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Mafic tiers and transient mushes: Evidence from Iceland

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It is well-established that magmatism is trans-crustal, with melt storage and processing occurring over a range of depths. Development of this conceptual model was based on observations of the products of magmatism at spreading ridges, including Iceland. Petrological barometry and tracking of the solidification process has been used to show that the Icelandic crust is built by crystallisation over a range of depths. The available petrological evidence indicates that most of the active rift zones are not underlain by extensive and pervasive crystal mush. Instead, the microanalytical observations from Iceland are consistent with a model where magmatic processing in the lower crust occurs in sills of decimetric vertical thickness. This stacked sills mode of crustal accretion corresponds to that proposed for the oceanic crust on the basis of ophiolite studies. A key feature of these models is that the country rock for the sills is hot but subsolidus. This condition can be met if the porosity in thin crystal mushes at the margins of the sills is occluded by primitive phases, a contention that is consistent with observations from cumulate nodules in Icelandic basalts. The conditions required for stabilisation of transcrustal mushes may not be present in magmatic systems at spreading ridges.

1. Introduction

It is well-established that terrestrial magmatism is predominantly *trans-crustal*, meaning that magma batches are thought to be processed over a range of depths within the crust and uppermost mantle [1]. Of particular relevance for this contribution is that the trans-crustal nature of magma storage and crustal accretion has been the concensus view of Icelandic magmatism (figure 1) for almost 20 years [2,3].

Simplistic textbook models of volcanic systems involve supply of eruptions from a single, shallow magma chamber which is itself fed directly from the mantle. Icelandic volcanic systems (figure 2) do not conform to this model and provide strong evidence for the storage of melts at a range of depths in the crust. Furthermore, figure 1 shows that eruptions can be fed directly from storage zones as deep as the Moho (20–40 km under Iceland) or from as shallow as 5 km. Global observations from geology, geophysics and petrology have been used to argue for *stacked-sills* or *trans-crustal* models. Magma must be stored for sufficient duration at a given depth to leave a recognisable imprint of storage on these observational records.

Geophysical imaging of seismic velocity structure or resistivity provides a snap-shot of a magmatic system at the present day, but with limited spatial resolution and poor accuracy in the recovery of desirable properties such as temperature and porosity. Ancient plutonic bodies can be studied at high spatial resolution, from microns to kilometres [70]. Plutonic rocks, however, may be influenced by magmatic and near-solidus processes operating over a wide range of timescales (10^3–10^{12} s). It can therefore be challenging to make the link between geophysical images of active magmatic systems that capture one moment in time and petrological observations of solidified plutonic rocks that record a temporally intergrated signal. For example, does petrological evidence of late-stage fluid flow at low porosity from plutonic rocks have significance for the seismic observations, or the overall fluxes of mass and heat in the magmatic system?

The petrology of volcanic rocks provides some complementary information about a magmatic system that may be helpful in linking the plutonic record to geophysical observations. Erupted liquid compositions record conditions of final equilibration and perhaps the depth of storage [5-8]. The cargo of crystals and nodules carried to the surface with these liquids provides another opportunity to determine the depths of magma crystallisation and storage [9,10]. Such petrological barometry has been a key part of establishing the importance of multi-tiered magmatic processing beneath individual volcanic systems. Some of the crystal cargo appears to have escaped the protracted overprinting which complicates the interpretation of plutonic rocks. These volcanic samples can therefore provide a clearer record of the timescales of processes operating in the magmatic system. The rapid development of diffusion chronometry is helping to sharpen these temporal controls [71–73]. In certain cases, nodules of disaggregating magmatic mushes are brought to the surface, which can be used to investigate processes taking place at the margins of the open liquid of a magma chamber [11,12].

In a handful of systems, where recent eruptions have taken place and geophysical monitoring is available, it has been possible to directly link the petrological barometry to depths of magma storage inferred from seismic or geodetic data [13,14]. While this barometry may provide some spatial control on the depth of crystallisation and magma storage, it is extremely challenging to use the crystal cargo of volcanic eruptions to infer anything about the spatial arrangement of the components of that cargo on a scale of $<10^3$ m within the storage zones. Furthermore, the volumes of individual eruptions are typically a tiny fraction of that of the magmatic system and these eruptions can only sample parts of the system where the magma is mobile. The utility of volcanic petrology is greatly enhanced when it can be combined with geophysical constraints on crustal structure or magma movement. It is important and alluring to make the link between petrological and geophysical data. This connection is, however, seldom straightforward. Misrepresentation and misunderstanding of the different data types can lead to erroneous models of sub-volcanic structure.

The purpose of this manuscript is to assess modern conceptual models of transcrustal magmatism using the substantial body of detailed petrological observations available from Iceland's active volcanic regions.

2. Transcrustal mush or solid country rock?

The building concensus regarding the transcrustal nature of magma storage has been mirrored by an increasing incidence of conceptual models of active magmatic crust that involve large quantities of mush (figure 3). Mush is normally used to refer to mechanical mixtures of melt and crystals with interconnected solid and liquid. As porosity increases crystals disaggregate and the mixture can be referred to as magma: interconnected liquid without interconnected solids. In some conceptual models the crust has developed into a large pile of mush, with separated pockets of transient, higher porosity magma chambers [1,15]. Not all models of multi-tiered magmatism involve pervasive mush: the influential *stacked-sills* models of oceanic crustal accretion involve sills of ∼10 m height that are separated by hot, but subsolidus, cumulate rock [16-19]. These sills are likely to have thin mushy layers on their margins. In both conceptual models, mush-dominated and rock-dominated, the final products of magmatism have transitioned from mush to rock. The key difference is the proportion of the crust that is mushy at any one time and, accordingly, the duration of the transition from mush to rock .

Unfortunately geophysical imaging seldom provides sufficient spatial resolution to be able to distinguish between pervasive mush and stacked sills [1,25]. The typical wavelengths of seismic energy that can be used to investigate magmatic systems preclude imaging of individual features of less than a few hundred metres extent. When low velocity zones or high V_p/V_s regions are imaged, the standard interpretation is that these indicate regions of higher melt fraction over the lengthscales of hundreds of metres. The effective properties of this block of rock might be the result of increased porosity in a uniform mush with melt evenly distributed at the crystal scale (10^{-3}–10^{-2} m). Alternatively, these regions may correspond to volumes of solid rock that contain a higher proportion of melt pockets on a greater length-scale (10^1–10^2 m): decimetric sills in hot, subsolidus country rock.

Reflection seismic data collected above submarine volcanoes, most notably at spreading ridges, has a higher frequency content and can be used to image smaller features. The axial melt lens has been imaged as a strong reflector beneath some segments of the mid-oceanic ridge system [26–29]. In one case on the southern East Pacific Rise, full waveform inversion modelling was used to argue for the presence a 50 m thick axial melt lens, with a solid roof and floor [27]. In another, at the Juan de Fuca Ridge, a near-ridge lower crustal melt lens of ∼100 m thickness was reported but it was not clear whether the host material for the melt was mush or solid rock [28]. These studies indicate that melt-rich sills on decimetric scale do exist in magmatic systems, but they do not exclude a role for a pervasive mush pile in these same systems.

3. Mid-ocean ridges: Stacked sills in mostly solid rock?

Mid-ocean ridge systems provide an excellent opportunity for understanding magmatic processes more generally. There are several good reasons to look carefully at spreading systems as a complement to arcs. A crucial advantage is that the tectonic setting allows for accurate reconstruction of the long-term flux of mass and heat through the system because for most mid-ocean ridges we know the spreading rate and for many segments an estimate of the crustal thickness is available. These features have aided the development of thermal models of mid-ocean ridge accretion with incorporation of mechanical or petrological details to match observations from ridges and ophiolites [30-33]. Conceptual models of magmatism at mid-ocean ridges have evolved from the multi-kilometre-scaled, Stillwater-inspired models of axial vats of liquid [34] through to models with much more modest porosities. Many models now involve the presence of a small axial melt lens of limited vertical extent (<200 m). Over the decades, key arguments have focussed on whether this axial melt lens is the principal source of solid cumulate material that makes up the lower crust (the *gabbro glacier* [31,35,36]) or the shallowest of a vertical stack of thin sills beneath the axis (the *stacked sills* model [16-19]). Consensus is now building around a hybrid model of accretion, hinted at by [16] and found to be consistent with thermal models and geophysical, petrological and geological observations from active ridges and ophiolites [32] and cooling rate constraints [37].

Some conceptual models of mid-ocean ridges have involved substantial quantities of mush between the shallow axial melt lens and the Moho [23,24]. If intergranular liquid is widely dsitributed then this can have significant consequences for the mechanical properties of the lower crust and the plausbility of the lower-crustal flow required in gabbro-glacier models. Korenaga and Kelemen [17,18] carried out a detailed examination of rock and mineral compositional zonation in cumulate gabbros from close to the Moho that are exposed in the Oman ophiolite. First, they concluded that the cumulate rocks had formed in small, open-system, melt-filled lenses near the Moho [17]. Next, they used correlations in mineral compositions (e.g. Ni and Mn in olivine cores preserved over the lengthscales of the sills) to argue that melt flux through the mush could account for less than 1% of the total melt flux for the ridge system [18]. In this model, the dominant mode of melt transport would be through high porosity, possibly open, vertical channels. The absence of important flux through the intercrystalline space indicates that pervasive interconnected porosity was not available. Their model of lower-crustal accretion involves decimetric sills encased in near-solidus rock.

More recently, Lissenberg & MacLeod [38] have reported abundant evidence at the crystal and hand-specimen scale for reactive porous flow in cumulate rocks from the lower oceanic crust. These rocks must have been part of a mush that was open to chemical exchange during the occlusion of porosity. The question remains, however, about how these observations of trace element zonation in clinopyroxene can be related to a quantification of the inter-crystalline melt flux, and the temporal and spatial persistence of pervasive mush in the oceanic lower crust.

4. Iceland: A volcanic window into oceanic crustal accretion

The presence of a mantle plume under the Mid-Atlantic Ridge generates oceanic crust of 20–40 km thickness at Iceland [22]. Active volcanism takes place on approximately 30 volcanic systems, which are grouped into a number of volcanic zones (figure 2). These zones are either classified as flank zones or rift zones. The flank zones, including systems 25–30 in figure 2, host alkaline magmatism and do not accomodate a substantial portion of the plate spreading. In contrast, the rift zones generate tholeiitic magma and accommodate the bulk of the extension associated with the full spreading rate of 20 mm yr^{-1}. The two northernmost volcanic zones of the Northern Volcanic Zone (NVZ) are Theistareykir (system 24) and Krafla (system 23). These systems have been the focus of detailed petrological work by groups from Cambridge and the University of Iceland - much of which is described below. The petrology, geochemistry and volcanic structure of other systems in the NVZ and those of the Western Volcanic Zone (WVZ) and Reykjanes Peninsula (REP) have also been the target of study [40,66,67,68]. The available observations indicate that models of crustal magmatic plumbing for these systems (1–4, 8, 21, 22 from figure 2) have much in common with Krafla and Theistareykir. This similarity may reflect the fact that the crustal thicknesses and magmatic fluxes in these systems are equivalent. It may also be important that these volcanic zones have been active for more than 5 Myr. In contrast, activity on the Eastern Volcanic Zone (EVZ: systems 12–20) started relatively recently (3 Ma). This region of high magma flux hosts volcanic systems that are petrologically and volcanically distinct from the rest of Iceland's rift zones. For example, the EVZ volcanic output is characterised by giant fissure eruptions and explosive eruptions from large central volcanoes, while the NVZ and WVZ contain large lava shields and monogenetic subglacial tuyas [69]. These observations indicate that models of magma transport and storage that are applicable to the EVZ are not entirely appropriate for the NVZ, WVZ and REP. This contribution therefore focusses on observations and models for Krafla, Theistareykir and the broader NVZ, WVZ and REP.

(a) Barometry indicates stacked-sills accretion

It has proven difficult to use the erupted products of mid-ocean ridge volcanoes to test models of magmatic systems because the 1σ pressure uncertainties in many petrological barometers of ± 1.5 kbar are equivalent to a depth of ± 4.5 km, greater than the thickness of typical oceanic crust [5-10]. However, Iceland's thick crust allows petrological barometry to be used to establish whether eruptions are fed from storage zones at different depths as might be expected from a *stacked-sills* accretion model, or if they are all fed from a single shallow storage zone, consistent with *gabbro-glacier* style accretion. A study of the Krafla and Theistareykir volcanic systems in the NVZ (figure 2) used petrological barometry to show that magmas stored at a range of depths in the crust and uppermost mantle (5–30 km) can be fed to the surface for eruption [2]. This barometry was based on both clinopyroxene-liquid equilibirum (see [10] for the most up-to-date iteration of this method) and parameterisation of the composition of liquids that are in equilibrium with olivine, plagioclase and clinopyroxene as a function of pressure [6,14].

These barometers have undergone substantial improvement over the last 15 years, but the original conclusion is robust. Furthermore, the relationship between the estimated depth of equilibration and the extent of crystallisation indicates that solid material is being added uniformly throughout the lower and middle crust under the NVZ [4]. These findings are consistent with a *stacked-sills* model of accretion (figure 1), which is significant because seismic imaging indicates that the Krafla volcanic system hosts a shallow melt lens [39] and therefore this imaged lens is simply the shallowest of a number of storage zones within the crust of the NVZ.

(b) Macrocrysts, melt inclusions, carrier liquids and mush

These barometric findings not only show that Icelandic magmatism is transcrustal: they also have significance for understanding the distribution of mushy zones within the Icelandic crust. This significance is most easily understood when the barometric results are combined with the findings of detailed microanalytical studies of the crystal cargoes of Icelandic mafic eruptions [40]. These eruptions often carry macrocrysts of olivine, plagioclase, clinopyroxene and more primitive magmas sometimes contain chromian spinel. Clean matrix glasses, available in tephra or as pillow-rims, provide a reliable estimate of the composition of the liquid that carried the crystals to the surface for eruption. Large glassy melt inclusions are present in these macrocrysts, and several hundred of these have been analysed for their trace element content by ion-microprobe.

The rims of the macrocrysts are almost always in equilibrium with the carrier liquid as far as chemical exchange (e.g. K_d^{Fe-Mg} for olivine) or textural criteria are concerned. The macrocryst cores, however, are almost always too primitive (high in Mg# or An content) to be in equilibrium with the carrier liquid [40,41].

The relationship between the trace element composition of the melt inclusions and those of the carrier liquid is also systematic. Trace element ratios such as La/Yb, which are little affected by crustal processes in Iceland, show enormous diversity in olivine-hosted melt inclusions. This diversity has its origins in the fractional melting of compositionally heterogeneous mantle [42]. Inter-eruption variation in carrier liquid compositions from single volcanic systems is substantial (e.g. La/Yb varies from 0.4 to 4.0 in Theistareykir primitive lava flows over the last 30 kyr), but intra-flow variation in carrier liquids in Icelandic basaltic eruptions is muted [40,43]. However, melt inclusions from single eruptions can show diversity in certain chemical indicators of mantle melt heterogeneity that is greater than the full diversity available in rock samples from a single volcanic system [40]. The crucial point here is that the average La/Yb of melt inclusions from a single eruption is very similar to that of the carrier liquid for that eruption [40]. Furthermore, in any given eruption, the variance of melt inclusion compositions drops as a function of the forsterite content of the host olivine. The inclusions within the least forsteritic macrocrysts, the macrocrysts closest to major-element equilibrium with the carrier, also have limited trace element variability.

These observations are summarised in figure 4 and strongly suggest that the macrocrysts have a well-defined relationship with the liquid that carries them to the surface. They are not xenocrysts picked up from cumulate rock or mush that was encountered on the transit path as the carrier liquid ascended prior to eruption. It is instead likely that these macrocrysts were derived by disaggregation of a crystal mush that formed on the walls of the magma body where storage and evolution of the carrier liquid took place. The mushy regions may form thin fringes round the sills of open liquid, rather than pervasive transcrustal mushes.

The observations can be accounted for by a model where diverse mantle melts enter a storage region at depth, undergo concurrent mixing, cooling and crystallisation to produce a relatively evolved and homogeneous melt. This melt then carries some of the disaggregated mushy products of this interval of cooling and crystallisation upwards for eruption.

These observations indicate that magma can rise from close to the Moho and reach the surface without entraining observable quantities of crystal cargo *en route*. This magma is unlikely to have encountered mushy regions on its transcrustal path, indicating that even in volcanic areas of relatively high magma flux such as Iceland, the crust remains dominantly solid. This point is neatly exemplified by pairs of eruptions which took place within a few thousand years of each other, have vents within a few kilometres of each other, but yet have compositionally distinct cargoes of olivine macrocrysts and melt inclusions. Good examples are Bóndhólshraun and Gæsafjöll in the Theistareykir volcanic system (number 24, figure 2) and Stapafell and Háleyjabunga in the Reykjanes system (number 1, figure 2). For each of these flows, the melt inclusion mean trace element composition is equivalent to that of the carrier liquid [40].

The strong relationship between carrier liquid and crystal cargo for individual eruptions and the clear diffference in carrier liquid and crystal cargo between eruptions indicates that eruptions that are closely related in time and space may have separate plumbing systems. If melts had to transit a pervasive transcrustal mush prior to eruption it is likely that their crystal cargoes would show less well-defined relationships with the carrier liquid (e.g. melt inclusion trace element mean would not be equal to that of the melt) and the crystal cargoes of separate eruptions would show significant overlap in their compositional range. The balance of petrological evidence from the NVZ, WVZ and REP of Iceland therefore indicates that pervasive transcrustal mushes are not present under the main active rift zones [40].

Recent work using diffusion chronometry has established that these carrier liquids and their crystal cargoes rise from near-Moho depths of ∼20 km and reach the surface in as little as 4 days in the case of the Borgarhraun eruption in the Theistareykir system [45]. It is difficult to envisage how these ascent rates, and the preservation of high equilibrium pressures in both OPAM and clinopyroxene-liquid barometers, can be reconciled with passage through a crust that contains a pervasive crystal mush.

5. Creating solid rocks in the lower crust

The previous sections have summarised some of the arguments for transcrustal magmatism in oceanic-ridge settings and particularly in Iceland. In well-studied cases it is clear that melt and crystal cargoes can ascend rapidly from the Moho to the surface and preserve no evidence for interaction with pervasive transcrustal mush. One such well-studied eruption is Borgarhraun, an 8000 year old primitive basalt/picrite flow from the Theistareykir volcanic system. The available petrological evidence from the active rift zones of the NVZ, WVZ and Reykjanes Peninsula indicates that the bulk of the crystal cargo is derived from mush that is closely related to the carrier liquid - perhaps from thin mushy layers at the margins of small melt-dominated sills. If the crust under these active volcanic zones is not mushy, it is worth understanding what processes might lead to the generation of solid country-rock for the magma bodies that build the crust by crystallisation.

Observations of the mineralogy of cumulate nodules brought to the surface by primitive eruptions such as Borgarhraun indicates that cumulate wehrlites and gabbros are present in country-rock of the near-Moho storage zones. The nodules contain phases that formed at high pressures and temperatures, with major and trace element compositions in equilibrium with liquids that could plausibly have mixed to form the Borgarhraun carrier liquid [46,47]. For example, in the wehrlitic nodules, highly forsteritic olivine chadacrysts are encapsulated in high Mg# clinopyroxene oikocrysts. Both the primocrysts and the interstitial crystals were in equilibirum with primitive liquids: no evidence is preserved of differentiated liquids produced by in-situ crystallisation. Chemical exchange between the insterstitial liquids and the primitive melt in the chamber must have been effective.

The cooling interval preserved in the range of olivine core compositions present in the Borgarhraun products is ∼100°C. Therefore, hot, near-primary, melts stall in a storage zone and cool and crystallise, losing heat to their surroundings. In consequence, the country-rock will receive heat and its temperature and/or melt fraction will rise. Repeated juxtaposition of hot melts with country rock is one mechanism for generating a substantial region of partial melt within the lower crust. A common misconception amongst modellers is that oceanic crustal material has a single uniform composition and therefore that its melting behaviour does not vary. It is important to note, however, that compositional variation in the crust, the result of magmatic differentiation, has important implications for the interpretation of geophysical data and its linkage to thermal models [32]. The development of mushy zones is also controlled by the melting interval of the country-rock material.

If the nodules of cumulate material carried by Borgarhraun are representative of its country rock, then we can use them to explore the effect of the intrusion and cooling of hot mantle melts on the development of mush in the country rock.

A crystallisation model, performed using the MELTS software [48,49], was used to investigate this problem. The purpose of this model was to generate a simple, self-consistent examination of the behaviour of cumulate wall-rock when intruded by a liquid with the same composition and temperature as its parent. First, a putative parental melt for the Borgarhraun tephra glasses was obtained by addition of equilibrium olivine. This parental melt was required to be in equilibrium with Fo_{90} olivine. Then, the parental melt was cooled at a model pressure of 5 kbar until about 20% crystallisation had taken place (figure 5). This range of fractional crystallisation was sufficient to generate most of the range of olivine compositions observed in macrocryst cores in Borgarhraun, as well as providing olivine, clinopyroxene and plagioclase in the crystallisation assemblage, matching the observed macrocryst mode. The liquid composition also lies within the field of observed high MgO basalts from Theistareykir [2].

The model olivine, clinopyroxene and plagioclase material generated by this crystallisation interval was then converted into a mean cumulate composition, which has a composition similar to that of the mean observed cumulate clots in the Borgarhraun samples: about half ultramafic cumulates and half primitive cumulate gabbros [46]. The melting behaviour of this cumulate was then investigated using MELTS, so that a self-consistent relationship between the crystallising melt and the cumulate wall-rock could be obtained. The crucial point from figure 5 is that at the liquidus temperature of the initial melt, the cumulate composition is completely solid.

If the interstitial melt in the mush at the margins of the chamber can maintain chemical exchange with the primitive liquid in the interior, and the interstitial/oikocryst phases have compositions in equilibrium with that liquid rather than an evolved and isolated mush liquid, then it is possible to generate cumulate crust with a solidus temperature that is higher than the liquidus temperature of the intruded melt. This arrangement is consistent with a model where sills with high melt fractions sit in a country rock of hot, but solid, cumulate material. Pervasive mush is not formed in this case. The generation of widespread mush is hindered by effective chemical exchange between mush liquids and hot melts in the open chamber. The handful of observations of cumulate nodule compositions that are available from Borgarhraun [46,47] indicate cumulate formation Iceland appears to involve effective chemical exchange, or, at least, the generation of primitive oikocrysts. Whole-rock and mineral compositions from near-Moho cumulates exposed in Oman also indicate that melt was effectively extracted, leaving behind cumulate rocks with compositions in equilibrium with primitive liquids [16-19]. Observations of oceanic cumulate rocks exposed on the sea-floor at Hess Deep are consistent with these observations from Oman and Iceland [50] and mafic plutonic rocks from the Pito Deep have been shown to contain trapped-melt fractions of less than 5% [51].

These observations and simple model results are consistent with a distribution of melt in the lower oceanic crust that is characterised by large alternations in melt fraction over lengthscales of metres, by open sills with thin mushy margins embedded in hot, but subsolidus, cumulates (figure 3a). This model hangs upon the generation of primitive cumulate rocks with very small trapped melt fractions: a crucial question for future study is to understand the process by which porosity is occluded in lower-crustal mushes.

6. Concurrent mixing and cooling: A constraint on sill thickness?

In the previous section it was argued that the distribution of melt in the oceanic lower crust may be dominated by the presence of liquid sills encased in hot cumulate rock. The next question to address is that of the characteristic thickness of such sills. The fact that individual melt bodies are difficult to image with geophysical approaches places an upper bound on their size on the scale of 100s of metres. Petrological and geological observations from ophiolites indicate that the melt layer thickness may be substantially smaller, perhaps as little as a metre. The vertical evolution of mineral compositions on the sub-metre scale in near-Moho cumulate gabbros from both Troodos [52] and Oman [17] have been used to support this finding. It is likely that these metre-scale estimates are minima because near-Moho bodies in ophiolites may have undergone some flattening after formation of the layering [17]. Nevertheless, the ratio of preserved cumulate layer thickness to original liquid thickness is likely to be preserved, and [17] estimated that 5–20% crystallisation took place in near-Moho melt lenses. This corresponds to a temperature drop of $<20^{\circ}$C for crystallisation of basalt to generate cumulate gabbro.

Observational tests of these models of metre-scale melt-rich sills have been challenging to identify. However, detailed examination of the composition of melt inclusions, their olivine hosts and the carrier liquid in primitive basalts may provide a novel constraint on this problem. It is well known that melt inclusions trapped in forsteritic olivines from single samples preserve compositional heterogeneity that originates in the mantle [42]. This compositional variability is best understood using trace element ratios (such as La/Yb) or isotope ratios (e.g. ^{207}Pb/^{206}Pb) which are not strongly influenced by crustal processes (other than melt mixing). Ideally, these geochemical quantities can be used as passive tracers of the melt mixing process. The observations from a number of settings including Iceland, mid-ocean ridges and oceanic islands also indicate that as the forsterite content of the host olivine drops, the diversity of the melt inclusions in these trace element ratios also drops [40,53,54]. This observation can be accounted for by a model where concurrent mixing and crystallisation of melts takes place in the magma storage zones (figure 4). In the following paragraphs it is demonstrated that these observations may provide a novel constraint on the thickness of the melt layer in lower-crustal sills.

(a) Petrological modelling

Quantitative models of magmatic processes require the evolution of the physical properties of the magma and its phases to be understood as a function of temperature. In order to determine the physical characteristics of the convecting melt, the method of [55] was used to calculate the viscosity and [56] the density. The melt temperatures and compositions were obtained by running a starting composition of primitive Icelandic glass from Borgarhraun through the PETROLOG software [57]. In order to generate a suitable primary melt for the calculations, olivine was added to the glass composition until the liquid was in equilibrium with Fo_{90} olivines. Then, the crystallisation of this liquid at 5 kbar was modelled using PETROLOG.

(b) Cooling and mixing timescales

The observations in figure 4 show that destruction of compositional variation of passive tracers (such as incompatible trace element ratios) in the melt is coupled to cooling of the melt as recorded in the composition of the crystallising olivine. Melt mixing and cooling are concurrent.

If melt mixing were to proceed more rapidly than cooling, then heterogeneity in the passive tracer would either be entirely absent or limited to inclusions hosted in olivines with the very highest forsterite content on figure 4a. In contrast, if mixing is slower than cooling, then diversity in the compositional tracer should be preserved across the range of olivine compositions: Figure 4a would show a broad band in variability in melt inclusion chemistry across the range of olivine compositions rather than the clear narrowing that is observed at low forsterite content.
The properties plotted on figure 4 are directly derived from the data and do not involve assumptions relating to a physical model. The timescale of the mixing and cooling processes cannot be directly estimated from these properties, but examination of the relative rates of mixing and cooling may provide observational constraints on simple models of fluid convection within a sill. The fact that a record of concurrent mixing and cooling is preserved in the melt inclusion observations indicates that the timescales of mixing and cooling must be similar. As will be demonstrated below, this equivalence of timescales provides a means of estimating sill thickness.

The timescale of conductive cooling, τ_c, of the interior of a sill of thickness, h, (e.g. figure 6) is given by

$$\tau_c = \frac{h^2}{\kappa} \tag{6.1}$$

where κ is the thermal diffusion coefficient. However, given the relatively low viscosity of hot basaltic melts and the availability of substantial buoyancy contrasts in the system, it is highly likely that vigorous convection will occur in basaltic magma bodies. This problem was examined by [58,59] who carried out a series of tank experiments involving fluids with highly temperature dependent viscosity. They found that the temperature difference that drives convection, ΔT_v, is linked to the temperature dependence of the fluid viscosity. The Rayleigh number of the chamber can then be approximated by

$$Ra_v = \frac{g\rho\alpha\Delta T_v h^3}{\kappa\mu} \tag{6.2}$$

with g being gravitational acceleration, μ the temperature-dependent kinematic viscosity, ρ density, α the thermal expansion coefficient and

$$\Delta T_v = \frac{\mu}{d\mu/dT}. \tag{6.3}$$

Following the expressions of [58-60], the characteristic cooling timescale in this case is given by

$$\tau_{vv} = 6.38\tau_c Ra_v^{-1/3}. \tag{6.4}$$

This approximation was developed to describe experiments where the upper boundary of the layer was held at a fixed temperature. However, when basalt is emplaced into country rock, the temperature of the roof rocks rises rapidly. In this case, the cooling of the chamber is controlled by the conductive flux of heat through the roof. The background heat flux, Q_c, imposed by a fixed geothermal gradient at the time of intrusion, $(dT/dz)_i$, provides the minimum rate of heat loss from the chamber.

$$Q_c = k\left(\frac{dT}{dz}\right)_i \tag{6.5}$$

where k is the conductivity. The temperature difference driving the convection in the chamber can then be approximated by

$$\Delta T_c = \left(\frac{Q_c}{-0.47k_m}\right)^{3/4}\left(\frac{\kappa\nu}{\alpha g}\right)^{1/4} \tag{6.6}$$

and the corresponding Rayleigh number and cooling time are

$$Ra_{vc} = \frac{g\rho\alpha\Delta T_c h^3}{\kappa\mu} \tag{6.7}$$

and

$$\tau_{vc} = 6.38\tau_c Ra_{vc}^{-1/3}. \tag{6.8}$$

This slow cooling by conduction through the roof rocks dictates that τ_{vc} is an upper limit on the cooling time by convection in the chamber, while τ_{vv} is a lower limit when cooling is rapid.

The timescale of mixing of passive chemical tracers in fluids convecting at high Rayleigh number has been studied by [61] and applied to magmatic systems by [62]. These authors expressed the mixing time as

$$\tau_h = \frac{1}{2\dot{\epsilon}}\log\left(\frac{\dot{\epsilon}h^2}{D}\right) \tag{6.9}$$

where D is the diffusion coefficient of the chemical tracer of interest and the strain rate is given as

$$\dot{\epsilon} = 0.023\frac{\kappa}{h^2}Ra^{0.685}. \tag{6.10}$$

This equation allows the mixing time of passive tracers to be estimated for convection that is controlled by ΔT_v, when $Ra = Ra_{vv}$, or convection that is driven by conductive cooling through the country rocks, when $Ra = Ra_{vc}$.

The equations 6.4, 6.8 and 6.9 can be used to estimate the timescales of mixing and cooling of basaltic chambers of different thicknesses, as shown on figure 7. The observational constraints presented in figure 4 indicate that the timescales of convective cooling, τ_v, and mixing, τ_h, are approximately equal. Inspection of figure 7 shows that $\tau_v \sim \tau_m$ only when the basaltic chamber has a thickness of <5 m. For thickness of >10 m the cooling timescale becomes a factor of 10 or more longer than the mixing time.

The calculations presented in figure 7 were carried out for $T_m = 1200^\circ\mathrm{C}$, $T_b = 1150^\circ\mathrm{C}$ and $dT/dz = 0.38^\circ\mathrm{C\,m}^{-1}$. This magmatic temperature provides a viscosity estimate of $\sim 3\,\mathrm{Pa\,s}$. For comparison, the range of crystallisation temperatures estimated for the Borgarhraun olivines spans from 1240–1350°C [43,46]. If a higher T_m of 1300°C is used then the calculated viscosity is even lower, resulting in a sill thicknesses of about 2 m as the maximum where the timescales are equivalent.

7. Sill thickness, mush thickness and timescales

The simple analysis presented above indicates that convection in a sill with a convecting melt layer thickness of less than about 10 m can account for the observed geochemical evidence for concurrent mixing and crystallisation in primitive Icelandic basalts. The crystallisation interval associated with the range of forsterite contents observed in olivines from Borgarhraun is approximately 20% and if the mush porosity is 50% then the we might expect a mush layer of $\sim$4 m thickness to form at the base of a 10 m thick sill. The simple convection calculations presented above provide a cooling timescale of $\sim 10^6$ s, on the order of a month. This calculation implies that heat loss, magmatic cooling and crystallisation can take place relatively rapidly.

It has previously been suggested that the relationship between the distribution of olivine macrocryst core compositions and carrier liquid compositions in Borgarhraun and other Icelandic basalts reflects partial diffusive re-equilibration of Mg-Fe through the mush liquid [41]. These authors found that the distribution of olivine compositions observed in Borgarhraun can be generated in a $\sim$5 m thick mush pile after about 3×10^{10} s (about 1000 years). Some previous studies of the likely duration of basalt storage in the Icelandic crust are consistent with this timescale, but are poorly constrained [63,64]. Intriguingly, more detailed storage timescales have recently been obtained by the modelling of diffusion profiles in spinel inclusions from Borgarhraun, and indicate that crystals may be stored for about 1000 years in mushes prior to eruption [65].

8. Synthesis: Evolution of a lower crustal sill

The observations from Borgarhraun can be combined with the results of simple physical reasoning to suggest a model of magmatic processes in the lower crust. This sequence of events is depicted in figure 8, and shows a scenario that may occur in the lowermost crust of the transcrustal model shown in figure 1.

First, it is assumed that diverse mantle melts are fed rapidly to a sill. This chemical diversity, which is clearest in trace elements ratios and isotope compositions, is depicted as varying shades of blue on figure 8 [40]. Estimates of Borgarhraun olivine crystallisation temperatures [43,46,74] indicate that the melt has an injection temperature, T_m of over 1300°C. The country rock temperature is set at a temperature that is close to that of the liquidus of the erupted Borgarhraun melt [45,46] at $T_b \sim 1230$°C. The results shown on figure 5 indicate that cumulate country rock can be solid at this temperature.

The analysis from the previous section (figure 7) indicates that the sill may have a vertical thickness of about about 10 m. The lateral extent of this body is not well-constrained. If it is assumed that the supply of mantle melt to the sill was very rapid and that the entire volume of erupted Borgarhraun lava, 0.35 km^3 [43] was stored in a single sill, then the lateral extent of the sill would be 35 km^2. This is area is similar to that of the Borgarhraun flow on the surface, equivalent to a disk with a radius of $\sim$3 km. The lateral extent of lower crustal melt sills imaged by reflection seismic data close to the East Pacific Rise is $\sim$4 km [75].

The large thermal gradients and low viscosities of the melts permit vigourous convection to take place (figure 8b). This convection is linked to rapid heat-loss from the sill, and also to stirring of the heterogeneous mantle melts. The characteristic cooling and mixing timescales presented in figure 7 are short, and it is likely in this case that trace element homogenisation of the melt will occur in under a year. Cooling and crystallisation are concurrent with this mixing, and fractional crystallisation models from figure 5 and [43] indicate that about 20% crystallisation can occur as the injected primary melt cools from the initial T_m towards T_b. The dense primitive crystals will settle rapidly to the base of the sill and form a mushy layer. If the initial porosity of this olivine-rich layer is close to 50%, then the mush thickness at the chamber base may be ∼4 m (figure 8c).

When the temperature difference between the melt and the country rock has dropped substantially, convection may weaken or halt (figure 8d). When the temperature variations are small, compositional variations play an increasingly important role in controlling the melt fraction. The basaltic liquid in the sill remains molten while the cumulate wall-rock is solid (figure 5). The distinctive distribution of olivine core compositions in Borgarhraun and other Icelandic eruptions has been interpreted as evidence for mush storage for ∼1000 years [41]. Diffusive exchange of Mg-Fe through the liquid and crystals of the mush pile may account for the olivine distributions. Recent diffusion chronometry results also indicate that spinel inclusions in crystalline nodules in Borgarhraun have been stored for ∼1000 years after their inclusion in a crystal framework [65].

After about a thousand years, a trigger event causes rupture of the sill, disaggregation of the mush pile, and then rapid transfer of the magma towards the surface (figure 8e). Recent diffusion chronometry results constrain the transport time to be shorter than ∼4 days [45].

Diverse petrological observations from Icelandic basalts, and Borgarhraun in particular, indicate that melt is stored in sills of decimetric height within the lower crust. This view is consistent with the model of [17] for the accretion of material in the lower oceanic crust, which was based on observations from ophiolite sequences. The model of crustal accretion dominated by storage in small sills may have some general applicability to magmatic systems.

9. Figures & Tables

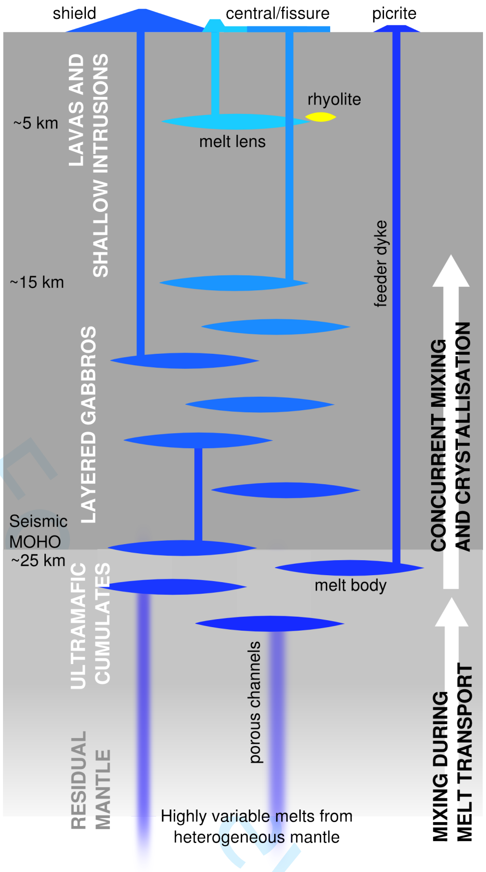

Figure 1. Schematic image of a model of magma storage and transport under an Icelandic rift-zone volcanic system, adapted from [2,4]. The observations and interpretations used to develop this model are described in the main text. Storage, cooling and crystallisation is transcrustal. Magma storage is dominated by stacked sills which may have a vertical thickness of about 10 m. Some eruptions are fed directly and rapdily from near-Moho magma storage zones, and undergo minimal interaction with the crust in transit. Pervasive, trans-crustal mush is not a feature of this model. Transient, spatially restricted mush zones are, however, present around the open liquid of the thin sills.

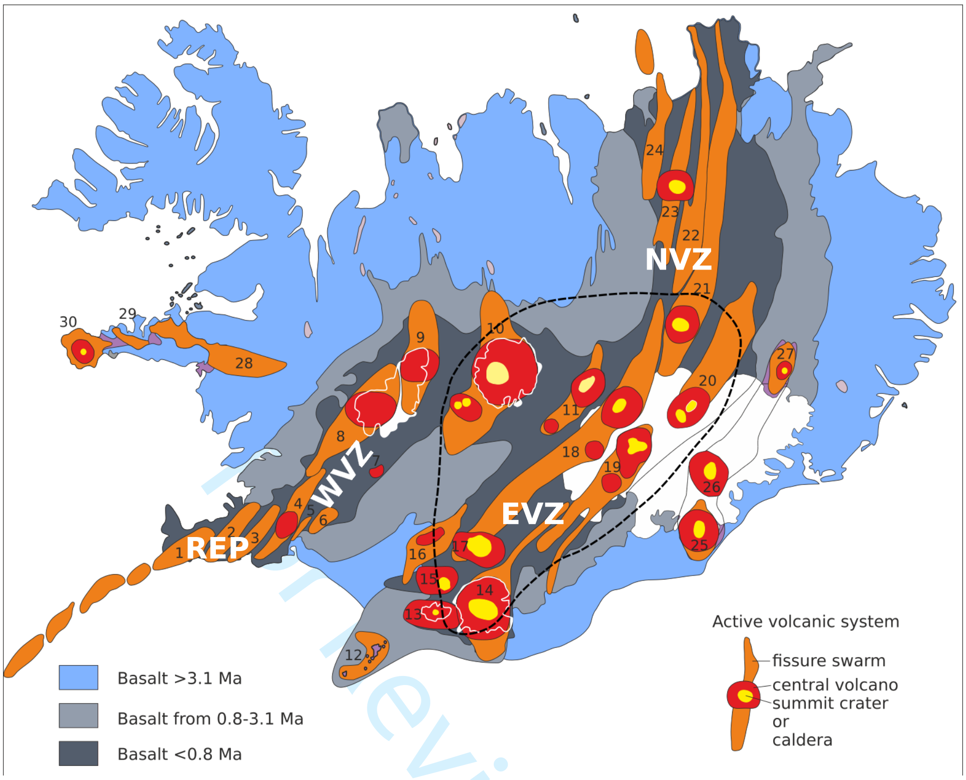

Figure 2. Map of the volcanic systems of Iceland, adapted from [20,21]. The volcanic systems are numbered. The active rift zones sit within the bands of relatively young basalt (<0.8 Ma) and are labelled : NVZ - Northern Volcanic Zone; EVZ - Eastern Volcanic Zone; WVZ - Western Volcanic Zone; REP - Reykjanes Peninsula. Most of the work described in this paper is based on study of the Krafla and Theistareykir volcanic systems, numbered 23 and 24 respectively. The dashed line is based on [22] and encircles the rift zone volcanoes that sit on crust that is >35 km thick. The crust under the Reykjanes Peninsula (systems 1–3) and Krafla/Theistareykir is about 20 km thick. This study focuses on the active rift zones of the NVZ, WVZ and REP outwith the dashed line.

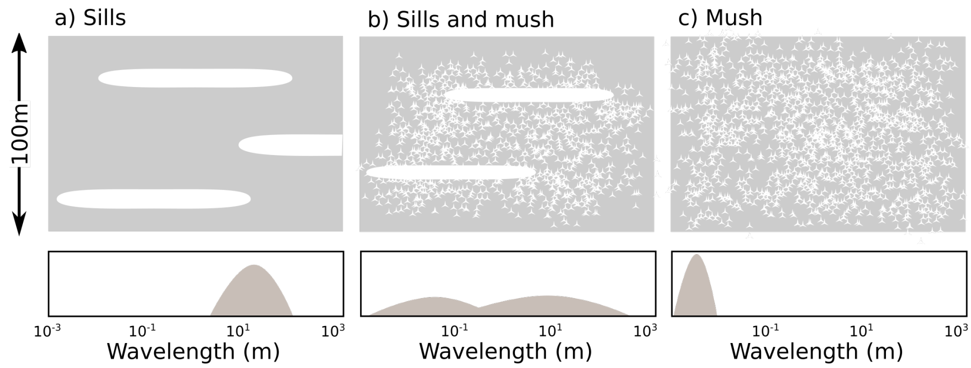

Figure 3. Possible distributions of melt in the porosity structure of a 100 m scale block of lower crust in an active volcanic system. a) Shows an end-member model, where melt is stored in sills of decimetric thickness and surrounded by solid country rock. This model is close to that suggested by [16] for ophiolites and fast-spreading ridges in general and [2,4] for Iceland. The lower panel shows an example power-spectrum of the porosity distribution for this case. b) A mixed model where melt pockets can be created within a pervasive mush, similar to the model presented by [1]. c) Pervasive, evenly distributed mush, with most of the power in the porosity distribution concentrated at millmetric scales. The lower crust of mid-ocean ridge volcanic systems has previously been viewed as such a mush [23,24].

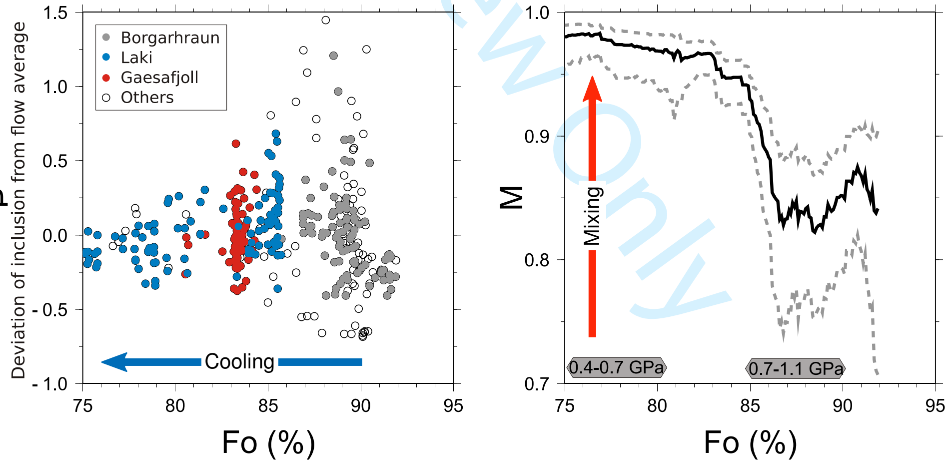

Figure 4. a) Diversity of melt inclusion trace element composition plotted as a function of the composition of the olivine host (Fo%). Plot adapted from [40] with data from Laki [44]. The data is aggregated from 10 eruptions, and the general pattern of reduced variability at lower host forsterite content is recapitulated within the products of individual eruptions, most notably Borgarhraun. The mean deviation is close to zero, highlighting the strong and systematic relationship between the trace element composition of the olivine-hosted melt inclusions from a given eruption and the composition of the carrier liquid. b) Variation in the mixing parameter, M, quantifying the mixing process. The grey boxes show the results of petrological barometry for different eruptions. Vigourous mixing of compositional heterogeneity in mantle melts takes place in the lower crust.

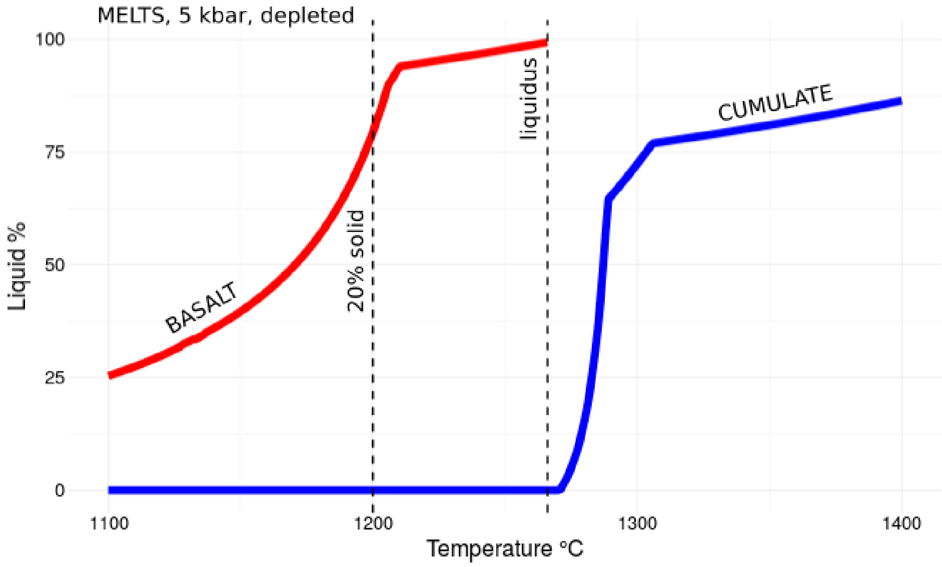

Figure 5. Results of MELTS calculations based roughly on behaviour of expected Borgarhraun parental melt. The red curve shows the melt fraction against temperature relationship for this melt during fractional crysallisation. The blue curve shows the melting behaviour of a composition that corresponds to that of the solids generated during the first 20% of crystallisation of the parental melt. This composition is solid at the liquidus temperature of the incoming primary melt.

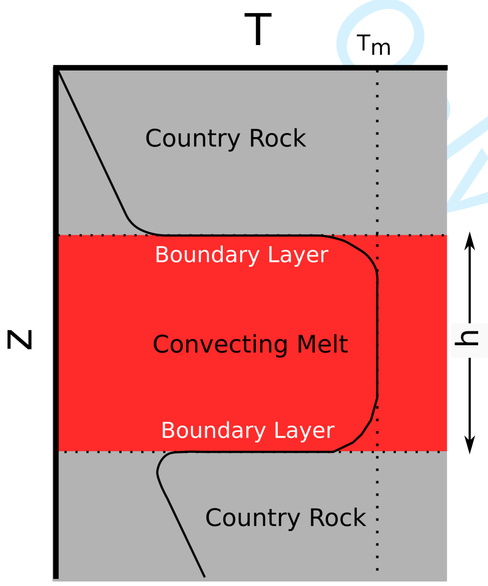

Figure 6. Model set-up for calculations relating to convection, cooling and mixing in a melt layer.

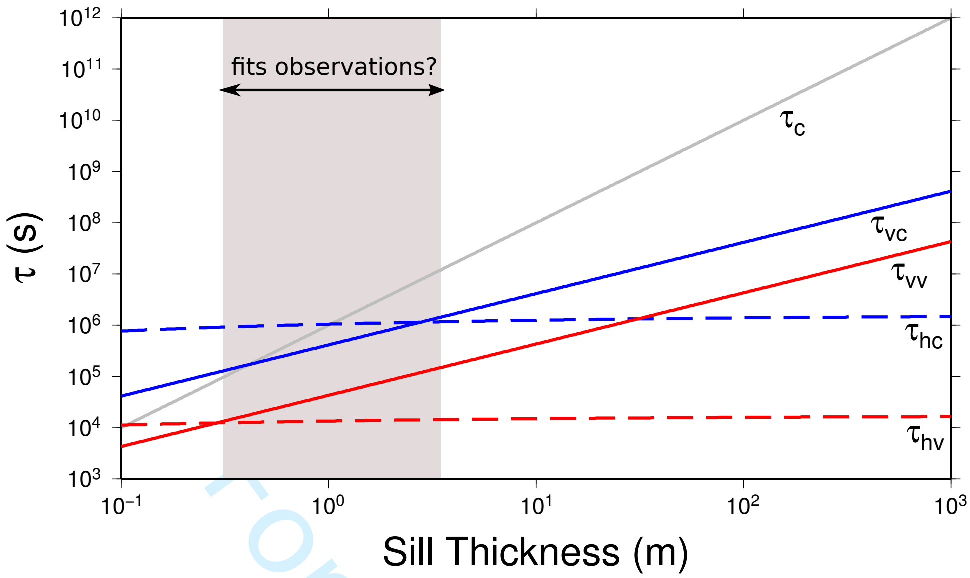

Figure 7. Characteristic timescales for cooling and mixing in a melt layer. The grey line is the conductive cooling timescale. The blue solid line is the convective cooling timescale in the case where heat loss from the sill is controlled by the thermal gradient in the country rock. The red solid line is the convective cooling timescale for when the heat loss is controlled by the temperature-dependence of viscosity of the melt. The dashed lines show the chemical homogenisation timescales associated with these two convective cooling timescales. The grey shaded box shows the range of sill thicknesses that approximately match the observations.

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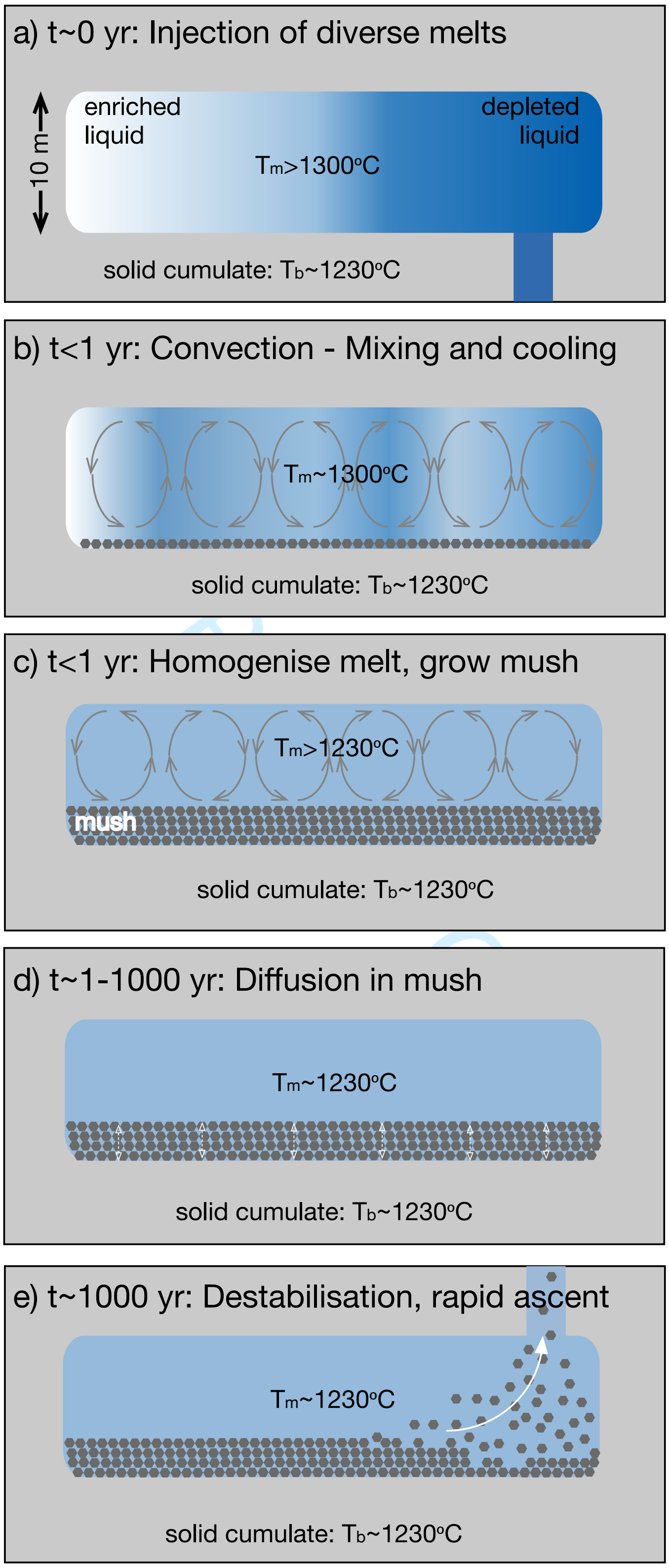

Figure 8. Evolution of a melt layer within the lower crust of an active magmatic system. See text for details.

10. Conclusion

There is strong evidence from geophysics, geology and petrology to support a model of *transcrustal* magmatism in the key magmatic settings on Earth. Iceland provides an excellent opportunity to develop and test models of magmatic processes and crustal accretion at spreading ridges more broadly. Petrological observations, modelled using a number of barometric methods, indicate that magma is stored and crystallises in several tiers of magmatic bodies under Iceland, with the deepest of these being close to the Moho (>20 km depth) and the shallowest at ∼5 km.

The barometric results also indicate that Icelandic magma can be fed directly from close to the Moho to the surface without being trapped and equilibrating at shallower levels. This rapid transport of melt from depth occurs even in the active rift zones of Iceland, where magma supply rates are high. Furthermore, the compositional relationship between melts, macrocrysts and melt-inclusions indicates that there is little petrological evidence of interaction between magma batches and the crust in the transit path between deep storage and eruption. Eruptions that are close in time and space have plumbing systems that are remarkably distinct. These observations indicate that the crust of several of Iceland's active rift zones (the NVZ, WVZ, and Reykjanes Peninsula) is not composed of an extensive, pervasive mush.

Geophysical and petrological results from Iceland are consistent with a *stacked sills* mode of crustal accretion, a model that was developed in response to observations from active mid-ocean ridges and ophiolite complexes. In these models, thin and transient mushes may form at the margins of thin melt sills, meaning that many rising magmas carry evidence of interaction with mush and all solid cumulate rocks have progressed through a mushy stage. The melt sills are encased in a hot, but subsolidus country rock. In order to generate suitable cumulate country rock it is vital that porosity in mushes is occluded by the crystallisation of primitive phases.

Geochemical evidence from Icelandic melt inclusion suites indicates that mixing and cooling of melts are concurrent in crustal magma storage zones. Convection is likely to couple these processes together and the fact that evidence for both mixing and cooling is preserved indicates that the timescales of these processes are similar. Simple fluid dynamical reasoning can be used to show that this equivalence of timescales is expected from mixing in basaltic sills that are less than about 10 m in height. These sill thickness are very similar to those envisioned for oceanic crustal accretion at spreading ridges on the basis of observations at ophiolites.

Ethics. Not applicable.

Data Accessibility. Not applicable.

Authors' Contributions. Not applicable.

Competing Interests. The author declares that they have no competing interests.

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Disclaimer. Not applicable

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