically with decreasing depth (Fig. 8), but only double in concentration from the base to the top of the crust. Plagioclase Ce concentrations double from base to top in Khafifah (Fig. 8), but increase 7-fold in Hess Deep.

On the basis of their observations in Hess Deep samples, Lissenberg et al. (2013) argued for melt transport dominated by reactive porous flow throughout an integrated permeable mush zone on the scale of the entire lower crust. It is not clear how this scenario can explain the remaining, large variations in clinopyroxene Mg#, since Korenaga and Kelemen (1998) demonstrated that such variation would be reduced or eliminated by large amounts of reactive porous flow of melt, which characteristically buffers compatible element concentrations and ratios to high, nearly constant values, while incompatible trace element concentrations vary widely (Collier and Kelemen, 2010; Kelemen, 1986).

In any case, the upper gabbros at Hess Deep appear to be significantly more evolved, and/or have experienced more modification by reactive porous flow of melt, and/or contain a larger proportion of melt crystallized in a closed system than those measured in our study. In Khafifah, the lack of major element

and compatible trace element compositional change in the lower gabbros, together with the preservation of cm and m-scale cryptic variability in the lower gabbros (Browning, 1984; Browning et al., 1989; Korenaga & Kelemen 1997, 1998) demonstrate that large-scale porous melt flow was not the dominant mechanism for melt extraction from the lower crust in the Samail ophiolite.

5.5 Proportion of lower gabbro to upper gabbro in the oceanic lower crust

In Wadi Khafifah in the southern Samail ophiolite, the lower gabbro comprises 71% of the total gabbroic section (3700 m / 5200 m). In Wadi Gideah, just 15 km to the east of Wadi Khafifah, Mock et al. (2021) documented a major change in plagioclase lattice preferred orientations at 3500 m depth in a crustal section of 5010 m (~69%). In Wadi Abyad, further to the north and west, in the Nakhl-Rustaq block of the Samail ophiolite (Fig. 2), the gabbroic crustal section is 2600 m thick, containing 1800 m of lower gabbro; approximately 69% (Macleod and Yaouancq, 2000). In Hess Deep layered gabbro with low incompatible trace element abundances comprise approximately 2550 m of the total 4350 m of gabbroic crust (Lissenberg et al., 2013), a total of 59% (though Gillis et al. (2014) subsequently estimated that the layered gabbro comprises approximately 67.5% of the plutonic section). Thus, it appears that the proportions of lower layered gabbro and upper gabbro are consistent, between c. 60-70%, regardless of the total lower crustal thickness.

5.6 A Full Sheeted Sills model for lower crustal accretion

A long-standing debate exists over the on-axis magmatic architecture and style of lower crustal accretion at mid-ocean ridges. Two end-member models and several hybrid models have been envisioned to account for where magmas are primarily crystallized within the lower oceanic crust (Fig. 14). The original Sheeted Sills model (Kelemen et al., 1997) postulates that the majority of the lower crust is emplaced as a series of small melt lenses at a variety of depths, and crystallized near the crustal depth where we now find them, in keeping with observations of ultramafic sills in the Bay of Islands ophiolite (e.g., Bedard, 1991; Bedard & Hebert, 1996, 1998; Bedard et al., 1988), the Rum intrusion (Emeleus and

Troll, 2014; Hepworth et al., 2018), and the Kap Edvard Holm intrusion (Bernstein et al., 1996). In contrast, the 'Gabbro Glacier' model (Sleep, 1975; Nicolas et al., 1989; Quick and Denlinger, 1993; Phipps Morgan and Chen, 1993; Henstock et al., 1993) requires that all lower crustal gabbros are crystallized in a shallow melt lens at the base of the sheeted dikes and flow downward and outward away from the ridge axis to form the lower crust. Two additional 'hybrid' models intermediate to the Sheeted Sills and Gabbro Glacier models have been proposed: Boudier et al. (1996) envisioned a crustal-scale 'Gabbro Glacier' into which small sills are periodically emplaced at a variety of depths. MacLennan et al. (2004) modeled a hybrid section with a ~ 1-1.5 km thick Gabbro Glacier just beneath the sheeted dikes, a ~1-1.5 km thick "mixed" section, and a ~1-1.5 km thick Sheeted Sills section at the base of the crust. In fact, the 'hybrid' model of MacLennan et al. (2004) is similar to the original Sheeted Sills model in Figure 6 of Kelemen et al. (1997), which included a thin gabbro glacier layer between the sheeted dikes and the layered gabbros. Mock et al. (2021) argued for a Hybrid-style model similar to MacLennan et al. (2004) and Kelemen et al. (1997) on the basis of plagioclase LPO. No one has actually illustrated or advocated a true, end-member Sheeted Sill model.

Our major and trace element data for the Khafifah lower crust in the Oman ophiolite, combined with previous work on the cooling rate and magmatic fabrics in the same section, allows us to place new constraints on melt dynamics and magmatic plumbing in the lower crust at the ridge axis. Our previous studies documenting fast cooling rates throughout the lower crust (Garrido et al., 2001; VanTongeren et al., 2008) and a lack of increasing strain with depth from plagioclase lattice preferred orientation (VanTongeren et al., 2015) are not consistent with the Gabbro Glacier or either variety of the Hybrid models for this section. Moreover, as noted above, the non-systematic but significant variation in mineral compositions in the lower gabbros rules out pervasive, reactive melt transport of the upper crustal magmas through the lower crustal gabbros. Because the large ductile strains required by the Gabbro Glacier model necessitate melt porosities of 10 to 20% to facilitate melt-lubricated, pressure-solution accommodated, grain boundary sliding (e.g., Nicolas and Ildefonse, 1996; Chenevez et al., 1998), and because the lower gabbro compositions do not contain such large proportions of melt crystallized in a

closed system (Fig. 9), the Gabbro Glacier models require large amounts of melt extraction via porous flow. Thus, the Gabbro Glacier models are not consistent with observed variation in the minerals and whole rock samples of the Khafifah lower gabbros. The similarity of mineral cores in the upper and lower gabbros in the Khafifah section is also inconsistent with prior illustrations of the Sheeted Sills model, in which a shallow melt lens and a small Gabbro Glacier is fed entirely by evolved melt from deeper lenses (e.g. Kelemen et al., 1997b; Korenaga and Kelemen, 1998; Kelemen and Aharanov, 1998).

Instead, we propose a Full Sheeted Sills model, in which the entire lower crust forms via crystallization from primary mafic magmas in lenses distributed at depths from the MTZ to the base of the sheeted dikes. The observation of mineral cores with primitive compositions in the upper gabbros suggests that primary melts from the mantle are not only restricted to the lower gabbros, but are also periodically emplaced in the upper gabbros and AMC. Indeed, in erupted basalts from the East Pacific Rise, Wanless and Shaw (2012) showed that between 60-100% of crystal cargos were crystallized at shallow crustal levels corresponding to the AMC, despite having very primitive major element basaltic compositions.

In the Full Sheeted Sills model, there is no *initial* distinction between upper and lower gabbro on-axis beneath an axial magma chamber (AMC) at the base of the sheeted dikes. After initial crystallization, evolved melt is efficiently extracted from the lower 60-70% of the gabbroic crust (the lower gabbros). Some of this evolved melt, together with earlier formed cumulate minerals, crystallizes to form the upper 30-40% of the gabbroic crust (the upper gabbros), while the remainder mixes with residual melt in the AMC and upper gabbros and erupts to form the overlying sheeted dikes and lavas.

Our Full Sheeted Sills model places tighter constraints on which crustal levels contribute magma during melt extraction events. Our model implies that periodic fracturing induced by magma recharge into the lower crust allows fractionated melt to quickly leave the lower crustal cumulates. While trapping pressures calculated from melt inclusions erupted to the seafloor show that some lavas are derived directly from the lower crust (Wanless and Shaw, 2012), the majority of evolved melts may stall and crystallize *in situ* when they encounter the axial magma chamber (AMC), or another high porosity region

below the AMC, as suggested by Kelemen and Aharonov (1998). The liquids calculated to be in equilibrium with the lower gabbro mineral compositions (Fig. 11) overlap with the upper gabbro whole rock compositions and the more primitive sheeted dike compositions in our section. It is therefore likely that much of the expelled melt from the lower gabbros accumulated within the upper gabbros in the Khafifah section prior to eruption to form the sheeted dikes and lavas.

Crystallization of hot primitive magmas at all levels within the lower crust requires the removal of a significant amount of latent heat. Using the same set of samples as this study, VanTongeren et al. (2008) showed that the lower crust in Wadi Khafifah experienced very rapid and uniform cooling rates, likely due to penetration of hydrothermal fluids from the seafloor all the way to the MTZ. Hydrothermal circulation of seawater through the oceanic crust is a highly efficient way to remove the latent heat of crystallization throughout the lower crust at mid-ocean ridges and allow for on-axis crystallization at all crustal levels (e.g. Cherkaoui et al., 2000; Hasenclever et al., 2014).

5.7 Influence of structure and emplacement on compositional variability

As mentioned above, the geochemical transition between upper and lower gabbro lies stratigraphically below the outcrop-scale distinction between 'layered gabbro' and 'transitional gabbro' of Pallister and Hopson (1981). The geochemical transition, however, is roughly coincident with a change in plagioclase fabrics at the grain-scale. Working with the same set of samples, VanTongeren et al. (2015) showed that there is a clear transition in plagioclase lattice preferred orientations (LPO) at ~3500 m in the W. Khafifah section, i.e. approximately 700 m below the layered gabbro - transitional gabbro contact based on outcrop foliations (e.g. Pallister and Hopson, 1981).

Below 3500 m, the lower layered gabbros have plagioclase LPOs defined by (010) axes aligned perpendicular to the MTZ, so that the long axes of plagioclase crystals are parallel to the paleo-seafloor (VanTongeren et al., 2015). In contrast, the gabbros above 3500 m have plagioclase (010) aligned parallel to the MTZ, resulting in near-vertical foliation with respect to the paleo-seafloor. A single

transitional sample, OM97-106 from 3260 m, records a sub-vertical fabric with respect to the seafloor; interestingly this sample also has more evolved mineral compositions.

The fact that the transition in the outcrop-scale textures is stratigraphically distinct from the coincident geochemical and plagioclase fabric transition is critical to understanding melt dynamics in the upper gabbros. We propose that the upper gabbros initially form in the same way as the lower gabbros, by crystallization in small sills of primitive melt, and that the change in outcrop-scale layering and plagioclase-defined foliation direction is a result of either (1) melt migration upwards during diking events (e.g. Macleod and Rothery, 1992; Macleod and Yauoancq, 2000; VanTongeren et al., 2015; Mock et al., 2021) or (2) compaction and shearing (e.g. Nicolas et al., 2009) in the presence of larger interstitial melt fractions in the upper gabbros as compared with the lower gabbros. This is distinct from a 'Gabbro Glacier' model *sensu strictu*, in that the upper gabbros in our model do not crystallize solely from a single thin axial melt lens and then flow downward and outward to form a thicker gabbroic layer. Instead, we infer that they are emplaced and crystallized *in situ* but are more susceptible to large-scale rotations because they contain larger melt fractions during on-axis deformation. Geochemical data from this study support the idea that the plagioclase fabric and outcrop-scale foliation are influenced by the proportion of interstitial melt on-axis (Fig. 15), as the stratigraphic change in plagioclase fabric coincides almost exactly with the geochemical transition to more evolved gabbros in the crust.

5.9 An estimated major element bulk composition for the crust

An estimated major and trace element bulk lower crust composition was calculated by weighting each whole rock analysis according to its position within the stratigraphy (Table 2), a method similar to that applied by VanTongeren et al. (2010) for the Upper Zone of the Bushveld Complex layered intrusion. A previous estimate for the bulk composition of the lower crust in the Wadi Tayin massif was made by simple averaging of < 20 "representative" whole rock compositions for each unit (<5 for the "high-level" gabbros) in the gabbroic stratigraphy (Pallister and Gregory, 1983; composition shown in Table 9). The method employed here for obtaining the bulk composition is an improvement over that of Pallister and

Gregory (1983) because it accounts for stratigraphic variation in the gabbro column due to crystal fractionation and evolving geochemistry.

The Lower Gabbros

Our estimated bulk composition for the lower gabbros is listed in Table 9. Root mean square errors on the estimate are determined by omitting a quarter of the samples (7 of 28) and repeatedly recalculating the bulk composition a total of four times (see Suppl. Table 2 for details). This jack-knife statistical resampling technique shows that our bulk composition estimate for the lower gabbros is highly robust and is unlikely to change with additional sampling.

Only gabbros with typical modal proportions (~50-60 plag: 35-40 cpx: 5-10 ol) were included in our compilation. While wehrlite and anorthosite layers are present in the Khafifah section, we do not include any analyses of these lithologies in our bulk composition. Wehrlites (also referred to as 'melanogabbro'), composed of olivine, clinopyroxene and minor plagioclase, intrude and are interlayered with gabbros throughout the Samail ophiolite (e.g., Koga et al., 2001; Benn et al., 1988). In general, these seem to have formed by crystallization of magmas with the same major and trace element composition as the gabbros, with the addition of enough water – perhaps seawater – to shift the crystallization sequence from ol-plag-cpx to ol-cpx-plag (Benoit et al., 1996; Koepke et al, 2009; Koepke et al., 2014; Feig et al., 2006). In the Khafifah section, wehrlites comprise less than 10%, probably less than 5%, and do not significantly affect the results presented here. That said, few if any wehrlites have been recovered from the mid-ocean ridges, so their presence in the Samail ophiolite may indicate some differences in the mechanism of crustal formation for the ophiolite compared to mid-ocean ridge crust. In the case of anorthosites, plagioclase-only layers are small (< m-scale) in the crustal section. They may form by typical magma chamber dynamics and crystal sorting, and/or as a result of decompression due to magmatic fracturing (Kelemen & Aharonov 1998, their Figure 9 and related text; Morales et al. 2011; Boudier and Nicolas, 2011).

The newly calculated bulk composition for the Khafifah lower gabbros is more primitive than that previously estimated for lower gabbros in the Samail ophiolite by Pallister and Gregory (1983) (Table 9).

Their lower gabbro composition has significantly higher SiO_2 (49.9 vs. 48% in this study) and higher FeO (6% vs. 5.5%); whereas, our estimate for Khafifah has significantly more Al_2O_3 , MgO , and CaO (Table 9). Pallister and Gregory (1983) included the transitional gabbro section (4200 -4700 m) in their compilation of lower gabbros, which is likely the cause of their more evolved composition relative to this study.

The nearby Wadi Gideah (~10 km to the east; Fig. 2) is the site of the recent ICDP Oman Drilling Project, which intersected the lower gabbros in core GT1. An average of 56 gabbro compositions measured over ~400 m (Chikyu curated depth) of core (Kelemen et al., 2020a) yields a bulk composition remarkably similar to our calculated Khafifah lower gabbro section (Table 9).

The Upper Gabbros

Due to a paucity of fresh outcrop for sampling in the upper gabbro section, our dataset includes only four exceptionally fresh samples from 3700 m - 4700 m, three of which correspond to the 'transitional gabbros' in the stratigraphic column of Pallister and Hopson (1981). We do not have any samples representing the 500 m thick 'high-level' gabbro section of Pallister and Hopson (1981), from 4700 -5200 m. We therefore incorporate the 'high-level' gabbro composition from Pallister and Gregory (1983) for this section, including their estimate of 0.1% plagiogranite (~5.2 m), into our upper gabbro bulk composition. The resulting upper gabbro bulk composition (Table 9) is distinct from that reported by Pallister and Gregory (1983) in that it includes the interval from 3700-4700 m, which was previously incorporated into their lower gabbro estimate.

Employing the same jack-knife statistical resampling strategy as was use in the lower gabbros above, we calculate RMSE uncertainties for the upper gabbro bulk composition shown in Table 9 (see full calculation in Suppl. Table 2 for details). While the uncertainties are higher than those reported for the lower gabbros, they are still very small (< 0.5 wt% for most elements), giving us good confidence in the compositions estimated here.

For comparison, we compile all analyses from the recent ICDP Oman Drilling Program boreholes through the upper gabbros in Wadi Gideah. Core GT2 drilled through 'foliated' gabbros into 'layered' gabbros, intersecting approximately 50 m of evolved, but olivine-bearing, gabbro at the top (Kelemen et al., 2020b). Core GT3 drilled through the sheeted dike to gabbro transition, intersecting evolved, olivine-free gabbro, diorite, and diabase in the lowermost 180 m (Kelemen et al., 2020c). The compositions of samples from the Khafifah upper gabbros measured here overlap with those in cores from GT2 and GT3 (Fig. 16). A very rough estimate of the bulk upper gabbro section of Wadi Gideah can be made by assuming a stratigraphic equivalent of 1000 m for the GT2 'foliated gabbros' of Wadi Gideah, and a 500 m stratigraphic equivalent for the GT3 gabbros and diorites (similar to the 'high-level' gabbro distinction of Pallister and Hopson, 1981). While it is not our intent to provide a detailed comparison of Wadi Gideah and Khafifah, this rough estimate of the upper gabbro section of Wadi Gideah is similar in most respects to our Khafifah estimate (Table 9), providing additional confidence in the results and interpretations presented here.

The complete bulk lower crust composition for the Khafifah section is calculated by stratigraphically weighted summation of the compositions of lower gabbro (3700 m) and the upper gabbro (1500 m). The bulk Khafifah gabbroic lower crust has very similar composition to that estimated for Hess Deep lower crust from Gillis et al. (2014) (Table 9), except that the Khafifah gabbro section has higher CaO and lower MgO. This difference could be caused by a higher An content of plagioclase in the Khafifah section as compared to Hess Deep (Figs. 3, 13), and/or the slightly less evolved upper gabbros in Khafifah (Mg# 63.7) compared to those reported by Gillis et al. (2014) and Lissenberg et al. (2013) for Hess Deep (Mg# = 62).

The bulk crustal composition of W. Khafifah (Table 9) includes the entire 5.2 km plutonic section, plus an additional 2 km (previously estimated for this section by Pallister and Gregory, 1983) of extrusive material represented by the average of the sheeted dike compositions reported in Table 2b. This new estimate of bulk crustal composition contains 49.91 wt% SiO₂, 8.97 wt% MgO, and has an Mg# of 68.7. Assuming that the primitive mantle melt that formed the Khafifah crust had molar Fe³⁺/Fe_{total} of 14-

16% (Cottrell and Kelley, 2011), this yields a composition with molar $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$ of 72.9 - 73.5, in equilibrium with Fo89-90 olivine typical of residual mantle harzburgites in ophiolites and mid-ocean ridge peridotites.

The bulk rock gabbro major element compositions from the Khafifah section appear to define a continuum in SiO_2 -MgO with the sheeted dikes and lavas in the southern massifs of the Samail ophiolite (Fig. 16). This continuum stretches from the depleted MORB mantle (from Workman and Hart, 2005) and encompasses the compositions of average MORB from Gale et al. (2013). The Khafifah bulk composition is similar to primitive MORB melts that have undergone little to no olivine fractionation after mantle melting. We infer that mantle-derived melts are directly transported from the melting region to the lower crust. In this view, most of the olivine in dunite in the Mantle Transition Zone is original mantle olivine, modified by reaction with primitive melt.

6 Conclusions

We present major and trace element compositions for whole rock and minerals from the lower crust of the Wadi Khafifah section of the Wadi Tayin massif of the Samail ophiolite. We also present geochemical data on sheeted dikes in the Samail and Wadi Tayin massifs, the two southern massifs of the Samail ophiolite. These two massifs have whole rock and mineral compositions that are more similar to samples from fast-spreading mid-ocean ridges than in any other ophiolite worldwide. Though the rock and mineral compositions are slightly but systematically different from mid-ocean ridge samples, our data shed light on the general processes of crustal genesis at oceanic spreading ridges.

Our data show a geochemical distinction between lower gabbros (0-3700 m above MTZ) and upper gabbros (3700 – 5200 m), which is approximately coincident with a change in plagioclase crystallographic orientations. Major element mineral compositions in the lower gabbros do not change

systematically with depth, and trace element enriched crystal rims and interstitial material forms less than 10% of the lower gabbros. In contrast, upper gabbros become markedly more evolved in both major and trace element concentrations and contain a significant fraction of enriched crystal rims and interstitial material, some of which may be melt that crystallized entirely in a closed system. We propose a new Full Sheeted Sills model for magmatic accretion of oceanic crust, in which the majority of melt is extracted from lower gabbros in magmatic fractures or conduits of focused porous flow, and transported into the upper gabbros prior to further crystallization and eventual transport via dikes to sites of eruption on the seafloor.

We reconstruct bulk compositional estimates for the lower gabbros, the upper gabbros, the sheeted dikes, and the entire Khafifah crustal section. Our estimated composition agrees well with estimates from other exposed sections in the Samail ophiolite, and from the tectonically exposed oceanic crust at Hess Deep on the fast-spreading EPR. These compositions form a continuum between the mantle source region (DMM) and the sheeted dikes and lavas, thus defining a likely liquid line of descent for aggregated MORB-like melts. Combining gabbro, sheeted dike, and lava compositions yields a bulk composition for the Khafifah crust that corresponds to a plausible mantle-derived primary MORB composition in equilibrium with depleted MORB mantle and parental to fast-spreading oceanic crust.

Acknowledgments, Samples, and Data

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Full datasets for this research are available from:

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1076
 1077 **Figure 1.** Stratigraphic units in the Penrose model of fast-spreading oceanic crust for an
 1078 approximately 7 km thick oceanic crust, similar to that of W. Khafifah in the southern Samail
 1079 ophiolite. Stratigraphic height of samples from this study denoted by stars. Stratigraphic
 1080 distinction between 'Layered Gabbro', 'Transitional Gabbro', and 'High-level Gabbro' from
 1081 Pallister and Hopson (1981).

1082
 1083 **Figure 2.** Large-scale map of the Oman ophiolite, adapted from Nicolas et al. (2000). Areas in
 1084 orange (gabbro) and red (sheeted dikes and lavas) indicate oceanic crustal sections; areas in grey
 1085 are mantle peridotite. Inset shows the location of W. Khafifah (this study) and W. Gideah (GT1
 1086 and GT2 drillcore site from the Oman Drilling Project), from Pallister and Hopson (1981).

1087
 1088 **Figure 3.** Plagioclase An content and clinopyroxene Mg# in oceanic gabbros from this study (W.
 1089 Khafifah), Hess Deep, East Pacific Rise, from Lissenberg et al. (2013) and Natland and Dick
 1090 (1996), and Pito Deep, East Pacific Rise, from Perk et al. (2007). W. Khafifah gabbros overlap
 1091 with the range found in extant ridges, but typically have slightly higher plagioclase An for a
 1092 given clinopyroxene Mg#.

1093
 1094 **Figure 4.** Thin section photomicrographs in crossed polarized light of representative samples
 1095 from the upper gabbros and lower gabbros. Note significant change in the textural character of
 1096 the samples from lower gabbro to upper gabbro. Top row: (a) OM97-114, DMTZ = 4367 m,
 1097 abundant plagioclase and pyroxene with no olivine; (b) OM97-113, DMTZ = 3989 m, greater
 1098 modal abundance of pyroxene as compared with sample OM97-114. Bottom row: (c) OM97-95,
 1099 DMTZ = 2303 m, pyroxene, plagioclase, and cumulus olivine; (d) OM97-67, DMTZ = 46 m,
 1100 similar in character to OM97-95, though slightly lower modal abundance of olivine present.

1101
 1102 **Figure 5.** Whole rock major element variation with stratigraphic height above the Mantle
 1103 Transition Zone (MTZ) in meters. See Table 2 for data. Lower gabbros in solid black, upper
 1104 gabbros in open circles, average sheeted dike composition shown in grey triangle, with standard
 1105 deviation as black line.

1106
 1107 **Figure 6.** Whole rock trace element variation with stratigraphic height above the MTZ (m).
 1108 Lower gabbros in solid black circles, upper gabbros in open circles, average sheeted dike
 1109 composition shown in grey triangle, with standard deviation as black line. Note that no sheeted
 1110 dike information is plotted for the incompatible trace elements, due to their extreme enrichment
 1111 in the sheeted dike samples relative to the gabbros. See Table 2 for data.

1112
 1113 **Figure 7.** Mineral major element variation with stratigraphic height above the MTZ (m). Lower
 1114 gabbros in solid black circles, upper gabbros in open circles.

1115

Figure 8. Mineral trace element variation with stratigraphic height above the MTZ (m). Lower gabbros in solid black, upper gabbros in open symbols.

Figure 9. Enrichment Factor (E) calculated according to equation 1 (see text). (a) E calculated using whole rock Zr content vs. stratigraphic height. (b) Correlation between E calculated from whole rock Zr vs. calculated from whole rock P_2O_5 .

Figure 10. Percent difference calculated between the calculated whole rock value (from mineral compositions and modes; see eqn. 2 in text) and measured whole rock values. % Difference = $100 * [WR_{\text{calculated}} - WR_{\text{measured}}] / WR_{\text{measured}}$. Larger percent difference seen in the upper gabbros is likely due to mineral zoning and/or presence of intercumulus material along grain boundaries.

Figure 11. Similarity between the liquid calculated to be in equilibrium with the lower gabbros, and the measured whole rock composition of the upper gabbros and sheeted dikes. Measured whole rock data from lower gabbros in solid black circles, from upper gabbros in open circles. Sheeted dike compositions are shown in filled yellow triangles; liquids calculated to be in equilibrium with lower gabbros are plotted in filled red circles. (a) Equilibrium liquid $Fe^{2+}/Mg_{\text{molar}}$ calculated from olivine, note there is no cumulus olivine present in the upper gabbros. Sheeted dike $Fe^{2+}/Mg_{\text{molar}}$ calculated assuming $Fe^{3+}/Fe_{\text{total}} = 0.16$ (Cottrell and Kelly, 2011). (b) Equilibrium liquid Ce (ppm) calculated from clinopyroxene in lower and upper gabbros, see Table 8 for full REE dataset.

Figure 12. Full trace element dataset for lower gabbros (solid black circles), upper gabbros (open circles), and sheeted dikes (yellow). (a) whole rock trace elements normalized to primitive mantle from Sun and McDonough (1995); (b) whole rock REE normalized to C1 chondrite (Sun and McDonough, 1995).

Figure 13. Comparison of changes in mineral major element chemistry with height above the MTZ between Hess Deep (EPR; open triangles) from Lissenberg et al. (2013) and W. Khafifah (this study; black circles). Both Plagioclase An content and clinopyroxene Mg# from Lissenberg are the averages measured.

Figure 14. A new model for the accretion of the lower oceanic crust. 'Gabbro Glacier' model based on (Sleep, 1975; Nicolas et al., 1989; Quick and Denlinger, 1993; Phipps Morgan and Chen, 1993; Henstock et al., 1993). 'Sheeted Sills: Original' based on Kelemen et al. (1997). 'Hybrid: Boudier' refers to the model of Boudier (1997), and 'Hybrid: MacLennan' refers to the model of MacLennan et al. (2004). 'Full Sheeted Sills' model is proposed in this study, melts derived directly from the mantle are shown in red, yellow regions correspond to evolved melt emplaced in the upper gabbros after fractional crystallization in the lower gabbros. The axial magma chamber beneath the sheeted dikes contains melts derived from the crystallization of the upper gabbros and subsequently erupted to the seafloor. See text for full descriptions.

Figure 15. Correlation between the plagioclase lattice preferred orientation and the Enrichment Factor (E) calculated in this study. Obliquity (alpha) is measured as the angle between the plagioclase b-axis (010) maxima to the modal layering in the sample (see cartoon inset 'a'), data from VanTongeren et al. (2015).

1162
1163 **Figure 16.** Whole rock compositions from this study compared to mid ocean ridge basalts and
1164 estimates of primitive melt of the MORB mantle. Large circles correspond to lower gabbros
1165 (black fill) and upper gabbros (white fill) from W. Khafifah (this study). Small black circles
1166 correspond to lower gabbros from the GT1 drillcore in nearby Wadi Gideah (data from Kelemen
1167 et al., 2020a). Small white circles correspond to upper gabbros from the uppermost 50m of the
1168 GT2 drillcore (data from Kelemen et al., 2020b) and gabbros and diorites from the lowermost
1169 180 m of the GT3 drillcore (data from Kelemen et al., 2020c). Open triangles are sheeted dike
1170 compositions from W. Tayin (this study). The average bulk plutonic crust from W. Khafifah is
1171 in the large red star, and average bulk crust including the sheeted dikes as the extrusive layer for
1172 W. Khafifah is represented by the large blue star, see Table 9 for details. Grey circles labeled
1173 "EPR, seg avg, Gale13" are segment averages from the East Pacific Rise from Gale et al. (2013).
1174 Large grey circle is the average of all MORB determined by Gale et al. (2013). The large orange
1175 star is the bulk plutonic crust estimate for Hess Deep from Gillis et al. (2013). The large yellow
1176 circle is 14% aggregated fractional mantle melt from the experiments of Kinzler and Grove
1177 (1992).

1178

1179

Penrose Structure

UPPER GABBROS

(a) OM97-114; DMTZ = 4367 m

(b) OM97-113; DMTZ = 3989 m

LOWER GABBROS

(c) OM97-95; DMTZ = 2303 m

(d) OM97-67; DMTZ = 46 m

Nominally compatible

Incompatible

Difference (Enrichment) between calculated and measured whole rock values

(a)

(b)

Table 1a. Sample Locations and Modes for W. Khafifah Gabbros

Sample Numl	Lithology	Collection	Height above		Location	
			MTZ (m)	UTM	UTM	Olivine
OM97-67a	gabbro	Garrido	46	0650333 E	2535082 N	7
OM97-63	gabbro	Garrido	119	0650333 E	2535082 N	11
OM97-70	gabbro	Garrido	135	0650333 E	2535082 N	7
OM97-45	gabbro	Garrido	162	0647495 E	2535235 N	10
OM97-52	gabbro	Garrido	525	064 74 95	25 35 235	11
OM97-59a	gabbro	Garrido	640	0647011 E	2534394 N	12
OM97-75	gabbro	Garrido	719	064 69 47	25 34 217	14
OM99-40	gabbro	z-gap	961	0646787 E	2533534 N	16
OM99-43	gabbro	z-gap	961	0646787 E	2533534 N	15
OM99-44	gabbro	z-gap	1253	064 61 24	25 33 154	16
OM99-47	gabbro	z-gap	1392	0647213 E	2532471 N	19
OM99-49	gabbro	z-gap	1392	0647213 E	2532471 N	18
OM99-51	gabbro	z-gap	1535	064 73 95	25 32 127	14
OM99-53	gabbro	z-gap	1535	064 73 95	25 32 127	10
OM97-84	anorthosite	Garrido	1663	0646064 E	2532410 N	2
OM97-85	gabbro	Garrido	1663	0646064 E	2532410 N	
OM97-89	gabbro	Garrido	1793	0647433 E	2531650 N	14
OM97-94a	gabbro	Garrido	2011	064 76 01	25 31 070	10
OM97-200	gabbro	Garrido	2181	064 95 66	25 30 116	18
OM97-99	gabbro	Garrido	2193	064 91 81	25 30 214	12
OM97-97a	gabbro	Garrido	2257	064 85 61	25 30 315	10
OM97-95	gabbro	Garrido	2303	0647632 E	2530434 N	16
OM97-102a	gabbro	Garrido	2369	064 95 07	25 29 684	14
OM97-104	gabbro	Garrido	2999	064 95 74	25 28 329	14
OM97-106	gabbro	Garrido	3260	0649106 E	2527817 N	10
OM97-204	gabbro	Garrido	3573	0648467 E	2527222 N	11
OM97-111	gabbro	Garrido	3594	0648373 E	2527198 N	13
OM97-110	gabbro	Garrido	3627	064 83 48	25 27 124	14
OM97-108	gabbro	Garrido	3632	064 82 55	25 271 37	25
OM97-112	gabbro	Garrido	3691	064 82 74	25 26 987	11
OM97-113	gabbro	Garrido	3989	0648812 E	2526220 N	0
OM97-114	gabbro	Garrido	4367	0649061 E	2525225 N	0
OM97-207	gabbro	Garrido	4468	0649484 E	2524862 N	0
OM97-209	gabbro	Garrido	4680	0650895 E	2523955 E	0

Accepted Article

Modal Abundance (wt%)					
Cpx	Plag	Opx	Ox	Amph	
41	52	0	0	0	
52	37	0	0	0	
38	54	0	0	0	
38	52	0	0	0	
35	54	0	0	0	
42	47	0	0	0	
37	49	0	0	0	
29	55	0	0	0	
39	47	0	0	0	
36	47	0	0	0	
37	43	0	0	0	
45	37	0	0	0	
47	39	0	0	0	
55	35	0	0	0	
20	78	0	0	0	
32	54	0	0	0	
30	59	0	0	0	
38	44	0	0	0	
41	47	0	0	0	
33	57	0	0	0	
35	49	0	0	0	
31	55	0	0	0	
35	50	0	0	0	
45	45	0	0	0	
36	53	0	0	0	
40	48	0	0	0	
36	50	0	0	0	
21	54	0	0	0	
41	48	0	0	0	
52	43	0	5	0	
31	63	0	6	0	
4	55	0	7	34	
15	84	0	1	0	

Table 1b. Sample locations for Sheeted Dike Samples from W. Khafifah

Sample Number	Lithology	Location		Orientation	
		UTM E	UTM N	Strike	Dip
OM01-09	Sheeted Dike	649193	2515356	342	40 E
OM01-10	Sheeted Dike	649193	2515356	3	34 E
OM01-11	Sheeted Dike	649193	2515356	342	40 E
OM01-12	Sheeted Dike	649159	2515385	340	42 E
OM01-13	Sheeted Dike	649144	2515386	333	36 E
OM01-14	Sheeted Dike	649144	2515386	333	36 E
OM01-15	Sheeted Dike	649004	2515511	327	41 E
OM01-16	Sheeted Dike	649004	2515511	327	41 E
OM01-17	Sheeted Dike	649004	2515511	340	43 E
OM01-18	Sheeted Dike	649004	2515511	340	43 E
OM01-20	Sheeted Dike	649004	2515511	340	43 E
OM01-21	Sheeted Dike	648978	2515585	0	34 E
OM01-22	Sheeted Dike	648978	2515585	0	34 E
OM01-23	Sheeted Dike	646697	2517840	29	69 E
OM01-24	Sheeted Dike	646678	2518027	353	85 E
OM01-26	Sheeted Dike	646702	2518229	195	81 W
OM01-27	Sheeted Dike	646702	2518229	195	81 W
OM01-28	Sheeted Dike	646702	2518229	2	90 E
OM01-29	Sheeted Dike	646749	2518271	205	67 W
OM01-30	Sheeted Dike	653678	2521694	343	43 E
OM01-31	Sheeted Dike	653678	2521694	343	43 E
OM01-33	Sheeted Dike	653500	2521311	340	64 E
OM01-34	Sheeted Dike	653511	2521349		
OM01-35	Sheeted Dike	653835	2521407	0	73 E
OM01-36	Sheeted Dike	660201	2521737	338	85 E
OM01-37	Sheeted Dike	660216	2521732	157	76 W
OM01-38	Sheeted Dike	660216	2521732	157	76 W
OM01-41	Sheeted Dike	661330	2522511	330	70 E
OM01-42	Sheeted Dike	661180	2523511	3	71 E
OM01-46	Sheeted Dike	656264	2525231	335	85 E
OM01-47	Sheeted Dike	656264	2525231	335	85 E
OM01-48	Sheeted Dike	656264	2525231	339	90 E

Table 2a. Whole Rock Compositions

Gabbros

Sample ID	OM97-67a	OM97-63	OM97-70	OM97-45	OM97-52	OM97-59a	OM97-75
DMTZ(m)	46	119	135	162	525	640	719
Lithology	LG	LG	LG	LG	LG	LG	LG
(wt%)							
SiO ₂	49.24	48.67	48.75	48.28	48.71	47.77	47.96
TiO ₂	0.21	0.18	0.21	0.19	0.22	0.24	0.23
Al ₂ O ₃	18.73	14.02	19.65	18.72	18.80	17.14	17.13
MgO	9.37	14.09	9.02	10.74	9.55	11.38	11.16
MnO	0.08	0.09	0.07	0.08	0.10	0.10	0.11
FeO	3.83	4.10	3.78	4.23	5.54	5.19	6.10
CaO	17.34	18.25	17.41	16.56	15.39	17.38	16.18
Na ₂ O	1.19	0.57	1.08	1.16	1.66	0.79	1.10
K ₂ O	0.00	0.01	0.01	0.02	0.01	0.01	0.01
P ₂ O ₅	0.01	0.01	0.01	0.01	0.02	0.01	0.01
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Mg#	81.4	86.0	80.9	81.9	75.5	79.6	76.5
(ppm)							
Sc	49.0	52.8	46.0	41.3	40.0	45.0	45.0
V	129	131	116	116	115	141	119
Cr	906	1027	442	509	278	266	96
Ni	166	339	127	162	89	138	102
Cu	98	138	53	141	98	99	110
Zn	14	12	10	14	14	17	22
Ga	12	9	10	10	14	13	12
Ti	1501	1364	1563	1385	1600	1775	1714
Rb	0.06	0.05	0.06	0.05	0.06	0.05	0.04
Sr	128.6	92.5	144.8	135.5	155.1	131.8	141.3
Y	5.0	4.3	5.0	5.3	6.0	5.0	6.0
Zr	3.3	2.4	4.9	2.4	4.5	3.2	5.8
Nb	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Ba	2.8	1.9	7.4	3.0	3.8	2.1	3.0
La	0.18	0.16	0.23	0.19	0.19	0.15	0.23
Ce	0.58	0.40	0.56	0.54	0.60	0.57	0.75
Pr	0.12	0.09	0.12	0.12	0.13	0.13	0.16
Nd	0.86	0.69	0.83	0.80	0.92	0.92	1.11
Sm	0.40	0.33	0.38	0.37	0.44	0.43	0.49
Eu	0.27	0.18	0.23	0.25	0.30	0.25	0.31

Gd	0.64	0.59	0.63	0.62	0.73	0.73	0.82
Tb	0.12	0.11	0.12	0.12	0.14	0.13	0.15
Dy	0.89	0.83	0.86	0.86	1.04	1.00	1.11
Ho	0.18	0.17	0.17	0.17	0.21	0.20	0.22
Er	0.50	0.46	0.49	0.48	0.58	0.54	0.62
Tm	0.07	0.06	0.07	0.07	0.08	0.07	0.09
Yb	0.41	0.38	0.41	0.41	0.50	0.45	0.52
Lu	0.06	0.06	0.06	0.06	0.08	0.07	0.08
Hf	0.16	0.13	0.19	0.13	0.20	0.17	0.25
Pb	0.44	n.d.	n.d.	0.40	0.36	5.97	0.45
Th	0.002	0.001	0.002	0.001	0.002	0.001	0.002
U	0.002	n.d.	0.002	n.d.	0.002	n.d.	n.d.
E (Zr)	8.2	6.0	12.2	5.9	11.2	8.0	14.4

*LG = lower gabbro; UG = upper gabbro

** E = enrichment factor, calculated as described in text

n.d. = not detected

OM99-40	OM99-43	OM99-44	OM99-47	OM99-49	OM99-51	OM99-53	OM97-84
961	961	1253	1392	1392	1535	1535	1663
LG	LG	LG	LG	LG	LG	LG	LG
47.04	47.64	46.78	47.37	48.06	47.87	48.74	48.58
0.15	0.24	0.20	0.19	0.22	0.20	0.24	0.12
18.83	16.03	16.55	15.19	13.24	14.50	13.12	26.50
11.03	11.81	12.66	14.74	15.63	14.41	14.23	4.04
0.10	0.12	0.12	0.11	0.12	0.09	0.09	0.04
5.76	6.47	6.03	5.75	5.94	4.16	4.18	2.14
15.01	15.41	15.72	15.17	15.71	17.28	18.16	16.48
1.15	1.19	0.89	0.88	0.80	0.55	0.58	2.06
0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.03
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
99.08	98.93	98.96	99.42	99.72	99.07	99.36	100.00
77.3	76.5	78.9	82.0	82.4	86.0	85.8	77.1
33.6	48.9	46.4	46.5	55.0	56.0	65.4	32.0
91	155	125	121	144	131	157	66
569	199	246	313	522	831	876	158
179	119	143	160	169	311	273	47
117	19	200	30	39	189	228	15
26	26	29	27	30	18	17	0
11	10	9	10	8	9	7	15
916	1417	1225	1133	1344	1170	1429	915
0.08	0.06	0.09	0.05	0.06	0.10	0.06	0.12
150.2	177.6	128.7	104.5	92.5	79.7	77.2	235.3
3.8	5.6	5.4	5.1	6.3	4.7	5.8	2.0
2.3	2.9	2.8	2.8	3.5	3.2	3.7	2.1
0.03	0.02	0.01	0.02	0.03	0.04	0.03	0.02
2.8	2.4	2.3	2.3	2.2	2.3	1.8	4.4
0.15	0.17	0.18	0.16	0.17	0.15	0.15	0.20
0.47	0.52	0.57	0.49	0.56	0.48	0.54	0.53
0.10	0.12	0.13	0.11	0.13	0.10	0.13	0.10
0.62	0.82	0.87	0.77	0.92	0.73	0.85	0.61
0.31	0.44	0.45	0.41	0.50	0.37	0.46	0.24
0.23	0.24	0.28	0.24	0.26	0.19	0.22	0.24

0.55	0.74	0.72	0.71	0.80	0.61	0.74	0.38
0.10	0.14	0.14	0.13	0.15	0.12	0.15	0.07
0.65	0.96	0.91	0.86	1.06	0.80	0.95	
0.14	0.20	0.20	0.18	0.22	0.16	0.20	0.10
0.39	0.55	0.53	0.50	0.63	0.45	0.56	0.26
0.05	0.08	0.07	0.07	0.09	0.06	0.08	0.04
0.33	0.47	0.46	0.45	0.55	0.38	0.49	0.22
0.05	0.08	0.07	0.07	0.08	0.06	0.07	0.03
0.11	0.16	0.15	0.13	0.17	0.15	0.18	0.07
0.06	0.03	0.09	0.04	0.04	0.05	0.23	1.74
0.005	0.002	0.006	0.003	0.003	0.004	0.003	0.002
0.001	0.001	0.001	0.001	0.001	0.003	0.001	n.d.
5.7	7.4	7.0	7.0	8.8	8.1	9.2	5.2

OM97-89	OM97-94a	OM97-200	OM97-99	OM97-97a	OM97-95	OM97-102a	OM97-104
1793	2011	2181	2193	2257	2303	2369	2999
LG	LG	LG	LG	LG	LG	LG	LG
47.78	47.91	47.35	47.93	48.21	47.81	47.59	47.73
0.13	0.14	0.20	0.28	0.19	0.18	0.22	0.19
19.74	21.34	16.38	16.47	19.35	17.68	18.35	18.28
10.76	9.17	14.81	11.17	9.89	12.15	11.37	11.19
0.09	0.07	0.11	0.11	0.09	0.09	0.10	0.10
4.79	4.13	5.46	6.04	4.53	5.23	5.55	5.43
15.56	15.90	14.78	17.09	16.57	15.88	15.76	16.04
1.09	1.31	0.86	0.87	1.15	0.94	1.01	1.01
0.05	0.02	0.02	0.02	0.01	0.01	0.03	0.01
0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.02
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
80.0	79.8	82.9	76.7	79.6	80.6	78.5	78.6
39.0	41.0	42.0	46.0	43.0	45.0	35.0	40.0
73	77	90	133	102	102	106	102
508	332	201	174	399	435	585	618
203	185	169	135	107	140	184	197
80	100	29	164	38	137	137	125
20	14	30	22	20	24	23	19
9	14	12	11	14	13	13	14
854	1041	1282	1878	1217	1182	1366	1281
0.17	0.09	0.13	0.10	0.14	0.05	0.14	0.07
137.6	171.4	103.9	147.0	141.2	119.8	128.6	133.2
3.0	4.0	4.0	6.0	4.0	4.0	5.0	4.0
2.0	2.5	3.6	5.7	4.0	2.8	3.8	3.2
0.04	0.03	0.04	0.04	0.07	0.03	0.03	0.02
3.7	3.6	3.1	4.0	4.2	2.6	3.8	3.5
0.21	0.19	0.29	0.32	0.27	0.17	0.24	0.23
0.58	0.54	0.73	1.06	0.84	0.52	0.75	0.67
0.11	0.10	0.14	0.21	0.15	0.11	0.14	0.13
0.67	0.66	0.90	1.42	0.96	0.74	0.97	0.87
0.27	0.27	0.39	0.61	0.40	0.33	0.41	0.38
0.25	0.21	0.25	0.34	0.29	0.24	0.28	0.27

0.45	0.44	0.66	1.02	0.67	0.57	0.69	0.65
0.08	0.08	0.12	0.18	0.12	0.10	0.13	0.12
0.62	0.59	0.91	1.35	0.90	0.78	0.94	0.88
0.12	0.12	0.18	0.27	0.18	0.16	0.19	0.17
0.34	0.33	0.50	0.73	0.49	0.41	0.51	0.46
0.05	0.05	0.07	0.10	0.07	0.06	0.07	0.06
0.28	0.28	0.42	0.61	0.41	0.35	0.42	0.39
0.04	0.04	0.07	0.09	0.06	0.05	0.06	0.06
0.09	0.10	0.15	0.23	0.16	0.13	0.18	0.15
0.80	0.32	4.87	3.90	14.28	10.76	0.91	n.d.
0.001	0.003	0.004	0.003	0.005	0.002	0.004	0.002
n.d.	0.002	n.d.	n.d.	0.002	n.d.	n.d.	n.d.
5.0	6.1	9.0	14.2	10.1	7.0	9.6	8.1

OM97-106	OM97-204	OM97-111	OM97-110	OM97-108	OM97-112	OM97-113	OM97-114
3260	3573	3594	3627	3632	3691	3989	4367
LG	LG	LG	LG	LG	LG	UG	UG
49.69	47.95	48.32	48.49	46.29	48.92	49.72	49.29
0.37	0.21	0.23	0.23	0.12	0.27	0.47	0.83
16.24	18.79	17.01	16.91	18.71	15.98	16.78	21.29
10.24	11.25	11.24	12.04	14.24	11.79	10.23	5.71
0.12	0.08	0.11	0.10	0.11	0.09	0.12	0.09
5.59	4.12	5.49	4.95	6.26	4.41	6.51	6.47
16.13	16.43	16.55	16.08	13.08	17.54	14.30	13.49
1.59	1.10	1.01	1.15	1.16	0.97	1.75	2.67
0.01	0.05	0.02	0.02	0.02	0.02	0.07	0.11
0.02	0.02	0.02	0.02	0.02	0.02	0.04	0.04
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
76.5	82.9	78.5	81.3	80.2	82.7	73.7	61.1
51.0	42.0	44.3	47.0	27.0	52.0	41.0	34.0
153	98	126	116	59	125	135	294
517	487	438	687	479	1062	424	117
162	158	158	203	285	205	138	55
89	25	136	92	109	97	79	122
26	18	21	29	28	20	28	18
13	12	10	12	11	11	12	15
2112	1351	1516	1562	787	1772	2478	4441
0.06	0.49	0.08	0.15	0.10	0.13	0.33	0.26
138.2	129.0	135.8	123.0	146.2	128.0	139.0	185.8
9.0	6.0	6.5	7.0	2.0	8.0	12.0	12.0
7.0	5.6	4.7	6.6	2.9	7.7	32.1	13.8
0.04	0.07	0.04	0.11	0.05	0.13	0.60	0.60
3.4	3.8	2.9	4.2	3.3	4.3	12.4	12.5
0.35	0.27	0.23	0.33	0.21	0.37	1.21	0.95
1.13	0.82	0.77	1.05	0.58	1.21	3.57	2.94
0.24	0.16	0.16	0.21	0.10	0.22	0.59	0.49
1.66	1.00	1.08	1.25	0.60	1.46	3.35	2.73
0.77	0.42	0.49	0.53	0.23	0.60	1.17	0.95
0.44	0.27	0.31	0.34	0.22	0.32	0.56	0.53

1.31	0.70	0.84	0.87	0.37	0.96	1.72	1.41
0.24	0.13	0.15	0.16	0.06	0.17	0.31	0.25
1.75	0.94	1.14	1.17	0.48	1.29	2.21	1.86
0.35	0.19	0.22	0.23	0.09	0.25	0.44	0.38
0.92	0.52	0.63	0.63	0.26	0.72	1.27	1.07
0.13	0.07	0.08	0.09	0.04	0.10	0.18	0.15
0.77	0.45	0.51	0.55	0.22	0.60	1.13	0.98
0.12	0.07	0.08	0.09	0.04	0.09	0.18	0.16
0.34	0.20	0.20	0.22	0.10	0.27	0.85	0.45
0.31	n.d.	0.30	1.42	0.56	0.47	2.76	0.46
0.002	0.009	0.002	0.009	0.004	0.009	0.075	0.033
n.d.	0.004	0.002	0.004	n.d.	0.004	0.029	0.014
17.4	14.1	11.7	16.6	7.2	19.3	80.3	34.4

OM97-207 OM97-209**4468****4680**

UG

UG

50.01

50.70

2.21

0.69

18.53

19.66

5.10

5.55

0.14

0.11

10.53

5.32

9.48

14.86

3.66

2.94

0.27

0.12

0.06

0.05

100.00

100.00

46.3

65.0

27.0

41.0

386

230

17

43

27

2

15

23

23

19

16

11892

3894

1.52

0.56

203.3

224.9

14.0

17.0

30.5

26.7

0.71

0.81

25.5

15.0

1.41

1.47

4.28

4.53

0.71

0.75

3.94

4.30

1.36

1.55

0.91

0.71

1.95	2.29
0.34	0.41
2.50	3.01
0.50	0.59
1.45	1.69
0.21	0.24
1.31	1.49
0.21	0.23
0.84	0.81
0.74	0.43
0.070	0.061
0.031	0.025
76.3	66.6

Table 2b. Whole Rock Compositions

Sheeted Dikes

Sample ID	OM01-09	OM01-10	OM01-11	OM01-12	OM01-13a	OM01-13b	OM01-14	OM01-15	OM01-16
DMTZ(m)	5200	5225	5250	5275	5300	5325	5350	5375	5400
Lithology	SD	SD	SD	SD	SD	SD	SD	SD	SD
(wt%)									
SiO ₂	52.64	54.60	53.08	53.61	51.96	53.29	50.37	53.91	56.11
TiO ₂	0.95	1.34	1.16	1.35	1.03	1.09	0.81	1.41	1.12
Al ₂ O ₃	15.98	15.68	15.86	15.68	16.43	16.04	16.36	16.04	15.88
MgO	6.51	5.29	5.25	5.11	6.34	5.56	6.97	4.90	4.99
MnO	0.17	0.15	0.14	0.15	0.12	0.11	0.11	0.18	0.16
FeO	8.74	8.54	9.84	9.26	9.51	9.30	8.17	10.31	8.53
CaO	8.22	6.96	8.00	6.97	7.68	7.58	10.79	5.56	5.18
Na ₂ O	4.44	5.67	4.56	5.36	4.78	5.06	3.53	5.56	6.06
K ₂ O	0.34	0.50	0.11	0.38	0.38	0.45	0.05	0.54	0.33
P ₂ O ₅	0.09	0.13	0.10	0.13	0.10	0.10	0.08	0.14	0.10
Total	98.08	98.86	98.10	97.99	98.33	98.59	97.24	98.55	98.46
Mg#	57.04	52.48	48.75	49.59	54.30	51.59	60.33	45.86	51.05
(ppm)									
Sc	31.9	31.6	33.2	34.5	35.2	35.5	36.3	27.9	35.1
V	228	294	299	301	241	274	207	285	280
Cr	104	56	36	55	33	29	105	22	27
Ni	46	23	25	22	31	26	56	14	16
Cu	8	6	17	9	102	23	14	5	5
Zn	19	12	18	15	14	12	14	18	20
Ga	14.7	12.0	17.2	13.9	15.3	14.2	14.1	23.4	17.7
Rb	1.2	1.6	0.2	1.3	1.7	1.5	-0.1	1.8	1.1
Sr	335	349	93	337	354	291	174	204	186
Y	20.3	30.9	24.9	27.8	23.2	24.8	19.8	34.2	24.0
Zr	164.0	83.1	68.6	87.2	64.6	70.3	69.4	96.0	67.5
Nb	1.11	2.06	1.33	1.95	1.22	1.32	0.94	2.10	1.31
Ba	24	49	3	42	73	71	3	31	20
La	1.97	2.87	3.35	2.83	2.95	3.55	2.42	3.77	2.98
Ce	5.87	9.28	9.22	8.44	8.35	9.61	6.33	10.48	8.35
Pr	1.03	1.64	1.53	1.48	1.38	1.55	1.15	1.92	1.40
Nd	5.54	8.73	7.71	7.84	7.09	7.84	5.96	10.05	7.22
Sm	2.02	2.93	2.47	2.68	2.31	2.50	1.98	3.37	2.41
Eu	0.67	1.08	0.88	1.06	0.91	0.95	0.75	1.11	0.93
Gd	2.79	3.78	3.22	3.58	3.07	3.25	2.53	4.27	3.17

Tb	0.51	0.69	0.58	0.64	0.54	0.57	0.48	0.81	0.55
Dy	3.27	4.67	3.87	4.35	3.60	3.80	3.08	5.21	3.71
Ho	0.71	1.01	0.84	0.93	0.77	0.82	0.66	1.13	0.80
Er	2.05	2.88	2.39	2.66	2.20	2.31	1.91	3.23	2.30
Tm	0.31	0.44	0.37	0.41	0.34	0.35	0.30	0.50	0.35
Yb	2.05	2.78	2.36	2.61	2.18	2.28	1.89	3.15	2.26
Lu	0.33	0.43	0.37	0.40	0.34	0.36	0.30	0.49	0.36
Hf	3.84	2.36	1.97	2.40	1.79	1.98	1.85	2.59	1.97
Ta	0.098	0.158	0.142	0.152	0.105	0.107	0.078	0.163	0.108
Th	0.185	0.204	0.142	0.194	0.239	0.165	0.130	0.236	0.184
U	0.11	0.08	0.09	0.11	0.11	0.10	0.04	1.60	0.11

SD = sheeted dike

RSD = relative standard deviation

d.l. = detection limit

rec. =recommended

meas. = measured

DMTZ (m) for plotting purposes only

OM01-17 OM01-18 OM01-20 OM01-21 OM01-22 OM01-23 OM01-24 OM01-26 OM01-27 OM01-28

5425 SD	5450 SD	5475 SD	5500 SD	5525 SD	5550 SD	5575 SD	5600 SD	5625 SD	5650 SD
54.20	52.29	51.67	54.68	51.98	51.14	52.52	51.93	52.73	54.07
1.13	1.13	1.22	1.31	1.06	1.27	1.05	1.39	1.40	1.40
16.23	16.08	16.76	15.28	16.41	16.34	15.74	16.97	16.12	16.30
6.16	5.81	6.16	5.01	7.07	3.18	5.55	4.54	4.82	4.51
0.17	0.17	0.18	0.15	0.16	0.06	0.07	0.13	0.14	0.14
9.57	9.96	10.93	10.27	9.16	10.68	9.93	11.33	11.14	10.79
4.91	6.95	5.25	5.31	7.11	11.54	8.68	5.92	6.30	4.60
5.93	5.55	5.36	5.80	4.43	4.47	3.83	5.77	5.46	6.32
0.26	0.15	0.24	0.35	0.55	0.03	0.36	0.16	0.18	0.11
0.11	0.09	0.12	0.12	0.09	0.11	0.10	0.13	0.12	0.14
98.66	98.19	97.89	98.27	98.02	98.82	97.82	98.26	98.41	98.38
53.43	50.98	50.12	46.51	57.91	34.67	49.91	41.67	43.54	42.70
31.3	30.0	29.8	35.1	38.1	24.7	33.0	29.5	31.4	25.3
234	261	267	325	241	307	255	305	320	292
18	19	20	33	154	20	25	42	55	18
21	21	22	17	62	4	19	18	16	10
3	2	4	4	4	2	5	3	5	8
25	20	21	17	15	7	11	18	22	26
16.0	16.1	18.9	15.8	18.4	31.1	16.2	19.8	20.0	17.8
0.8	0.3	0.9	0.8	1.8	0.1	1.0	0.7	0.7	0.5
208	100	140	110	285	64	147	108	114	172
25.0	23.3	26.6	28.9	25.5	28.9	25.3	33.5	31.4	34.6
68.8	69.0	69.6	71.1	58.4	83.0	65.2	91.0	81.9	93.0
1.57	1.27	1.67	1.58	1.34	1.56	1.28	1.71	1.64	1.88
15	0	17	18	24	2	16	21	11	17
3.01	2.93	3.35	3.11	2.24	3.19	2.62	3.57	3.40	3.48
8.76	8.21	9.59	9.18	6.76	9.39	8.00	10.46	9.87	10.30
1.48	1.39	1.59	1.58	1.19	1.61	1.36	1.83	1.72	1.84
7.56	7.09	8.15	8.37	6.46	8.49	7.25	9.62	9.07	9.73
2.48	2.32	2.65	2.82	2.29	2.79	2.43	3.20	3.05	3.25
0.86	0.91	0.91	1.00	0.91	1.01	0.84	1.06	1.14	1.09
3.22	3.03	3.48	3.74	3.17	3.69	3.13	4.12	3.88	4.19

0.58	0.53	0.61	0.67	0.57	0.65	0.58	0.75	0.71	0.77
3.87	3.57	4.11	4.55	3.91	4.36	3.95	5.06	4.81	5.18
0.85	0.77	0.89	0.99	0.85	0.95	0.86	1.10	1.04	1.14
2.43	2.20	2.52	2.83	2.42	2.72	2.47	3.17	2.99	3.26
0.37	0.34	0.39	0.44	0.38	0.42	0.39	0.50	0.46	0.51
2.44	2.15	2.52	2.84	2.42	2.75	2.47	3.19	2.96	3.27
0.38	0.33	0.39	0.44	0.38	0.43	0.38	0.49	0.46	0.52
2.11	1.88	2.18	2.26	1.91	2.16	1.85	2.41	2.36	2.42
0.130	0.105	0.128	0.124	0.103	0.122	0.104	0.134	0.132	0.153
0.237	0.172	0.237	0.200	0.168	0.243	0.190	0.252	0.227	0.276
0.14	0.08	0.15	0.21	0.11	0.26	0.13	0.18	0.16	0.20

OM01-29 OM01-30 OM01-31 OM01-33 OM01-34 OM01-35 OM01-36 OM01-37 OM01-38 OM01-41

5675 5700 5725 5750 5775 5800 5825 5850 5875 5900
SD SD SD SD SD SD SD SD SD SD

54.85 53.91 51.46 52.15 52.82 49.80 58.04 61.08 61.55 55.60
1.60 1.73 1.72 1.84 1.66 2.08 1.40 1.21 1.26 1.71
16.82 15.21 14.98 15.10 15.38 14.30 14.97 14.03 14.28 15.13
3.66 4.18 4.57 4.93 4.48 4.39 2.70 2.08 2.41 4.16
0.12 0.09 0.12 0.10 0.09 0.28 0.28 0.13 0.12 0.18
7.22 11.80 13.31 12.35 12.79 20.80 10.94 10.74 9.92 11.54
7.69 6.27 6.69 6.81 5.33 2.10 5.16 3.92 3.08 5.31
5.35 5.72 5.11 5.16 5.97 3.63 3.21 3.42 5.43 3.70
0.08 0.26 0.13 0.23 0.23 0.06 0.53 0.73 0.25 0.76
0.17 0.15 0.13 0.15 0.13 0.14 0.19 0.21 0.20 0.20
97.56 99.31 98.22 98.82 98.89 97.58 97.42 97.54 98.49 98.29
47.47 38.71 37.97 41.58 38.44 27.34 30.55 25.66 30.22 39.12

22.0 31.3 34.0 34.2 32.4 34.4 24.3 20.1 20.1 27.0
270 393 437 530 449 454 159 73 277
11 26 28 35 31 23 8 0 36
6 9 10 16 11 13 4 6 22
3 5 16 11 9 14 39 5 3
23 12 22 19 15 120 85 31 18
17.0 17.2 19.5 15.9 18.0 19.7 18.7 14.7 15.1 19.0
0.3 1.0 0.0 1.2 0.6 0.6 2.1 3.4 1.0 4.0
115 220 90 167 148 50 303 169 141 262
36.8 33.5 31.5 38.7 36.7 34.6 42.9 45.5 42.2 42.6
108.5 90.3 84.6 96.0 91.0 89.3 122.6 133.0 128.3 134.0
2.72 2.44 2.21 2.36 2.28 2.27 2.45 2.74 2.89 3.62
7 18 8 10 26 5 35 41 29 49
3.77 5.16 3.71 4.73 4.17 4.14 5.06 5.32 5.25 5.70
10.99 13.31 10.51 14.85 14.20 11.67 14.72 15.98 14.74 16.33
1.81 1.97 1.67 2.41 2.47 1.95 2.50 2.57 2.45 2.71
9.55 9.90 8.71 12.07 12.80 10.16 12.88 13.15 12.74 13.71
3.31 3.23 2.98 3.85 3.97 3.32 4.17 4.27 4.40 4.30
1.21 1.30 1.08 1.61 1.56 1.29 1.41 1.37 1.47 1.45
4.50 4.15 3.95 4.96 5.05 4.40 5.30 5.48 5.79 5.34

0.81	0.75	0.71	0.88	0.86	0.78	1.01	1.01	1.05	0.96
5.55	5.07	4.83	5.87	5.70	5.25	6.46	6.91	6.79	6.39
1.21	1.10	1.05	1.28	1.23	1.15	1.41	1.52	1.43	1.37
3.50	3.16	2.99	3.63	3.48	3.23	4.04	4.35	4.16	3.85
0.54	0.49	0.46	0.56	0.53	0.50	0.64	0.67	0.62	0.59
3.52	3.15	2.92	3.52	3.33	3.19	4.03	4.27	3.84	3.80
0.55	0.49	0.44	0.53	0.49	0.48	0.62	0.64	0.55	0.58
2.83	2.54	2.42	2.53	2.43	2.44	3.28	3.39	3.58	3.45
0.202	0.180	0.165	0.169	0.165	0.176	0.189	0.204	0.216	0.256
0.317	0.219	0.170	0.221	0.181	0.218	0.338	0.313	0.295	0.291
0.17	0.16	0.14	0.15	0.17	0.16	0.21	0.17	0.22	0.14

0.69	0.44	0.47	0.53	0.38	3.22	0.36	0.72	1.11
4.78	2.88	3.17	3.57	2.49	4.13	2.51	3.99	1.02
1.04	0.63	0.69	0.77	0.56	3.18	0.56	0.78	1.94
2.98	1.76	1.95	2.22	1.67	3.57	1.66	2.15	1.36
0.46	0.28	0.30	0.34	0.25	4.78	0.25	0.33	0.81
2.99	1.74	1.91	2.20	1.66	2.91	1.65	2.06	1.11
0.47	0.27	0.29	0.34	0.26	3.82	0.25	0.32	0.95
2.27	1.42	1.36	1.62	0.57	5.41	0.58	3.46	1.60
0.130	0.085	0.092	0.119	0.038	5.46	0.036	1.79	1.57
0.139	0.111	0.098	0.135	0.034	16.06	0.032	8.43	1.20
0.12	0.08	0.05	0.04	0.008	20.38	0.01	1.65	1.31

JB-1a
rec.

d.l.

27.9	0.3
212	0.07
403	0.2
140	0.3
56	0.3
82	0.4
17.9	0.02
40.1	0.03
442	0.3
24	0.02
145	0.05
27	0.09
501	0.40
37.8	0.01
66	0.01
7.3	0.003
25.7	0.006
5.07	0.005
1.47	0.002
4.61	0.03

0.69	0.01
4.09	0.003
0.68	0.001
2.18	0.003
0.32	0.001
2.1	0.003
0.32	0.004
3.45	0.002
1.96	0.001
8.9	0.002
1.58	0.004

Table 3. Average Clinopyroxene Compositions

Sample No.	DMTZ(m)	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO total	MnO	MgO	CaO	Na ₂ O	Total	Mg#	Wo	En	Fs
OM97-67a	46	52.64	0.49	2.84	0.44	5.63	0.11	16.17	21.35	0.26	99.93	0.84	0.44	0.47	0.09
OM97-63	119	53.66	0.38	2.73	0.21	4.29	0.13	17.33	21.53	0.22	100.48	0.88	0.44	0.49	0.07
OM97-70	135	52.65	0.52	2.71	0.17	5.30	0.15	16.63	21.15	0.26	99.56	0.85	0.44	0.48	0.09
OM97-45	162	52.56	0.49	2.69	0.26	5.53	0.12	16.58	20.96	0.25	99.44	0.84	0.43	0.48	0.09
OM97-52	525	51.50	0.61	2.82	0.15	7.42	0.22	15.64	20.76	0.33	99.45	0.79	0.43	0.45	0.12
OM97-59a	640	51.79	0.57	3.10	0.14	6.35	0.13	15.62	21.31	0.25	99.27	0.81	0.44	0.45	0.10
OM97-75	719	52.11	0.60	2.78	0.05	6.77	0.12	15.59	21.16	0.30	99.49	0.80	0.44	0.45	0.11
OM99-40	961	51.81	0.39	2.53	0.30	6.66	0.17	16.67	21.16	0.34	100.03	0.82	0.43	0.47	0.10
OM99-44	1253	52.03	0.46	2.50	0.17	6.46	0.15	16.72	21.41	0.25	100.15	0.82	0.43	0.47	0.10
OM99-47	1392	52.60	0.42	2.29	0.15	5.57	0.16	17.61	21.47	0.28	100.56	0.85	0.43	0.49	0.86
OM99-51	1535	52.68	0.39	2.40	0.27	4.36	0.09	17.76	22.39	0.26	100.59	0.88	0.44	0.49	0.67
OM97-84	1663	52.88	0.57	2.53	0.13	6.68	0.13	16.28	21.32	0.29	100.80	0.81	0.43	0.46	0.11
OM97-89	1793	53.08	0.38	2.45	0.25	4.75	0.12	16.86	21.44	0.29	99.61	0.86	0.44	0.48	0.08
OM97-94a	2011	52.76	0.41	2.41	0.22	5.64	0.10	16.51	21.27	0.24	99.57	0.84	0.44	0.47	0.09
OM97-200	2181	53.43	0.47	2.27	0.09	5.41	0.15	17.22	21.20	0.24	100.47	0.85	0.43	0.49	0.09
OM97-99	2193	52.19	0.62	2.48	0.08	6.65	0.14	15.93	21.39	0.26	99.74	0.81	0.44	0.45	0.11
OM97-97a	2257	51.98	0.53	2.41	0.13	6.42	0.17	17.33	20.14	0.23	99.34	0.83	0.41	0.49	0.10
OM97-95	2303	53.07	0.51	2.46	0.10	5.53	0.12	16.65	22.02	0.23	100.69	0.84	0.44	0.47	0.09
OM97-102a	2369	52.67	0.57	2.63	0.31	6.00	0.12	15.80	21.29	0.31	99.70	0.82	0.44	0.46	0.10
OM97-104	2999	51.80	0.54	2.97	0.35	6.05	0.11	15.65	21.12	0.25	98.84	0.82	0.44	0.46	0.10
OM97-106	3260	52.42	0.81	2.70	0.24	6.91	0.18	15.61	20.64	0.41	99.91	0.80	0.43	0.45	0.11
OM97-204	3573	52.28	0.45	2.45	0.23	4.96	0.13	16.68	21.57	0.25	99.01	0.86	0.44	0.48	0.08
OM97-111	3594	52.27	0.54	2.28	0.15	6.04	0.15	16.30	21.43	0.27	99.42	0.83	0.44	0.46	0.10
OM97-110	3627	52.03	0.51	2.60	0.38	5.40	0.18	16.70	21.00	0.30	99.09	0.85	0.43	0.48	0.09
OM97-108	3632	53.15	0.48	2.70	0.44	4.77	0.11	16.93	21.78	0.25	100.60	0.86	0.44	0.48	0.08
OM97-112	3691	53.09	0.52	2.72	0.46	5.14	0.15	16.61	21.75	0.26	100.70	0.85	0.45	0.47	0.08
OM97-113	3989	52.97	0.53	2.30	0.15	5.69	0.18	16.41	21.57	0.25	100.05	0.84	0.44	0.47	0.09
OM97-114	4367	52.14	0.47	2.40	0.19	6.08	0.17	16.66	21.13	0.24	99.47	0.83	0.43	0.47	0.10
OM97-207	4468	53.93	0.06	0.24	0.02	9.06	0.37	13.68	23.09	0.13	100.57	0.73	0.47	0.39	0.14
OM97-209	4680	51.48	0.66	2.65	0.04	7.89	0.22	15.66	20.83	0.28	99.70	0.78	0.43	0.45	0.13

Table 4. Average Olivine Composition

Sample ID	DMTZ(m)	SiO2	FeO total	MnO	MgO	CaO	Total	Fo
OM97-67a	46	39.31	18.65	0.32	41.58	0.03	100.14	79.9
OM97-63	119	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
OM97-70	135	38.74	17.81	0.26	42.13	0.03	99.05	80.8
OM97-45	162	39.17	18.39	0.30	42.39	0.03	100.45	80.4
OM97-52	525	37.48	23.03	0.33	38.40	0.06	99.41	74.8
OM97-59a	640	38.74	20.67	0.35	40.20	0.08	100.18	77.6
OM97-75	719	37.94	22.98	0.36	38.45	0.05	99.92	74.9
OM99-40	961	37.92	22.18	0.29	39.91	0.08	100.49	76.2
OM99-43	961	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
OM99-44	1253	38.27	21.10	0.31	41.00	0.06	100.81	77.6
OM99-47	1392	38.82	18.29	0.24	43.01	0.05	100.54	80.7
OM99-49	1392	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
OM99-51	1535	39.45	14.73	0.23	46.00	0.03	100.61	84.8
OM99-53	1535	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
OM97-84	1663	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
OM97-89	1793	38.53	18.91	0.26	41.39	0.04	99.28	79.6
OM97-94a	2011	38.33	19.55	0.35	40.91	0.04	99.35	78.9
OM97-200	2181	39.05	17.64	0.27	43.00	0.05	100.19	81.3
OM97-99	2193	37.89	22.77	0.37	38.36	0.06	99.64	75.0
OM97-97a	2257	38.19	20.58	0.30	40.23	0.07	99.47	77.7
OM97-95	2303	38.49	18.89	0.27	41.72	0.05	99.57	79.7
OM97-102a	2369	38.63	20.70	0.37	39.65	0.05	99.61	77.3
OM97-104	2999	38.26	20.62	0.37	39.69	0.04	99.19	77.4
OM97-106	3260	37.99	22.54	0.25	37.77	0.06	98.86	74.9
OM97-204	3573	38.43	17.05	0.25	42.78	0.04	98.72	81.7
OM97-111	3594	38.10	21.31	0.30	39.61	0.05	99.55	76.8
OM97-110	3627	38.18	19.79	0.26	41.04	0.04	99.46	78.7
OM97-108	3632	38.77	18.53	0.30	42.27	0.05	100.07	80.3
OM97-112	3691	38.00	18.49	0.23	41.78	0.05	98.77	80.1
OM97-113	3989	-	-	-	-	-	-	-
OM97-114	4367	-	-	-	-	-	-	-
OM97-207	4468	-	-	-	-	-	-	-
OM97-209	4680	-	-	-	-	-	-	-

n.a. = not analyzed

- = no cumulus olivine present

Table 5. Average Plagioclase Compositions

Sample ID	DMTZ(m)	SiO₂	Al₂O₃	FeO	CaO	Na₂O	K₂O
OM97-67a	46	47.56	33.75	0.42	16.58	1.97	0.01
OM97-63	119	45.90	34.26	0.35	17.17	1.50	0.01
OM97-70	135	46.46	33.75	0.43	16.54	1.78	0.01
OM97-45	162	47.49	33.94	0.43	16.61	2.00	0.02
OM97-52	525	48.97	32.17	0.55	14.83	2.81	0.02
OM97-59a	640	46.32	34.10	0.55	17.24	1.52	0.01
OM97-75	719	47.22	33.49	0.55	16.43	1.96	0.00
OM99-40	961	48.07	33.08	0.48	16.37	2.27	0.02
OM99-43	961	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
OM99-44	1253	47.25	33.59	0.49	16.99	1.89	0.01
OM99-47	1392	47.69	33.39	0.39	16.72	2.08	0.02
OM99-49	1392	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
OM99-51	1535	46.40	34.68	0.38	17.95	1.38	0.01
OM99-53	1535	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
OM97-84	1663	48.11	32.99	0.49	16.44	2.25	0.01
OM97-89	1793	46.87	33.74	0.42	16.33	1.95	0.01
OM97-94a	2011	47.76	33.61	0.49	16.32	2.13	0.02
OM97-200	2181	47.63	33.91	0.40	16.85	1.86	0.02
OM97-99	2193	46.82	34.05	0.58	17.12	1.66	0.01
OM97-97a	2257	46.73	33.81	0.45	16.64	1.79	0.01
OM97-95	2303	47.07	33.71	0.41	17.04	1.89	0.01
OM97-102a	2369	47.47	33.88	0.50	16.62	1.88	0.01
OM97-104	2999	47.35	33.64	0.46	16.37	1.90	0.01
OM97-106	3260	49.96	31.81	0.45	14.37	3.12	0.03
OM97-204	3573	46.11	33.55	0.42	16.82	1.74	0.02
OM97-111	3594	47.79	33.51	0.44	16.60	2.03	0.01
OM97-110	3627	46.83	33.41	0.37	16.24	2.05	0.01
OM97-108	3632	47.65	33.64	0.45	16.57	2.08	0.02
OM97-112	3691	46.88	33.67	0.34	16.58	1.91	0.02
OM97-113	3989	48.64	32.40	0.44	15.20	2.67	0.08
OM97-114	4367	48.97	32.40	0.53	14.81	2.73	0.08
OM97-207	4468	56.87	27.63	0.33	9.72	6.07	0.15
OM97-209	4680	48.14	32.98	0.49	15.70	2.28	0.04

Total	An
100.32	82.31
99.24	86.31
99.01	83.69
100.53	82.07
99.42	74.46
99.76	86.27
99.69	82.22
100.33	79.82
n.a.	n.a.
100.26	83.17
100.35	81.55
n.a.	n.a.
100.83	87.71
n.a.	n.a.
100.36	80.13
99.36	82.26
100.36	80.88
100.69	83.34
100.32	85.05
99.47	83.71
100.15	83.32
100.37	83.02
99.76	82.60
99.77	71.83
98.69	84.26
100.42	81.91
98.93	81.41
100.42	81.50
99.42	82.79
99.46	75.92
99.57	74.99
100.81	46.98
99.66	79.18

Table 6. Plagioclase trace elements from LAICPMS

Sample No	OM97-67	OM97-63	OM97-45	OM97-59a	OM99-40	OM99-44	OM99-47	OM99-51	OM97-85	OM97-89	OM97-94a	OM97-95	OM97-104	OM97-106	OM97-204	OM97-111	OM97-113	OM97-114
DMTZ (m)	46	119	162	640	961	1253	1392	1535	1663	1793	2011	2303	2999	3260	3573	3594	3989	4367
(ppm)	Mean, n=21	Mean, n=20	Mean, n=15	Mean, n=20	Mean, n=20	Mean, n=15	Mean, n=17	Mean, n=11	Mean, n=19	Mean, n=17	Mean, n=18	Mean, n=15	Mean, n=20	Mean, n=20	Mean, n=14	Mean, n=15	Mean, n=14	Mean, n=12
V	1.85	1.94	2.66	1.97	1.72	2.06	1.68	1.83	1.83	1.74	2.21	2.32	1.58	2.03	1.79	1.81	1.62	1.98
Co	0.25	0.41	0.44	0.22	0.27	0.47	0.24	0.38	0.36	0.19	0.34	0.33	0.45	0.27	0.16	0.21	0.18	0.35
Zn	2.15	4.28	2.53	1.93	2.16	2.10	2.02	2.24	2.38	1.84	1.59	2.00	2.25	2.21	1.45	1.97	1.83	3.02
Rb	0.02	0.01	0.01	-0.01	0.22	0.02	0.04	0.08	0.00	0.02	0.02	0.07	0.06	0.04	0.09	0.02	0.05	0.05
Sr	224.49	201.72	257.71	274.69	275.56	271.61	218.31	186.80	257.45	232.77	249.02	255.43	225.03	276.33	219.27	276.97	223.86	225.91
Y	0.16	0.08	0.15	0.13	0.19	0.15	0.17	0.10	0.16	0.20	0.17	0.17	0.13	0.22	0.22	0.18	0.63	0.32
Zr	0.02	0.00	0.01	0.00	0.01	0.03	0.03	0.09	0.01	0.01	0.05	0.02	0.02	0.02	0.03	0.02	0.09	0.02
Ba	4.23	2.35	5.76	3.66	5.48	4.75	4.10	4.03	4.60	4.28	4.43	4.85	5.71	6.76	5.36	5.37	8.06	4.04
La	0.20	0.10	0.20	0.16	0.19	0.20	0.18	0.14	0.19	0.22	0.20	0.22	0.24	0.39	0.31	0.30	0.40	0.18
Ce	0.37	0.22	0.41	0.35	0.37	0.40	0.38	0.31	0.38	0.42	0.43	0.46	0.50	0.76	0.64	0.59	0.84	0.39
Pr	0.06	0.03	0.05	0.05	0.06	0.06	0.05	0.04	0.06	0.07	0.06	0.06	0.06	0.11	0.08	0.08	0.14	0.06
Nd	0.27	0.17	0.28	0.24	0.28	0.27	0.29	0.21	0.33	0.32	0.29	0.30	0.34	0.48	0.43	0.36	0.65	0.34
Sm	0.06	0.05	0.06	0.06	0.07	0.06	0.07	0.04	0.08	0.07	0.06	0.06	0.06	0.08	0.09	0.08	0.17	0.08
Eu	0.24	0.14	0.23	0.18	0.24	0.24	0.23	0.16	0.23	0.27	0.22	0.24	0.24	0.36	0.24	0.30	0.41	0.27
Gd	0.06	0.02	0.05	0.04	0.07	0.05	0.06	0.04	0.07	0.07	0.07	0.06	0.06	0.09	0.08	0.07	0.16	0.09
Tb	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01
Dy	0.04	0.02	0.03	0.04	0.04	0.04	0.04	0.03	0.04	0.05	0.04	0.04	0.03	0.05	0.05	0.04	0.13	0.06
Ho	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.03	0.01
Er	0.02	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.02	0.02	0.01	0.06	0.04
Tm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Yb	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.02
Lu	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pb	0.06	0.04	0.09	0.03	0.11	0.12	0.04	0.18	0.05	0.04	0.06	0.06	0.15	0.10	0.07	0.11	0.26	0.11
Th	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 7. Average Clinopyroxene trace elements by LAICPMS

Sample ID	OM97-67	OM97-63	OM97-45	OM97-59a	OM99-40	OM99-44	OM99-47	OM99-51	OM97-85	OM97-89	OM97-94a	OM97-95	OM97-104	OM97-106	OM97-111	OM97-204	OM97-113	OM97-114
DMTZ (m)	46	119	162	640	961	1253	1392	1535	1663	1793	2011	2303	2999	3260	3573	3594	3989	4367
# Analyses	Mean, n=20	Mean, n=20	Mean, n=16	Mean, n=19	Mean, n=18	Mean, n=15	Mean, n=18	Mean, n=18	Mean, n=19	Mean, n=21	Mean, n=12	Mean, n=16	Mean, n=10	Mean, n=18	Mean, n=17	Mean, n=20	Mean, n=12	Mean, n=7
Sc	108.64	n.a.	101.43	99.77	106.20	102.85	107.95	97.39	108.21	99.43	100.20	101.47	108.11	117.21	105.42	101.56	108.32	103.97
V	295.84	276.45	315.64	339.30	304.86	315.70	304.27	260.05	341.26	239.79	289.11	249.93	276.20	417.66	319.89	285.94	320.34	290.24
Cr	3038.94	n.a.	1362.04	1966.85	2096.78	972.74	818.85	1612.18	693.99	2225.76	1397.63	2046.10	2561.85	1294.40	1090.74	1434.39	2018.65	1222.02
Co	38.56	34.97	40.61	37.77	46.58	41.23	39.25	33.87	40.56	34.48	39.73	34.56	35.18	40.82	37.88	36.26	37.78	38.53
Ni	n.a.	202.58	137.41	112.64	n.a.	82.96	97.34	174.70	114.45	n.a.	147.50	107.24	119.47	131.84	104.61	133.81	n.a.	108.97
Cu	2.66	n.a.	0.20	0.90	0.89	0.38	0.37	1.76	0.49	0.96	0.41	0.31	0.82	0.40	0.26	0.25	0.85	0.24
Zn	25.02	16.52	23.47	23.61	26.86	29.31	25.47	18.80	28.21	19.65	23.70	21.54	25.59	36.02	30.20	21.42	30.07	23.50
Sr	10.69	10.39	11.05	11.85	10.00	10.41	9.92	8.50	11.33	9.83	8.71	9.27	8.58	10.48	10.64	10.06	8.76	9.99
Y	9.55	7.65	10.76	9.70	10.86	11.18	11.12	7.36	12.38	7.15	9.13	8.05	11.08	18.49	12.36	10.40	13.75	9.15
Zr	6.50	4.10	5.97	6.38	6.27	6.54	6.09	5.17	7.19	4.13	6.46	5.97	9.06	15.53	9.17	7.19	10.23	5.00
Nb	0.01	0.00	0.01	0.01	0.04	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.03	0.02	0.02	0.01	0.01
Ba	0.00	0.01	0.01	0.01	0.21	0.05	0.02	0.01	0.01	0.01	0.04	0.01	0.09	0.02	0.03	0.01	0.01	0.01
La	0.15	0.11	0.18	0.16	0.16	0.16	0.14	0.12	0.18	0.11	0.16	0.15	0.20	0.32	0.22	0.20	0.28	0.13
Ce	0.88	0.58	0.94	0.93	0.87	0.91	0.81	0.67	0.99	0.59	0.89	0.79	1.02	1.92	1.23	1.04	1.42	0.73
Pr	0.22	0.14	0.23	0.23	0.22	0.23	0.21	0.16	0.25	0.15	0.21	0.20	0.25	0.46	0.30	0.25	0.35	0.19
Nd	1.61	1.23	1.78	1.76	1.66	1.88	1.73	1.17	2.04	1.10	1.67	1.50	1.96	3.52	2.29	1.87	2.39	1.48
Sm	0.88	0.65	0.98	0.93	0.95	0.97	0.92	0.64	1.12	0.63	0.86	0.80	1.00	1.73	1.18	0.96	1.29	0.78
Eu	0.35	0.28	0.41	0.42	0.39	0.42	0.39	0.29	0.47	0.26	0.36	0.32	0.42	0.68	0.47	0.39	0.42	0.35
Gd	1.46	1.06	1.54	1.42	1.68	1.57	1.51	1.03	1.81	1.11	1.28	1.21	1.60	2.70	1.80	1.51	2.06	1.32
Tb	0.27	0.21	0.30	0.28	0.29	0.31	0.30	0.20	0.35	0.19	0.26	0.24	0.31	0.54	0.36	0.29	0.39	0.27
Dy	1.88	1.48	2.06	1.87	2.07	2.13	2.15	1.43	2.42	1.37	1.77	1.58	2.17	3.58	2.39	2.02	2.64	1.84
Ho	0.39	0.30	0.45	0.40	0.44	0.45	0.44	0.31	0.52	0.30	0.38	0.33	0.45	0.78	0.51	0.43	0.57	0.38
Er	1.11	0.85	1.19	1.04	1.24	1.23	1.22	0.78	1.37	0.83	0.99	0.89	1.25	2.01	1.35	1.15	1.60	1.00
Tm	0.15	0.11	0.16	0.14	0.17	0.17	0.17	0.11	0.19	0.11	0.14	0.12	0.17	0.27	0.19	0.16	0.22	0.14
Yb	0.94	0.78	1.08	0.98	1.04	1.15	1.11	0.74	1.27	0.70	0.92	0.80	1.15	1.91	1.27	1.08	1.39	0.90
Lu	0.13	0.11	0.15	0.13	0.15	0.16	0.15	0.10	0.17	0.10	0.12	0.11	0.16	0.26	0.18	0.15	0.20	0.13
Hf	0.33	0.23	0.31	0.34	0.32	0.34	0.31	0.24	0.38	0.23	0.34	0.32	0.44	0.76	0.45	0.34	0.47	0.26
Pb	0.01	0.01	0.02	0.01	0.00	0.01	0.01	0.01	0.00	0.01	0.00	0.01	0.14	0.02	0.02	0.01	0.02	0.02
Th	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00
U	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00

Table 8. Equilibrium liquid calculated from clinopyroxene D and olivine Fe/Mg Kd

Sample Number	OM97-67	OM97-63	OM97-70	OM97-45	OM97-52	OM97-59a	OM97-75	OM99-40	OM99-44	OM99-47	OM99-51	OM97-85	OM97-89
DMTZ (m)	46	119	135	162	525	640	719	961	1253	1392	1535	1663	1793
<i>Calculated Equilibrium Liquid from CPX Ds (ppm)</i>													
La	0.85	0.56	n.a.	0.98	n.a.	0.91	n.a.	0.96	0.96	0.82	0.65	1.07	0.57
Ce	2.79	1.69	n.a.	2.98	n.a.	3.10	n.a.	3.07	3.17	2.69	2.07	3.37	1.79
Pr	0.55	0.33	n.a.	0.57	n.a.	0.61	n.a.	0.61	0.63	0.54	0.38	0.67	0.35
Nd	2.66	1.88	n.a.	2.95	n.a.	3.07	n.a.	3.05	3.42	3.00	1.88	3.65	1.74
Sm	0.94	0.65	n.a.	1.06	n.a.	1.06	n.a.	1.13	1.15	1.03	0.67	1.30	0.64
Eu3+	0.38	0.28	n.a.	0.44	n.a.	0.48	n.a.	0.46	0.49	0.43	0.30	0.54	0.27
Gd	1.24	0.83	n.a.	1.31	n.a.	1.27	n.a.	1.58	1.46	1.34	0.84	1.66	0.90
Dy	1.51	1.10	n.a.	1.66	n.a.	1.59	n.a.	1.85	1.88	1.80	1.12	2.11	1.05
Er	0.97	0.68	n.a.	1.03	n.a.	0.95	n.a.	1.20	1.17	1.10	0.66	1.28	0.69
Yb	0.87	0.66	n.a.	1.00	n.a.	0.95	n.a.	1.07	1.16	1.07	0.66	1.27	0.62
Lu	0.13	0.10	n.a.	0.15	n.a.	0.14	n.a.	0.16	0.17	0.16	0.10	0.19	0.10
<i>Calculated Equilibrium liquid from olivine</i>													
Fe2+/Mg molar	0.84	n.a.	0.79	0.81	1.12	0.96	1.12	1.04	0.96	0.80	0.60	n.a.	0.85
<i>n.a. = not analyzed</i>													

OM97-94a 2011	OM97-200 2181	OM97-99 2193	OM97-97a 2257	OM97-95 2303	OM97-102a 2369	OM97-104 2999	OM97-106 3260	OM97-204 3573	OM97-111 3594	OM97-108 3632	OM97-112 3691	OM97-113 3989	OM97-114 4367
0.87	n.a.	n.a.	n.a.	0.82	n.a.	1.16	1.90	1.06	1.29	n.a.	n.a.	1.54	0.77
2.87	n.a.	n.a.	n.a.	2.55	n.a.	3.32	6.49	3.22	4.11	n.a.	n.a.	4.58	2.44
0.54	n.a.	n.a.	n.a.	0.50	n.a.	0.65	1.23	0.61	0.80	n.a.	n.a.	0.89	0.49
2.82	n.a.	n.a.	n.a.	2.51	n.a.	3.34	6.25	3.04	3.99	n.a.	n.a.	4.03	2.61
0.93	n.a.	n.a.	n.a.	0.87	n.a.	1.11	2.00	1.01	1.33	n.a.	n.a.	1.41	0.89
0.40	n.a.	n.a.	n.a.	0.35	n.a.	0.47	0.78	0.41	0.53	n.a.	n.a.	0.46	0.40
1.11	n.a.	n.a.	n.a.	1.04	n.a.	1.40	2.46	1.26	1.60	n.a.	n.a.	1.78	1.18
1.45	n.a.	n.a.	n.a.	1.29	n.a.	1.80	3.10	1.59	2.02	n.a.	n.a.	2.16	1.57
0.87	n.a.	n.a.	n.a.	0.78	n.a.	1.12	1.87	0.97	1.23	n.a.	n.a.	1.41	0.92
0.86	n.a.	n.a.	n.a.	0.75	n.a.	1.09	1.89	0.98	1.23	n.a.	n.a.	1.30	0.88
0.13	n.a.	n.a.	n.a.	0.11	n.a.	0.16	0.28	0.15	0.19	n.a.	n.a.	0.20	0.14
0.89	0.77	1.11	0.96	0.85	0.98	0.97	1.12	-	1.01	0.82	0.83	-	-

Table 9. Bulk composition of Khafifah lower crust

	Lower Gabbros					Upper Gabbros					Bulk Plutonic Crust			Average	Total Crustal	***Primitive MORB melt Kinzier and Grove (1992)
	This Study	RMSE	3700 m Gideah, GT1 avg	Pallister & Gregory 1983	Hess Deep, Gillis et al. '14	This Study	RMSE	Gideah, GT2- GT3 avg	1500 m Pallister & Gregory 1983	Hess Deep, Gillis et al. '14	This Study	Pallister & Gregory 1983	Hess Deep, Gillis et al. '14	Sheeted Dikes 2000 m	Section 7200 m	
SiO ₂	48.01	0.13	47.64	49.9	47.22	49.93	0.09	49.28	50	51.22	48.56	49.94	47.65	53.40	49.91	49
TiO ₂	0.21	0.01	0.24	0.31	0.16	0.97	0.14	0.69	1.2	1.15	0.43	0.40	0.46	1.31	0.67	0.88
Al ₂ O ₃	17.67	0.32	17.49	16.9	19.5	17.36	0.77	17.67	15.1	15.05	17.58	16.72	17.57	15.77	17.08	16.8
FeO (T)	5.21	0.1	5.28	6	4.95	8.14	0.41	6.99	10.5	9.09	6.05	6.44	6.47	10.53	7.30	7.85
MnO	0.1	0	0.10	0.11	0.09	0.12	0.01	0.12	0.15	0.17	0.11	0.11	0.12	0.14	0.12	n.d.
MgO	11.41	0.22	11.18	10.5	13.4	8.01	0.72	7.69	8.6	8.09	10.43	10.30	13.66	5.16	8.97	11.6
CaO	16.07	0.11	16.30	14.6	13.39	12.81	0.42	14.55	11.7	12.02	15.13	14.30	12.35	6.88	12.84	11.9
Na ₂ O	1.1	0.05	1.07	1.5	1.46	2.49	0.16	2.50	2.6	2.41	1.50	1.61	1.56	4.71	2.39	2.48
K ₂ O	0.02	0	0.02	0.03	0.1	0.12	0.02	0.07	0.13	0.05	0.05	0.04	0.1	0.29	0.12	0.05
Total	99.81	-	99.39	99.85	100.78	99.62	-	99.56	99.98	99.32	99.76	99.86	100.3	98.32	99.36	100.56
Mg#	79.5	0.26	78.97	75.7	82.6	63.70	2.41	65.66	59.4	61.8	75.4	74.0	79.0	46.18	68.65	72.5

*Gillis et al. (2014) lower gabbro composition for the layered series only

**Pallister and Gregory (1983) estimate of upper gabbros includes 0.1% plagiogranite

***14% aggregated fractional melting of the mantle, from Kinzier and Grove (1992)

RMSE calculations for the lower and upper gabbros can be found in Supplementary Table 2

Upper gabbros composition in this study includes 500 m of high-level gabbros and 0.1% (5.2 m) plagiogranite from estimates of Pallister and Gregory (1983)

Gideah, GT1 avg is the average of all gabbros measured in the ICDP drillcore GT1 through the lower gabbros in Wadi Gideah. Data from Kelemen et al. 2020a

Gideah, GT2-GT3 avg is the average of 5 foliated gabbro samples from the uppermost 50 m of the GT2 drillcore and 38 high-level gabbros and diorites from the lowermost section of the GT3 drillcore. Data from Kelemen et al. 2020b,c