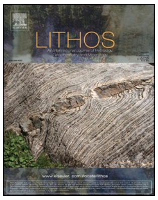
LITHOS 482–483 (2024) 107725

Contents lists available at ScienceDirect

LITHOS

journal homepage: www.elsevier.com/locate/lithos



Magma mingling in plagiogranites of the Oman ophiolite suggests an origin by fractional crystallisation

Hugh Rollinson [*]

School of Built and Natural Environment, University of Derby, UK

ARTICLE INFO

Keywords:
Oman
Ophiolite
Plagiogranite
Magma mingling
Fractionation

ABSTRACT

Late-stage plagiogranites in the Oman-UAE ophiolite are frequently associated with layered and massive gabbro bodies, intrusive into the mid-crustal section of the ophiolite. This study reports persuasive field evidence from five different localities for magma-mingling between plagiogranites and melts with a mafic and dioritic composition. It is argued from these relationships that mafic and felsic magmas coexisted in the same magma chamber. On this basis it is suggested that the range of melt compositions is related by a process of fractional crystallisation. The plagiogranites are interpreted as the end-product of this fractionation process and the associated gabbros are thought to be related cumulates. The hypothesis is supported with geochemical evidence which shows from the major element chemistry a continuum of compositions between the most mafic and felsic endmembers (47.6–80.6 wt% SiO_2). These compositions 'capture' the fractionation process in operation. Modelling these variations using the major and trace element chemistry indicates that the fractionating assemblage comprised olivine-clinopyroxene-plagioclase+/−amphibole and that some plagiogranites contained cumulus plagioclase. The mafic rocks associated with late stage plagiogranite formation are derived from a highly depleted mantle source, which implies melting of an already-depleted mantle. This is consistent with previous models for the origin of the Oman ophiolite and implies a supra-subduction setting for this phase of ocean crust evolution in this ophiolite.

1. Introduction

Plagiogranites form a relatively minor component of ophiolites and yet their geochemistry can provide important constraints on the processes operating in these areas of former ocean crust. In the Oman-UAE ophiolite there are two very different types of plagiogranite which are distinguished in the field on the basis of their position within the ophiolite stratigraphy (see the review by Angelo et al., 2023). In the crustal section of the ophiolite, plagiogranites are low-K granitoids and comprise relatively Fe-rich tonalites and trondhjemites. These plagiogranites are thought to be derived from a basaltic host and are the product of processes operating *within the ophiolite*. In contrast in the mantle section of the ophiolite, plagiogranite dykes are more potassic and more magnesian and range in composition from tonalite to granite (sensu stricto). They are thought to reflect the input of a felsic component *external to the ophiolite*, probably by the partial melting of sediments and basalt within a subducting slab beneath the mantle section (Rollinson, 2015).

The focus of this paper is on those plagiogranites which are located *within the crustal section of the ophiolite* and in origin are closely associated with the mafic magmas of the ophiolite. The early research in Oman by the Open University group (Lippard et al., 1986) showed that in the crustal section of the ophiolite there were two episodes of plagiogranite emplacement each associated with a major phase of mafic magmatism. These findings have been amplified by more recent geochemical studies. Following Goodenough et al. (2010), Haase et al. (2016) showed that the two phases of plagiogranite were coeval with two distinct lava sequences designated V1 and V2. The early plagiogranites (designated P1) are associated with relatively dry magmas from a depleted MORB source with relatively flat rare earth element (REE) patterns, whereas the later plagiogranites (designated P2) are associated with wetter magmas from a light REE depleted source. Further work by de Graaff et al. (2019) confirmed these findings and showed that the later magmatic phase is particularly abundant in the northern area of the ophiolite in the United Arab Emirates. Using very precise U—Pb zircon geochronology Rioux et al. (2021) identified a temporal distinction between the two magmatic phases indicating that V1/P1 formed between 96.1 and 95.6 Ma and V2/P2 between 95.6 and 95.2 Ma.

---

* Corresponding author.
E-mail address: h.rollinson@derby.ac.uk.

https://doi.org/10.1016/j.lithos.2024.107725
Received 15 March 2024; Received in revised form 2 July 2024; Accepted 5 July 2024

The origin of the crustal plagiogranites in the Oman ophiolite has been the subject of considerable discussion. Their association with a mafic host would suggest an origin either by the partial melting of that host, or by fractional crystallisation in a mafic magma chamber. Melting experiments of a hydrated mafic source support the partial melting hypothesis (France et al., 2010; Koepke et al., 2004). Field evidence for this model was provided by Rollinson (2009) who showed that over a distance of about 1 km in Wadi Rajmi there is a transition from hornblende gabbro with an increasing number of plagiogranite veins, interpreted as in situ partial melts, into plagiogranite proper. On the other hand, there is persuasive geochemical evidence for an origin by fractional crystallisation for the Jebel Fayyad intrusion. These rocks form a continuum of compositions from gabbro to plagiogranite as is illustrated by their major element and REE chemistry (Rollinson, 2009). Some resolution to this debate has come from the recent study by Haase et al. (2016) who examined a very large number of plagiogranite intrusions from the full length of the ophiolite. These authors concluded, on the basis of both field and geochemical evidence, that whereas some plagiogranites may be the product of localised partial melting of a mafic source, as for example in Wadi Tayn, the dominant process is that of fractional crystallisation in a mafic magma chamber.

The focus of this paper is on the later of the two plagiogranite episodes (P2) and argues for their origin via the processes of fractional crystallisation. Although this conclusion agrees with that of several previous workers, the argument is novel and is as follows.

- Field relationships in the Oman ophiolite show that in some localities there are two coexisting magmas – a mafic and a felsic (plagiogranite) magma. These magmas have not lost their identities through physical mixing, rather they remain distinct as two separate magmas showing evidence of magma mingling. A full discussion of the distinction between magma mixing and magma mingling is given in Perugini and Poli (2012).
- Because of their close proximity it is inferred that the mafic and felsic magmas co-existed in the same magma chamber.
- Geochemical data show that the coexisting mafic and felsic magmas have a continuous range of compositions - the mafic magmas range in composition from basalt to diorite and the felsic magmas from tonalite to trondhjemite. Given that there is no evidence of physical mixing to explain the continuum of compositions it is argued that a range of evolving melt compositions have been preserved.
- If the principal mechanism had been partial melting then the relationship would be between a 'solid' source and a partial melt. Instead, two melts are observed and it is on this basis that it is argued that the mafic and felsic magmas are related.
- The most obvious mechanism by which the range of melt compositions might be related is that of fractional crystallisation.
- Geochemical arguments are deployed to verify this hypothesis.

2. Samples and field relationships

This section gives examples of magma mingling between mafic and felsic magmas in the Oman-UAE ophiolite. The terminology used to describe the relationship between the mafic and felsic rocks in this study has been characterised in the literature in a number of different ways. A popular term, but one with only local usage in the Oman-UAE ophiolite, is 'vinaigrette' which uses the imagery of the immiscible relationship between olive oil and vinegar in a French salad dressing. More generic are the terms magmatic breccia, mafic-felsic breccia or simply mafic xenoliths in a plagiogranite host. Some authors have adopted the more widely used term of mafic microgranular enclaves (MMEs), after Barbarin and Didier (1992). Here the terms 'mafic xenolith', 'magmatic breccia' and 'plagiogranite breccia' are also used to describe the presence of rounded basaltic blocks in a plagiogranite host. A previous study of larger plagiogranite bodies identified some mafic blocks as stoped blocks of gabbro and dyke in the plagiogranite (Stakes and Taylor, 2003). Here however, in smaller plagiogranite bodies the field relationships indicate a process of magma mingling, as summarised below. Some petrographic detail and photomicrographs are given in the studies by Tsuchiya et al. (2013), de Graaff et al. (2019) and also in Lippard et al. (1986).

2.1. Lasail

The Lasail intrusive complex is located in the Hilti Massif of the ophiolite in northern Oman (Fig. 1) and is a composite gabbro-plagiogranite intrusion about 5 × 4 km in size emplaced at a relatively shallow level in the ophiolite sequence at the contact between the pillow lavas and dykes. It has been described previously by Lippard et al. (1986), Stakes and Taylor (2003) and Tsuchiya et al. (2013) who subdivided the complex in to an earlier, small volume massive gabbro-quartz diorite intrusion and a later, larger, gabbro-trondhjemite intrusion. Rioux et al. (2021) measured a U—Pb zircon age of 95.336 +/− 0.044 Ma in a younger quartz diorite from this complex.

In this study samples were collected from a subhorizontal massive plagiogranite sheet up to 10 m thick flanked by plagiogranite 'magmatic breccia' zones up to 5 m wide located in the northern part of the intrusive complex (Fig. 2) and part of the larger, gabbro-trondhjemite intrusion. The field relationships suggest that (a) the magmatic breccia formed first followed by the injection of the massive plagiogranite sheet and (b) that both the mafic and felsic rocks were comagmatic. The magmatic breccia contains medium grained basaltic blocks with rounded and angular margins mostly between 15 cm to 1 m long and elliptical in shape; these mafic blocks were termed mafic microgranular enclaves (MMEs) by Tsuchiya et al. (2013). The basaltic blocks have rounded but not chilled margins and are frequently closely packed although in places there may be as much as 1 m of plagiogranite between the blocks. The plagiogranite magmatic breccia described here was attributed by Tsuchiya et al. (2013) to the later phase of the complex, consistent with the geochronology of Rioux et al. (2021), and is thought to have formed in the roof zone of gabbro-tonalite magma chamber.

In addition, six further plagiogranite samples were collected from the Lasail intrusive complex within about 1 km of the outcrops described above. One of these plagiogranite samples is cut by later mafic dykes.

2.2. North of Somra

Six km north of Somrah, 5 km west of the Ibra road near Wadi Uq in the Sumail block is an unnamed wadi known by the French team working in Oman as 'vinaigrette valley' (Fig. 1). At this locality the plagiogranites are located at a deeper level in the ophiolite than the Lasail intrusion and are hosted in massive hornblende gabbros and leucogabbros. There are abundant small scale magma mingling features some of which are illustrated in Fig. 3(a-h) comprising for the most part subhorizontal, plagiogranite sheets between 30 cm and 2 m wide. These sheets contain up to 50% of angular and rounded dolerite fragments taking many forms. There are sharp boundaries between the dolerite xenoliths and the plagiogranite but these boundaries are frequently irregular with a lobate form and flame structures of plagiogranite penetrate the dolerite (Fig. 3(c)). Some are dyke-like in form up to 15 cm wide and 1 m long (Fig. 3(d,f,h)) with rounded lobate terminations (Fig. 3(b,c)). These bodies may be located at the margin or the centre of the plagiogranite sheet. Some fragments are elliptical in shape and invaded by micro-veins of plagiogranite 10 cm long (Fig. 3(h)). Some dolerite xenoliths form patches of smaller elliptical inclusions typically 10 to 50 cm across (Fig. 3(a,f)) and in places much smaller. Occasionally flow textures are observed at the margin of plagiogranite sheets. There are also places where there are abundant mafic inclusion bands interspersed between narrower bands of trondhjemite and over the space of about 1 m wide there may be as many as 8 irregular bands. There is also evidence for multiple, composite plagiogranite-dolerite intrusive events where one composite dyke cuts an earlier one Fig. 3(g,h).

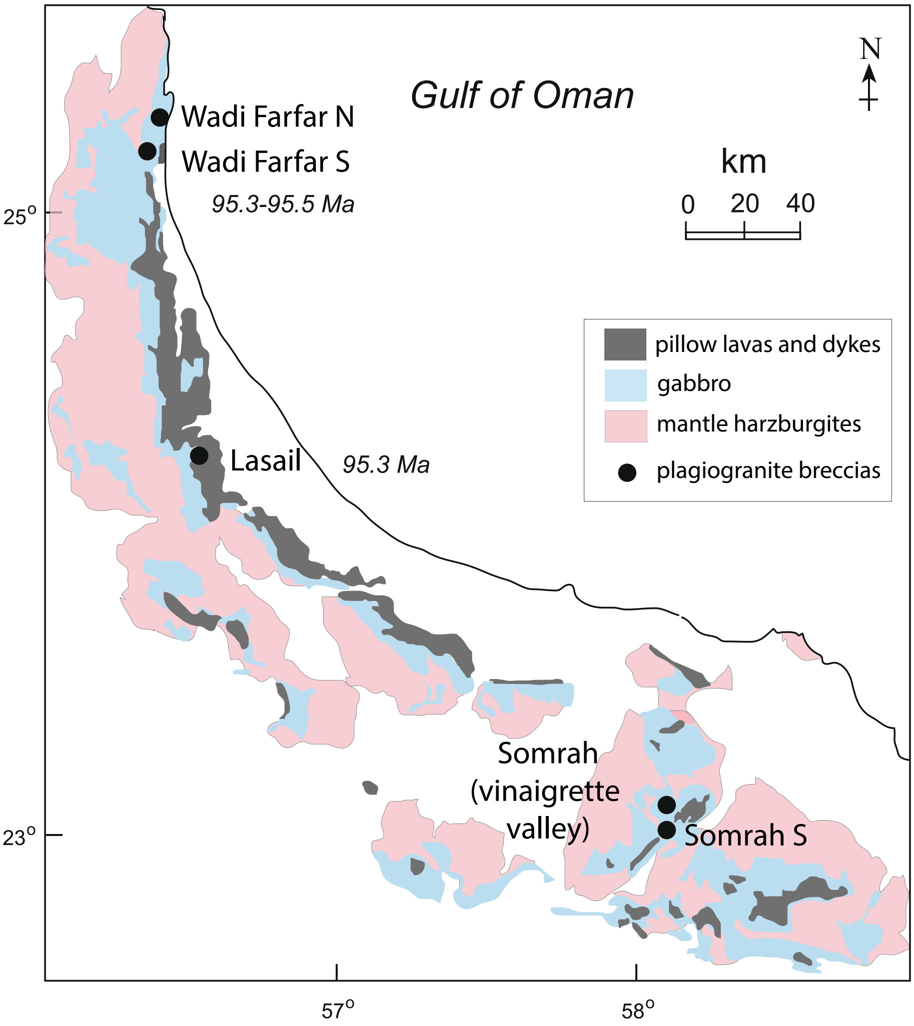


Fig. 1. Locality map showing outcrops studied. U—Pb zircon ages from Rioux et al. (2021).

At Somrah three samples were collected over a distance of 2.2 km from the host gabbro and plagiogranite and from two separate dykes, 2–3 m wide with doleritic xenoliths. In addition three samples from this locality are reported in Angelo et al. (2023) and one in Haase et al. (2016, their SU16). Also included here are data from Haase et al. (2016) from a small (400 m) intrusion of hornblende-bearing plagiogranite with dolerite xenoliths, located 7 km to the south (their site SU8) (Fig. 1).

2.3. Wadi Fafar, UAE

More extensive plagiogranite xenolithic breccias are found in the northern part of the ophiolite, where it extends into the United Arab Emirates. In the Aswad block of the ophiolite plagiogranites form mappable units up to 1 km across; they are rich in gabbro xenoliths and are emplaced into massive gabbro. The data for these samples were reported in de Graaff et al. (2019) and are discussed more fully here. A gabbro xenolith-plagiogranite host pair was sampled at each of six sites. Samples KGUAE-2, −3 and − 7 were collected in Wadi Farfar – close to the Sheikh Khalifa Bin Zayed Road, about 15 km west of Fujairah city (Fig. 1). The outcrop types are illustrated in Ambrose and Searle (2019), their Fig. 7) and show plagiogranite sills and dykes intrusive into massive gabbro and containing a mosaic of rounded dolerite xenoliths up to about 50 cm in length. The dolerite makes up >50% of the outcrop. 25 km south, samples KGUAE-4, −5 and − 6 were collected from an unnamed wadi, north of Wadi Al Quor (Fig. 1). Samples 131213MO6 and 131211MO4 were also collected from this area and are described by Rioux et al. (2021). These plagiogranites contain rounded and elongate gabbro xenoliths 10–50 cm long with sharp but irregular lobate margins in a plagiogranite matrix. The two samples from the study of Rioux et al. (2021) have U—Pb zircon ages of 95.5 +/− 0.15 and 95.298 +/− 0.067 Ma (and also with some slightly older grains) – respectively.

2.4. Field relationships - summary

In summarising the field relationships described above the following features are regarded as salient to the relationship between the mafic and felsic melts and provide strong evidence for the mingling of cogenetic magmas

- There are discrete blocks of mafic rock in a plagiogranite host with no obvious mixing of the two lithologies, nor macroscopic evidence of diffusion between the two;
- the majority of the mafic blocks have rounded margins;
- some of the mafic blocks have margins characterised by embayments and flame textures (fingers of the mafic magma propagating towards the felsic host);
- the mafic blocks show no evidence of chilled margins.

These features suggest that the plagiogranite and doleritic/gabbroic melts coexisted as separate melts, with a similar rheology, and that their relationship represents one of ‘mingling’ rather than mixing. The lack of angular fragments argues against their being part of the wallrock and

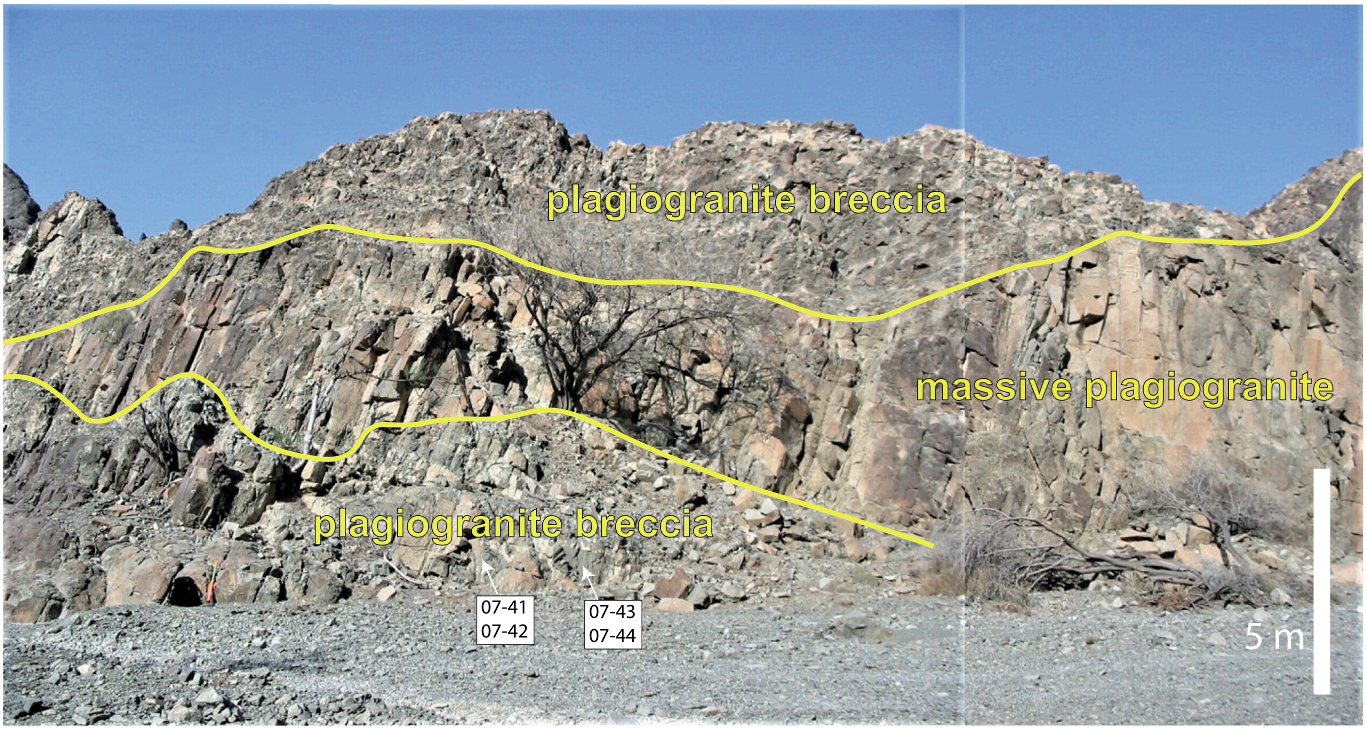


Fig. 2. Part of the Lasail intrusive complex showing a plagiogranite breccia intruded by a massive plagiogranite sheet. Sample locations for plagiogranite-mafic pairs are also shown. A 5 m scale bar is shown.

dragged from chilled margins by the plagiogranite magma. A schematic of the possible relationship between the two melts is given in Fig. 4 and discussed below in Section 4.1.

3. Geochemistry

3.1. Analytical methods

The analytical methods and other data sources used in this study are described in the Supplementary Data File. The geochemical data and GPS locations for all samples in this study are given in Supplementary Table 1.

3.2. Normative An-Ab-Or plot

The plagiogranites in this study are characterised by an extremely low K_2O content, in the range 0.04–0.56 wt% (mean = 0.21 wt% K_2O). Thus, when plotted on a normative An-Ab-Or diagram all samples, both enclaves and the host plagiogranite plot along the low-K margin of the diagram and define a common trend between An and Ab (Fig. 5). Plagiogranites with low-K are a distinctive feature of the crustal plagiogranites in the Oman ophiolite and of 'oceanic plagiogranites' in general. The plagiogranites plot in the fields of tonalite and trondhjemite. The mafic enclaves plot in the tonalite field but strictly are basalts and diorites. One or two mafic samples are host gabbro.

3.3. Harker diagrams

Fig. 6(a-e) shows Harker diagrams for the major element compositions of the mafic enclaves (red circles) and the plagiogranite hosts (black circles). There is also a small group of high silica plagiogranites with anomalous REE patterns; these are shown as yellow circles.

All rock compositions have been recalculated to 100 wt% dry. There is a continuum of compositions across the range of silica contents (47.6–80.6 wt%). Mafic samples have SiO_2 between 47.6 and 64 wt% and the felsic samples between 64.4 and 80.6 wt%. The oxides Al_2O_3, MgO and CaO (Fig. 6a,c,d) and the trace elements Sc and Co (not illustrated) show a single trend across the full range of silica compositions whereas the oxides $Fe_2O_3^T$, Na_2O and TiO_2 (Fig. 6b, e, f) show an inflection at ca 64 wt% SiO_2, the highest concentration of SiO_2 in the mafic enclaves and the point at which plagiogranite compositions begin. In this case the mafic enclaves define a positive trend and the plagiogranites a negative trend. The high silica samples (SiO_2 = 76.3–78.6 wt%) have low Fe_2O_3, MgO, TiO_2, Sc and Co but show a range of Na_2O and CaO values suggesting that they are the product of the removal of ferromagnesian phases but have experienced both the addition and removal of plagioclase and probably the addition of quartz, indicating that some rock compositions are cumulate in nature.

Two preliminary conclusions may be drawn from these observations. First, the continuum of rock compositions suggests that all the melts are related either by fractional crystallisation or by the mixing of mafic and felsic endmembers. But second, the inflection in some of the Harker diagrams at ca 64 wt% SiO_2 argues strongly for fractional crystallisation, rather than mixing, and suggests a change in fractionating phases as the magma evolves towards more siliceous compositions. Fe_2O_3 in the enclaves and Na_2O in the plagiogranites show scattered trends.

3.4. Fractionation vectors on Harker diagrams

The possibility of fractional crystallisation was tested quantitatively for the major element chemistry using mineral compositions from an experimental study of the wet partial melting of a dolerite from the sheeted dyke complex of the Oman ophiolite, illustrative of the mafic melts in the Oman ophiolite (France et al., 2010). In these experiments melt compositions vary continuously from 55.5 wt% SiO_2 at 1030 °C to 72.6 wt% SiO_2 at 850 °C. Early crystallising phases are olivine and clinopyroxene followed by plagioclase. Olivine ceases at ca 925 °C and amphibole and orthopyroxene appear at ca 950 °C when the melt

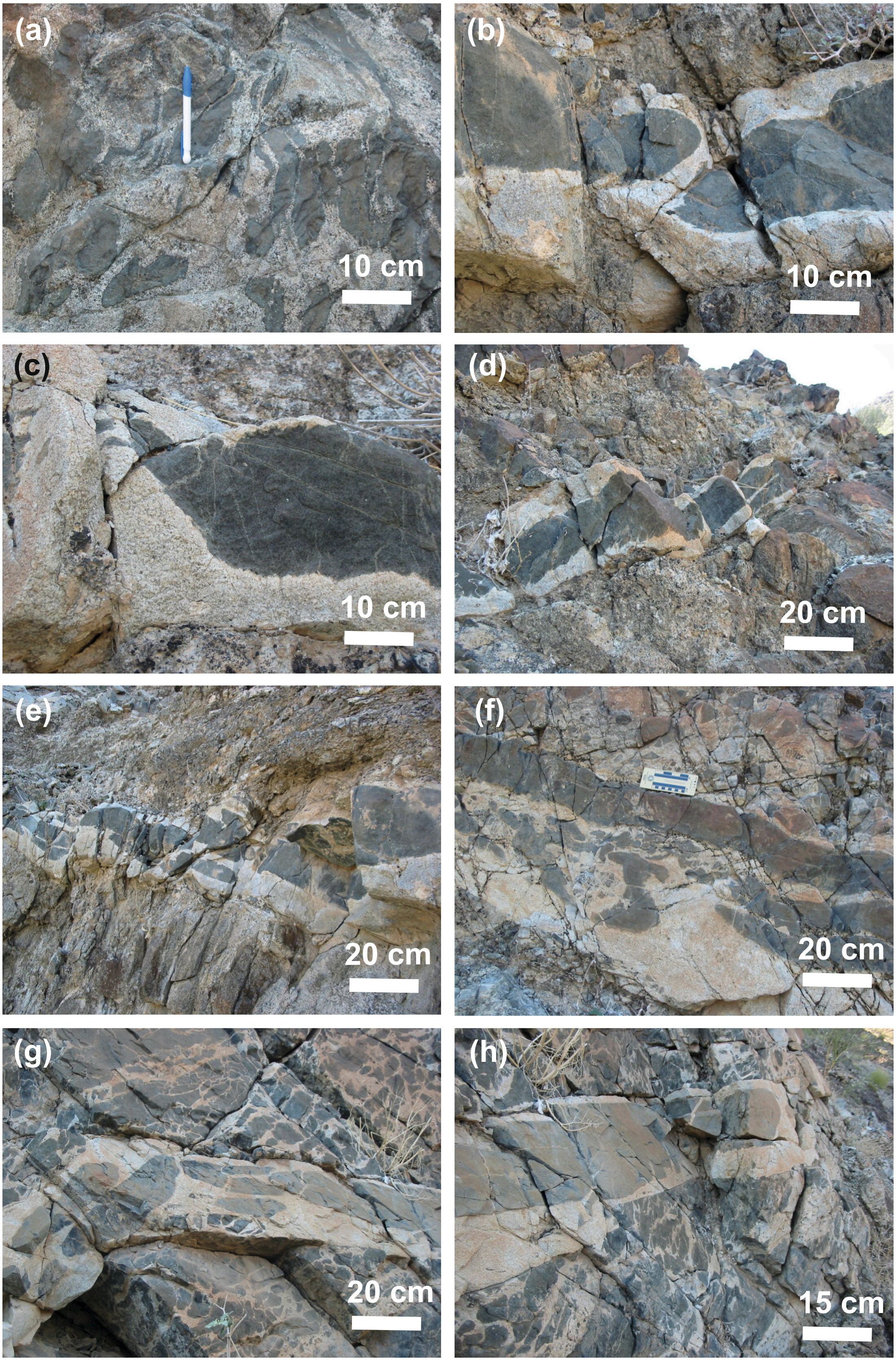


Fig. 3. Field relationships between mafic/ doleritic (dark) and felsic/ plagiogranite (light coloured) magmas at Vinaigrette Valley, north of Somrah. See the text for details.

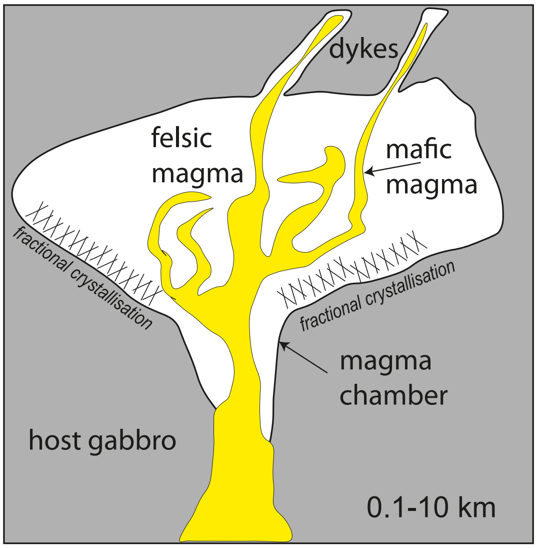


Fig. 4. Sketch of a fractionating felsic magma chamber and associate dyke network, replenished with a pulse of mafic magma which rapidly cools and collapses within the felsic magma chamber (modified after Perugini and Poli, 2012).

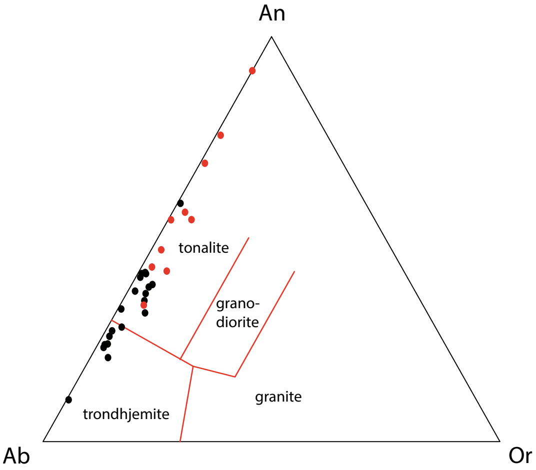


Fig. 5. CIPW normative An-Ab-Or (anorthite-albite-orthoclase) plot of plagiogranites (black symbols) and associated mafic rocks (red symbols). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

contains ca 64 wt% SiO_2. Clinopyroxene and plagioclase are present throughout the crystallisation sequence although they change in composition. Titano-magnetite appears at about 1015 °C and is joined by ilmenite at ca 960 °C.

The evolving melt major element compositions were modelled using the mineral assemblages olivine-clinopyroxene-plagioclase in the more mafic rocks and amphibole-clinopyroxene-plagioclase-titanomagnetite for the more felsic compositions. In the mafic enclaves the composition of the high temperature phases in the France et al. (2010) experiment (plagioclase An_{50}, olivine mg# $= 0.72$, clinopyroxene mg# $=$ 0.76) were used and a starting composition of 55 wt% SiO_2, 8.0 wt% MgO. In the plagiogranites the compositions of the lower temperature phases (plagioclase (An_{29}), clinopyroxene$+/-$orthopyroxene (mg# $=$ 0.68–0.69), amphibole (mg# $= 0.68$) and titanomagnetite) were used. The starting composition chosen was $SiO_2 = 67.4$ wt%, $MgO = 1.6$ wt%. Vector diagrams illustrating the effect of fractionation of the different phases for the oxides CaO and Fe_2O_3 in the mafic and felsic compositions are shown in Fig. 7.

Our results suggest that the variation in the oxides Al_2O_3, Fe_2O_3, MgO, CaO in the mafic melt compositions can be explained if the fractionating assemblage contains a mixture of olivine (up to 22%)-clinopyroxene (up to 50%)-plagioclase (up to 30%). Samples with low Al_2O_3 and Na_2O may be the result of plagioclase fractionation alone and samples with higher Fe_2O_3, MgO and CaO may be the result of clinopyroxene and/or olivine accumulation. Similarly, in the plagiogranite compositions the range in Fe_2O_3 and TiO_2 concentrations can be best explained by a small amount (up to 8%) of titanomagnetite fractionation. Al_2O_3, MgO and CaO concentrations are controlled by the fractionation of a mixture of plagioclase (up to 45%), clinopyroxene (up to 11%) or amphibole (up to 11%) $+/-$ titanomagnetite. The scattered range of values for Na_2O may suggest simple plagioclase fractionation (up to 30%) and accumulation.

Also shown in the Harker plots in Fig. 7 are tie-lines for the mafic-felsic pairs sampled in this study and suites of related samples from Lasail, Sumail and Vinaigrette Valley. The resulting trendlines are a guide as to the process whereby the two melt compositions might be related. These plots confirm that early clinopyroxene $+/-$ hornblende and plagioclase fractionation is a workable model, and that titanomagnetite has an important influence on Fe_2O_3 concentrations. The plagiogranite samples show scattered trends (not shown) of decreasing Sr with increasing SiO_2, confirming the role of plagioclase fractionation. They also show decreasing Y, Yb with increasing SiO_2, with the lowest values of Y and Yb in the samples with the highest SiO_2 suggesting some hornblende fractionation.

3.5. *Rare earth element plots*

Fig. 8 shows REE plots for selected plagiogranite samples. The full data set from each of the localities investigated is given in the Supplementary Data Fig. S1.

Many samples show a parallelism between the mafic and felsic compositions. The mafic rocks have fractionated REE patterns which are strongly depleted in the light REE indicating that they were derived from a highly depleted mantle source, consistent with their assignment to the P2/V2 magma series of Haase et al. (2016) and de Graaff et al. (2019) (qv. Rollinson, 2009; Tsuchiya et al., 2013). Heavy REE concentrations are between 2.4 and 20 x chondrite. A small number of samples (KGUAE-2, −6, −7) show a small upwards inflection from Pr to La (Fig. S1 d,f,i) suggesting that in some cases the highly depleted mantle source had experienced some subsequent re-fertilisation.

The plagiogranites can be divided into three groups on the basis of their REE patterns (Fig. 8):

- The majority of samples show progressive LREE depletion, (from Yb to La) $+/-$ a positive or negative Eu-anomaly and in which the REE patterns of the plagiogranites mirror those of their mafic counterparts. This is clearly illustrated in the samples from the Lasail intrusion (Fig. 8a). In some cases the light REE inflection in the mafic component is also replicated in the plagiogranite (Supplementary Fig. S1d).
- A smaller group of 5 samples have W-shaped REE patterns (Fig. 8b). These plagiogranites are those which are the most enriched in SiO_2 with values >76.0 wt% and have low Fe, Mg and Ti; these samples are shown as yellow symbols in Figs. 6 and 7.
- There is a single sample that has a highly fractionated REE pattern, strongly enriched in light REE (Fig. 8c). This sample also has high SiO_2 (76.3 wt%). Superficially this resembles the REE patterns found in some mantle plagiogranites, although in this case the plagiogranite is clearly crustal in origin as it has a characteristically low K_2O (0.05 wt%).

3.6. *REE modelling*

In this section the fractional crystallisation hypothesis for the mafic-

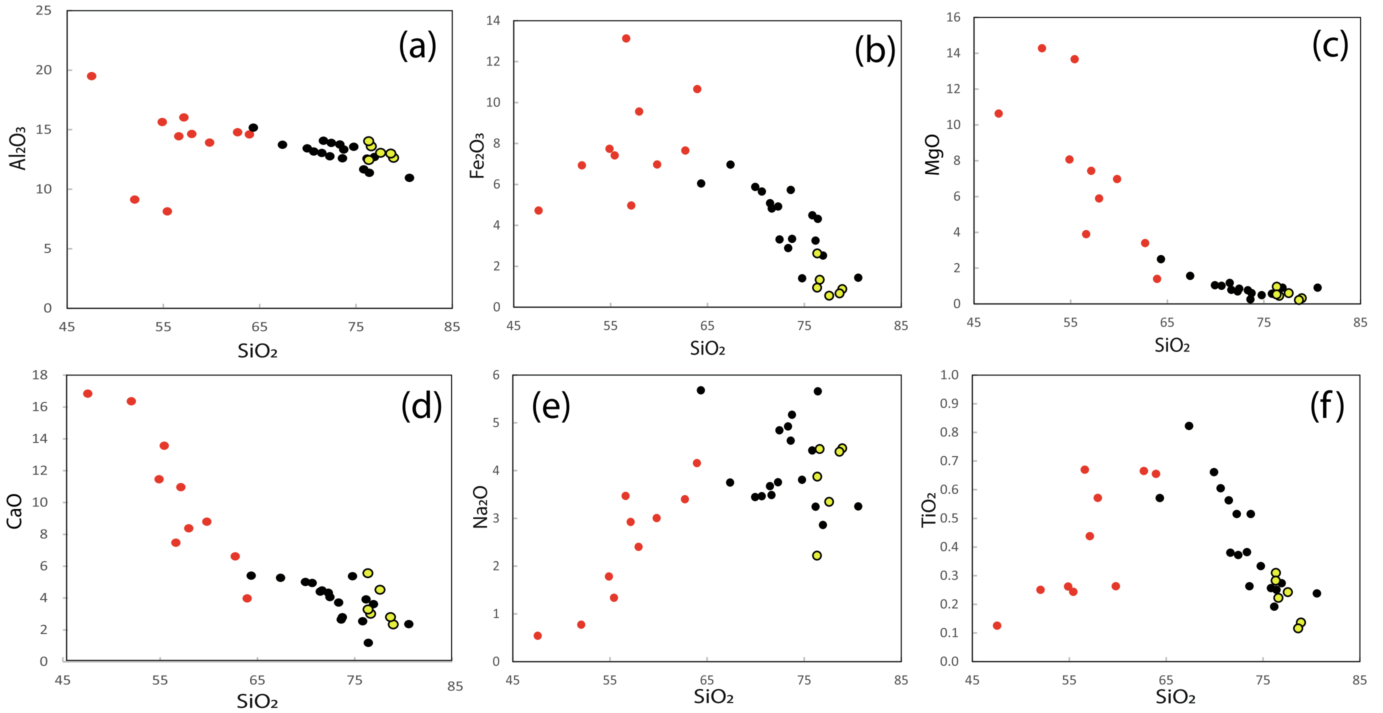


Fig. 6. Harker plots for the major element oxides Al_2O_3, Fe_2O_3, MgO, CaO, Na_2O and TiO_2 showing data for the plagiogranites (black symbols) and associated mafic rocks (red symbols). Plagiogranites with anomalous trace element chemistry and very high SiO_2 are show as yellow symbols. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

plagiogranite pairs is tested in a number of different ways. Assuming that the mafic magmas are part of a cogenetic suite their evolution is modelled as a single suite. Then the evolution of the plagiogranites is modelled in a similar way. The relationship between individual mafic-felsic suites at each of the localities sampled is outlined in the Supplementary Data File. It is important to note however, that these results are only indicative of possible magmatic fractionation processes since it is probable that not all the mafic rocks or the plagiogranites were co-magmatic, but rather represent different batches of magma within a common magmatic series.

3.6.1. *The mafic sequence*

It is possible to model the REE concentrations in the mafic samples with sample KGUAE6M as the starting composition ($SiO_2 = 55.4$ wt%; $MgO = 14.3$ wt%) and 60% fractionation of the assemblage 90% olivine, 10% clinopyroxene, using partition coefficients for mafic melts, followed by 50% fractionation of the assemblage 40% olivine, 30% clinopyroxene, 30% plagioclase, using partition coefficients for intermediate melts. The partition coefficients used are from Rollinson and Pease (2021) and are given in the Supplementary Data file). A summary of the modelling is given in Fig. 9a and the detail given in the Supplementary Data file, Fig. S2. These calculations imply a very substantial amount of fractional crystallisation within the magma chamber. Omitted from these calculations are two samples with very low REE concentrations SU8E (Somrah south) and gabbro 08–11 (Vinaigrette Valley) which are thought to be cumulates (see the discussion below, Section 4.1).

3.6.2. *The plagiogranites*

Most of the plagiogranites can be modelled by 25–60% fractionation of the assemblage plagioclase (90%)-clinopyroxene (10%), when sample KGUAE4 ($SiO_2 = 76.16$ wt%) is used as a starting composition (Fig. 9b). Samples with lower REE concentrations and strong positive Eu anomalies found at the Somrah South locality can be modelled by the addition of 50% the plagioclase residue formed at 50% fractionation to the existing melt (the details are given in the Supplementary Data file Fig. S3).

The samples with the characteristic W-shape REE patterns found at Vinaigrette Valley (and at Wadi Farfar N, sample KGUAE-3, Fig. 8b) are typical of the REE pattern found in the mineral plagioclase. Similar anomalous patterns are found Archaean TTG veins in the Lewsian of NW Scotland and were attributed to plagioclase accumulation (Rollinson and Fowler, 1987). It is thought that a similar process operated here and that these samples contain cumulus plagioclase. Their very high SiO_2 content suggests that they also contain some cumulus quartz. An approximation to the shape of the W-shaped patterns can be obtained by mixing melt obtained after 30% plagioclase fractionation from plagiogranite SU16A with the plagioclase residue obtained after 50% fractionation (Fig. 9c and Supplementary data file Fig. S4). The match is not exact for the resultant composition is depleted in the light REE. It is possible therefore that a small amount of an additional phase such as monazite was present in the cumulus residue.

Sample KGUAE-7 (Fig. 8c) from Wadi Farfar N is enriched the light REE but has low concentrations of the heavy REE. This melt too may be enriched in cumulus plagioclase (reduction in the heavy REE) but also contains a small amount of an accessory phase, such as monazite or allanite, enriched in the light REE.

4. Discussion

4.1. *The fractional crystallisation model*

The field relationships described above are thought to represent the replenishment of a felsic magma chamber by mafic magma during which some of the felsic magma is expelled into dykes and the hot mafic magma is quenched in the lower temperature environment of the felsic melt (Perugini and Poli, 2012). This is consistent with the small grain size of the mafic components. There is no visible evidence of mixing and it is thought that the rapid cooling prevented this process taking place. The denser mafic melt may subsequently collapse under its own weight

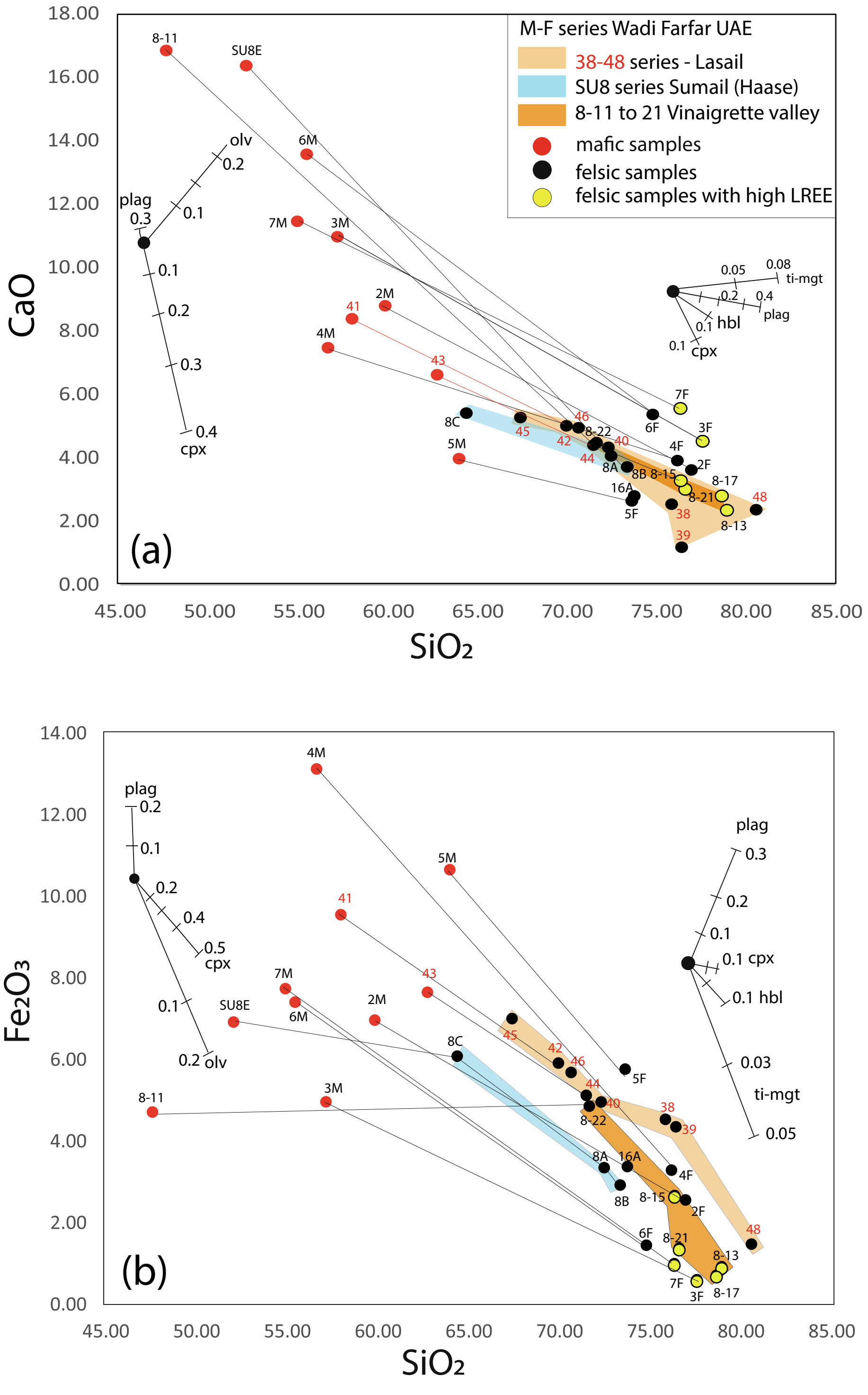


Fig. 7. Vector Harker diagrams showing mafic and felsic pairs for (a) CaO and (b) Fe_2O_3.The vectors, left for mafic rocks, right for felsic rocks are calculated from the experimental phase compositions in France et al. (2010). The fractionating phases are labelled plag = plagioclase, olv = olivine, cpx = clinopyroxene, hbl = hornblende, ti-mgt = titanomagnetite. The degree of fractionation is shown for each vector.

into rounded mafic blocks and smaller fragments (Weinberg et al., 2021). An additional effect may be the formation of rounded blocks of mafic rock due to the temperature contrast between the two melts in a manner analogous to the formation of pillow lavas during the eruption of hot lava into cold ocean water (Stakes and Taylor, 2003). A sketch illustrating a possible magma chamber model is given in Fig. 4.

Hence the working hypothesis of this study is that the late, crustal plagiogranites of the Oman ophiolite are the product of fractional crystallisation from their associated mafic hosts. The fractionating assemblages calculated from both major element and REE modelling are dominated by olivine, clinopyroxene and plagioclase, in the mafic rocks and by clinopyroxene and plagioclase in the felsic rocks. The role of hornblende, suggested in the major element modelling is less apparent in the REE modelling and may imply a relatively dry magma.

The model for the relationship between the two magmas illustrated in Fig. 4 shows that the mafic magmas *postdate* the plagiogranites and so cannot be their exact parent. Thus, the model requires that there were multiple batches of near-identical mafic melts involved in the

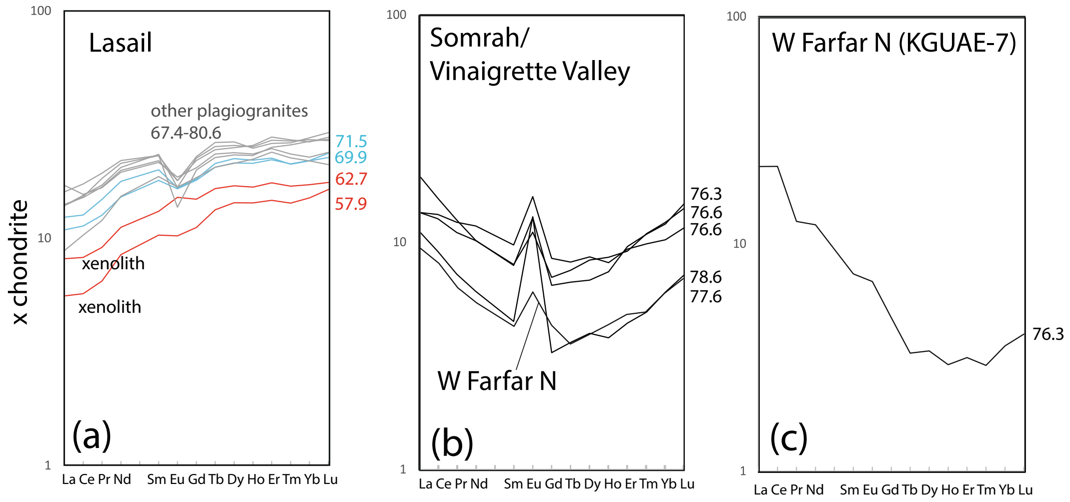


Fig. 8. (a) REE plots for plagiogranite (blue lines) - dolerite (red lines) pairs from the Lasail intrusion. The 'other plagiogranites' are from the same locality but were not sampled as mafic-felsic pairs; (b) REE patterns for plagiogranites with a W-shaped pattern from the Somrah and Wadi Farfar N localities; (c) Light REE enriched pattern for plagiogranite from the Wadi Farfar N locality. In each case the SiO_2 content of the melt is given to the left of the REE diagram. The full set of plagiogranite-mafic pairs is shown by locality in Fig. S1 in the Supplementary Data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

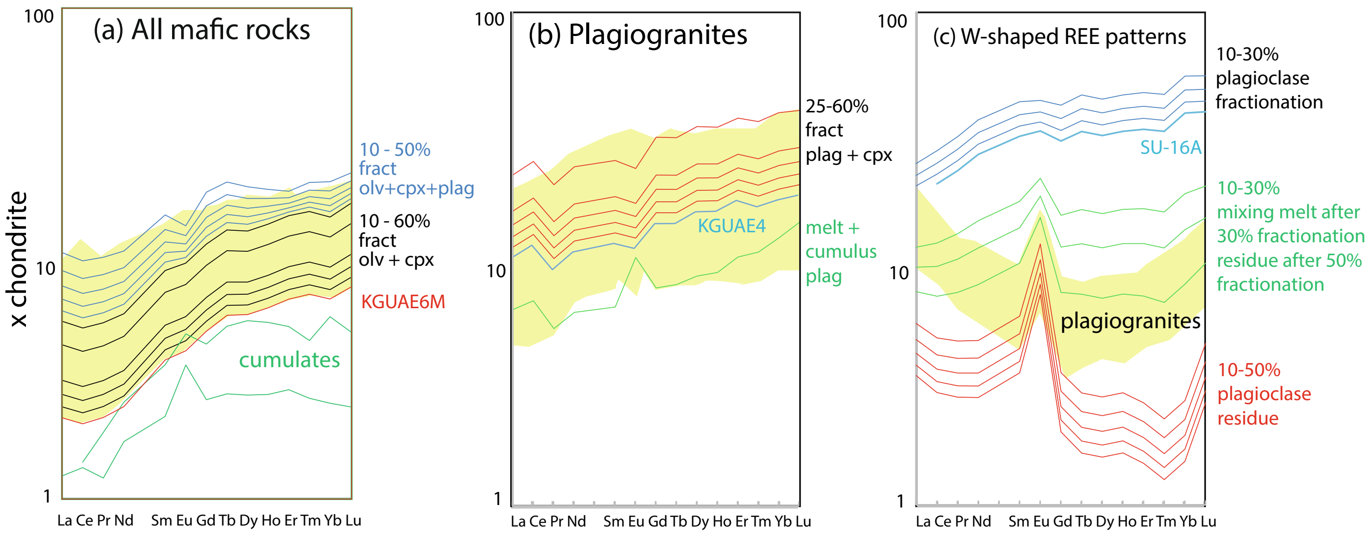


Fig. 9. (a) REE modelling for the mafic rocks sampled in this study. The range of compositions can be explained using sample KGUAE6M as a starting composition (red line) followed by 10–60% fractional crystallisation of the assemblage olivine-clinopyroxene (black lines), then the subsequent fractionation of the assemblage olivine-clinopyroxene-plagioclase (blue lines). The green lines represent gabbro samples of cumulate origin. (b) REE modelling for the plagiogranites using sample KGUAE4 as the starting composition (blue line). The red lines represent 25–60% fractional crystallisation of the assemblage plagioclase-clinopyroxene. The green line represents the addition of cumulus plagioclase to the melt. (c) REE modelling for plagiogranites with W-shaped REE patterns using sample SU-16 A as the starting composition (solid blue line). The blue lines represent melt composition resulting from 10 to 30% plagioclase fractionation. The red lines represent plagioclase residues as a result of 10–50% fractionation. The green lines represent 10–30% mixing between melt and plagioclase residue. In each case the yellow field represents the range of measured sample compositions. The individual rock compositions are given in the Supplementary Data in Figs. S2 (mafic rocks), S3 (plagiogranites) and S4 (plagiogranites with a W-shaped REE pattern). Abbreviations used: olv – olivine, cpx – clinoproxene, plag – plagioclase, fract – fractional crystallisation. See the Supplementary data file for further details of the modelling. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

plagiogranite genesis. The best supporting evidence for this comes from the Lasail intrusion where a plagiogranite sheet post-dates the magmatic breccia (Fig. 2) and plagiogranites themselves are cut by mafic dykes. This requires coexisting mafic and felsic melts, followed by a felsic melt followed by a mafic melt, together representing several magma pulses. North of Somrah there are cross-cutting plagiogranite dykes each containing mafic enclaves again implying multiple magma pulses involving both coexisting mafic and felsic melts (Fig. 3g, h).

A corollary of the fractional crystallisation model for plagiogranites is that there are associated cumulates representing the relatively large proportion of fractionated phases removed from a parent mafic magma, in some cases representing up to 60% fractionation. The most pertinent evidence in this study is the Lasail intrusion mapped by Tsuchiya et al. (2013) who showed that associated with the diorites and plagiogranites is a large volume of massive and layered gabbro cumulates. Similar associations are known for other plagiogranite intrusions in the Oman ophiolite (Rollinson, 2009).

4.2. Alternative petrogenetic mechanisms

This paper argues for an origin of the Oman late plagiogranites by fractional crystallisation from a mafic parent. However, other models have been proposed and in this section these alternative models are discussed.

4.2.1. Liquid immiscibility

The concept of liquid immiscibility has fallen in and out of favour as a means of explaining variations within suites of igneous rocks (Veksler et al., 2007). Dixon-Spulber and Rutherford (1983) explored experimentally the process of liquid immiscibility in ophiolites and mid-ocean ridge basalts as a means of explaining the presence of ophiolitic plagiogranites. Using a basaltic starting composition with ~50 wt% SiO_2 and ~ 9.0 wt% MgO they found that after 95% crystallisation an immiscible silicic melt formed coexisting with a FeO- (>20 wt%)-TiO_2-P_2O_5-rich basalt. However, since such Fe-rich basalts are not found in ophiolites this mechanism is not applicable to natural ophiolitic plagiogranites. Important for this study is whether the separate mafic and felsic phases as observed in the field *could not mix*, ie were truly immiscible, or simply *did not mix* because perhaps of the temperature contrast between the two as discussed above. The observed field relationships support the latter explanation.

4.2.2. Partial melting

Koepke et al. (2004, 2007) and France et al. (2010) argued from experimental studies that the majority of the Oman plagiogranites were the product of partial melting of rocks in the crustal section of the ophiolite. Further, Koepke et al. (2007) proposed that it is possible to distinguish between plagiogranites produced by crystal fractionation from an oceanic basalt and those produced by anatexis using a TiO_2-SiO_2 discrimination plot. By this measure many of the low TiO_2 plagiogranites discussed here are the product of anatexis (Fig. 10a) contrary to a central argument of this paper. However, it has become clear in more recent studies that the TiO_2 content of mafic rocks in the Oman ophiolite is very variable. For example, Haase et al. (2016) showed that the later V2 lavas in the Oman ophiolite, the magmatic sequence to which the plagiogranites in this study belong, have much lower TiO_2 contents than in the older V1 lavas. For this reason, it is concluded that the TiO_2-SiO_2 discrimination proposed by Koepke et al. (2007) is not sufficiently robust to rule out an origin by fractional crystallisation for the plagiogranites examined in this study.

A further discriminant between an origin by fractional crystallisation and by partial melting in oceanic plagiogranites was proposed by Brophy (2009), who suggested that a plot of La vs SiO_2 will differ according to the magmatic process. In hydrous partial melting La abundances initially increase but then decrease with increasing SiO_2 in the melt, whereas for fractional crystallisation La abundances steadily increase with increasing SiO_2 and the relative enrichment in La is much greater than in the case of partial melting. The plagiogranites in this study appear to conform to the equilibrium partial melting model (Fig. 10b), again contrary to the hypothesis proposed here, although it should be noted that the parental magmas in this study are highly depleted in light REE and so more difficult to enrich in La.

The field-based study by Marien et al. (2022) sheds further light on the work of Brophy (2009) for they describe two types of plagiogranite from the Fiji arc. Low-K plagiogranites have flat to light-depleted REE patterns similar to oceanic plagiogranites whereas medium-K plagiogranites have more fractionated (elevated La/Yb_N), concave REE patterns, with some similarities to Archaean TTGs. Trace element modelling is consistent with an origin of the low-K plagiogranites by dry fractional crystallisation from a contemporary basaltic source, whereas the medium-K plagiogranites are the product of dehydration melting of island arc tholeiitic crust. The samples in this present study have a closer affinity to the low-K light REE depleted plagiogranites whose origin is by fractional crystallisation, consistent with the model proposed here.

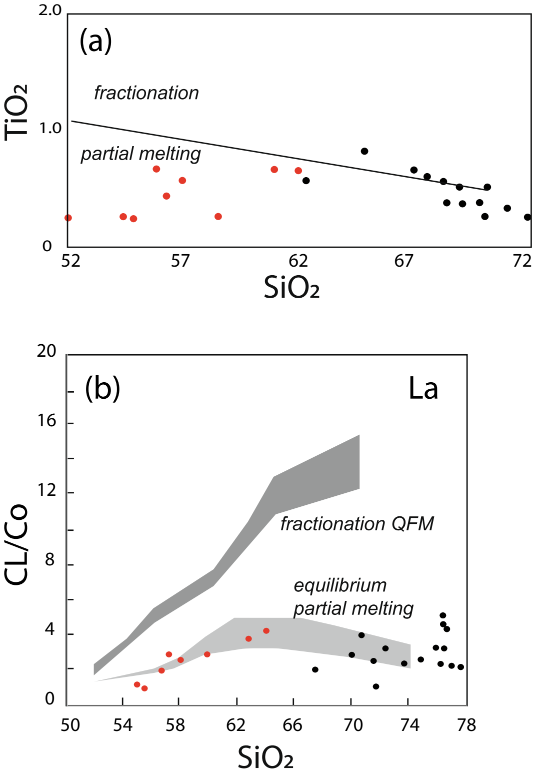


Fig. 10. (a) TiO_2-SiO_2 discrimination diagram after Koepke et al. (2007) for oceanic plagiogranites formed by fractional crystallisation and those formed by partial melting of a mafic source; (b) La-SiO_2 curves for oceanic plagiogranites formed by fractional crystallisation (data for the QFM oxygen buffer) and by equilibrium partial melting (after Brophy, 2009). The La data are plotted relative to a source (Co) with 0.5 ppm La. Red symbols mafic and dioritic rocks, black symbols plagiogranites. CL/Co represents the concentration in the melt relative to that of the source. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.2.3. Assimilation

Stakes and Taylor (2003) proposed that the assimilation of layered gabbro into the parental magma to the Oman plagiogranites plays a significant role in their genesis. They showed that the range of primary oxygen isotope values in plagioclase and quartz in the plagiogranites required the incorporation of altered mafic material into the parent fractionating magma. However, they indicate that whilst this may have been the case for the larger plagiogranite bodies it may not have been so for the smaller ones. This view was corroborated by Grimes et al. (2013) who showed that $\delta^{18}O$ values in zircon in the Oman plagiogranites ($\delta^{18}O = 4.3$–5.0 ‰, average 4.65 ‰, $n = 11$) are on average lower than in slow-spreading ocean crust ($\delta^{18}O = 4.7$–5.9‰). This implies that the plagiogranites are derived from an oceanic source in which the parent magma to the plagiogranites was modified by the assimilation of hydrothermally altered oceanic crust. However, Marien et al. (2022) regard $\delta^{18}O$ values in zircon as low as 4.81‰ as typical of arc mantle, perhaps a more suitable analogue for Oman. Further, Haase et al. (2016) point out that there is no trace element data to support an assimilation model, although it should be noted that such a model is hard to verify since the crust available for contamination is similar in composition to that of the intruding magmas (Grimes et al., 2013). It is possible therefore, but by no means certain, that some hydrothermally altered oceanic crust was incorporated into the mafic magma parental to some Oman plagiogranites.

4.2.4. Summary

There is good geochemical evidence to show that the relationship between the Oman late plagiogranites and basalts cannot be explained by liquid immiscibility. In the case of partial melting, whilst there are some examples of plagiogranite in the Oman ophiolite formed through the partial melting of a mafic source (Haase et al., 2016; Rollinson, 2009) there is no evidence that this is the case for the Oman vinaigrette plagiogranites, and the presence of two coexisting melts sits in opposition to the solid-melt relationship required in a partial melting model. The role of crustal assimilation in the genesis of these rocks is less clear. If it has occurred it would have influenced the composition of the parental magmas rather than the rocks described here. On this basis the fractional crystallisation model appears to be the most plausible explanation for the observations reported in this study.

4.3. Geotectonic setting

Although tangential to the main argument of this paper the geochemical data presented here also show that the mafic rocks associated with late stage plagiogranite formation (P2 of Haase et al., 2016) are derived from a highly depleted mantle source. Such mafic rocks imply the melting of a mantle source from which melts have been previously extracted; this process is normally facilitated by the presence of hydrous fluids. Previous authors have commented on the geotectonic implications of this melting model suggesting that it implies a supra-subduction setting for this phase of ocean crust evolution in the Oman ophiolite (Goodenough et al., 2010; Haase et al., 2016).

5. Conclusions

Late-stage plagiogranites in the Oman ophiolite are frequently associated with layered and massive gabbro bodies, intrusive into the mid-crustal section of the Oman ophiolite. The field relationships of the plagiogranites show strong evidence for magma-mingling with melts of a mafic and dioritic composition. This indicates that mafic and felsic magmas coexisted in the same magma chamber and it is possible to infer therefore, that the range of melt compositions is related by fractional crystallisation. The plagiogranites are interpreted as the end-product of this fractionation process and the associated gabbros are thought to be cumulates associated with this process.

The fractionation hypothesis is supported by the major element geochemistry which shows a continuum of rock compositions from 47.6 to 80.6 wt% SiO_2. Harker plots show either a single continuous trend or an inflection at ca 64 wt% SiO_2 suggesting a change in fractionating phases as the magma evolves towards more siliceous compositions. Modelling these variations indicate that the fractionating assemblage varied in mineralogy between olivine (up to 22%)-clinopyroxene (11–50%)-plagioclase (45–30%)-amphibole (up to 11%). Variations in Na_2O and CaO suggest some plagioclase accumulation.

REE modelling provides an alternative window into the fractionating assemblage. For the mafic sequence the fractionation process requires 60% fractionation of the assemblage 90% olivine, 10% clinopyroxene, followed by 50% fractionation of the assemblage 40% olivine, 30% clinopyroxene, 30% plagioclase. Most of the plagiogranites can be modelled by 25–60% fractionation of the assemblage plagioclase (90%)-clinopyroxene (10%). Hornblende appears to have a minor role in the fractionation process.

A number of authors have argued for an origin of the Oman ophiolite plagiogranites by partial melting, and whilst there are undoubted examples of this process operating in the Oman ophiolite, this study demonstrates that the dominant process for plagiogranite formation in the late-stage, P2 magmatic sequence is by fractional crystallisation.

CRediT authorship contribution statement

Hugh Rollinson: Writing – review & editing, Writing – original draft, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The fieldwork and geochemical analyses in this study were made possible by the award of research grant IG/SCI/ETHS/07/02 from Sultan Qaboos University, Oman. I am grateful to Francoise Boudier, for first introducing me to the outcrops at Vinaigrette Valley and to Kathryn Goodenough for sharing her data. Two anonymous reviewers are thanked for their helpful comments which have improved the clarity of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lithos.2024.107725.

References

Ambrose, T.K., Searle, M.P., 2019. 3-D structure of the northern Oman-UAE ophiolite: widespread, short-lived, suprasubduction zone magmatism. Tectonics 38, 233–252. https://doi.org/10.1029/2018TC005038.

Angelo, T.V., Spencer, C.J., Cavosie, A.J., Thomas, R., Li, H.Y., 2023. Petrogenesis of mantle-hosted granitoids from the samail ophiolite. J. Petrol. 64, 1–17.

Barbarin, B., and Didier, J., 1992, Genesis and evolution of mafic microgranular enclaves through various types of interaction between coexisting felsic and mafic magmas: Earth Environ. Sci. Trans. R. Soc. Edinb., 83, 145–153, doi: 10.1017 (/S0263593300007835).

Brophy, J.G., 2009. La–SiO_2 and Yb–SiO_2 systematics in mid-ocean ridge magmas: implications for the origin of oceanic plagiogranite. Contrib. Mineral. Petrol. 158, 99–111.

de Graaff, S.J., Goodenough, K.M., Klaver, M., Lissenberg, C.J., Jansen, M.N., Millar, I., Davies, G.R., 2019. Evidence for a moist to wet source transition throughout the Oman-UAE ophiolite, and implications for the geodynamic history. Geochem. Geophys. Geosyst. 20, 651–672. https://doi.org/10.1029/2018GC007923.

Dixon-Spulber, S., Rutherford, M.J., 1983. The origin of rhyolite and plagiogranite in oceanic crust: an experimental study. J. Petrol. 24, 1–25.

France, L., Koepke, J., Ildefonse, B., Cichy, S.B., Deschamps, F., 2010. Hydrous partial melting in the sheeted dike complex at fast spreading ridges: experimental and natural observations. Contrib. Mineral. Petrol. 160, 683–704. https://doi.org/10.1007/s00410-010-0502-6.

Goodenough, K.M., Styles, M.T., Schofield, D., Thomas, R.J., Crowley, Q.C., Lilly, R.M., McKervey, J., Stephenson, D., Carney, J.N., 2010. Architecture of the Oman-UAE ophiolite: evidence for a multi-phase magmatic history. Arab. J. Geosci. 3, 439–458. https://doi.org/10.1007/s12517-010-0177-3.

Grimes, C.B., Ushikubo, T., Kozdon, R., Valley, J.W., 2013. Perspectives on the origin of plagiogranite in ophiolites from oxygen isotopes in zircon. Lithos 179, 48–66.

Haase, K.M., Freund, S., Beier, C., Koepke, J., Erdmann, M., Hauff, F., 2016. Constraints on the magmatic evolution of the oceanic crust from plagiogranite intrusions in the Oman ophiolite. Contrib. Mineral. Petrol. 171, 1–16.

Koepke, J., Feig, S.T., Snow, J., Freise, M., 2004. Petrogenesis of oceanic plagiogranites by partial melting of gabbros: an experimental study. Contrib. Mineral. Petrol. 146, 414–432. https://doi.org/10.1007/s00410-003-0511-9.

Koepke, J., Berndt, J., Feig, S.T., Holtz, F., 2007. The formation of SiO_2-rich melts within the deep oceanic crust by hydrous partial melting of gabbros. Contrib. Mineral. Petrol. 153, 67–84.

Lippard, S.J., Shelton, A.W., Gass, I.G., 1986. The ophiolite of Northern Oman. Geol. Soc. Mem. 11, 178.

Marien, C.S., Drewes-Todd, E.K., Stork, A., Todd, E., Gill, J.B., Hoffmann, J.E., Tani, K., Allen, C.M., Munker, C., 2022. Juvenile continental crust evolution in a modern oceanic arc setting: petrogenesis of Cenozoic felsic plutons in Fiji, SW Pacific. Geochim. Cosmochim. Acta 320, 339–365.

Perugini, D., Poli, G., 2012. The mixing of magmas in plutonic and volcanic environments: analogies and differences. Lithos 153, 261–277.

Rioux, M., Garber, J.M., Searle, M., Kelemen, P., Miyashita, S., Adachi, Y., Bowring, S., 2021. High precision U-Pb zircon dating of late magmatism in the Samail ophiolite: a record of subduction initiation. J. Geophys. Res. Solid Earth, e2020JB020758126. https://doi.org/10.1029/2020JB020758.

Rollinson, H., 2009. New models for the genesis of plagiogranites in the Oman ophiolite. Lithos 112 (3–4), 603–614. https://doi.org/10.1016/j.lithos.2009.06.006.

Rollinson, H., 2015. Slab and sediment melting during subduction initiation: granitoid dikes from the mantle section of the Oman ophiolite. Contrib. Mineral. Petrol. 170 (3), 32. https://doi.org/10.1007/s00410-015-1177-9.

Rollinson, H., Fowler, M.B., 1987. The magmatic evolution of the Scourian complex at Gruinard Bay. In: Park, R.G., Tarney, J. (Eds.), Evolution of the Lewisian and

Comparable Precambrian High Grade Terrains, 27. Geological Society Special Publications, pp. 57–71.

Rollinson, H.R., Pease, V., 2021. Using Geochemical Data to Understand Geological Processes, Second Edition. Cambridge University Press, p. 346.

Stakes, D.S., Taylor, H.P., 2003. Oxygen isotope and chemical studies on the origin of large plagiogranite bodies in northern Oman, and their relationship to the overlying massive sulphide deposits. In: Dilek, Y., Robinson, P.T. (Eds.), Ophiolites, 218. Geol. Soc. Spec. Publ., pp. 315–351

Tsuchiya, N., Shibata, T., Yoshikawa, M., Adachi, Y., Miyashita, S., Adachi, T., Nakano, N., Osanai, Y., 2013. Petrology of Lasail plutonic complex, northern Oman ophiolite, Oman: an example of arc-like magmatism associated with ophiolite detachment. Lithos 156-159, 120–138. https://doi.org/10.1016/j.lithos.2012.10.013.

Veksler, I.V., Dorfman, A.M., Borisov, A.A., Wirth, R., Dingwell, D.B., 2007. Liquid immiscibility and the evolution of Basaltic Magma. J. Petrol. 48, 2187–2210. https://doi.org/10.1093/petrology/egm056.

Weinberg, R.F., Vernon, R.H., Schmeling, H., 2021. Processes in mushes and their role in the differentiation of granitic rocks. Earth Sci. Rev. 220, 103665.