

Geophysical evidence for current magma accumulation in the continental crust: Examples from the Andes.

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Deformation of the Earth's surface at volcanoes provides clues to the myriad processes occurring below and above the surface, and might provide warning of an imminent eruption. Unfortunately, because different volcanoes have different personalities, a history of precursory activity and eruption should be established for each volcano. Of the more than 1500 “potentially active” volcanoes around the world, the history of recent surface deformation is well documented at only a few dozen volcanoes. For example, as of 1997, surface deformation had been observed at only 44 different volcanoes using ground-based methods [Dvorak and Dzurisin, 1997]. In the last decade or so, observations of deformation at volcanoes have more than doubled to 110, due largely to the use of satellite-based interferometric synthetic aperture radar (InSAR). These InSAR results show that not only do different volcanoes have different personalities, but that different volcanic arcs appear to have differing relations between ground deformation and eruption.

Many of the deforming volcanoes discovered with InSAR were not thought to be active and thus the hazard from these presumed magma accumulations is unclear - will there be an eruption, or is this a benign intrusion? Two volcanic areas in the central Andes illustrate the difficulty in assessing eruptive hazard: Uturuncu volcano, Bolivia and the Lazufre area between Lastarria and Cordon del Azufre on the border between Chile and Argentina. These areas of uplift are globally anomalous in that they are not obviously associated with volcanoes with recent eruptions (within the last few 10 thousand years). The eruptive hazard seems low since, for example, Uturuncu has been long dormant (perhaps 270 ka [Sparks *et al.*, 2008]) and the “magma chambers” that are the inferred sources of the deformation are 15-20 km deep within the 70 km continental crust. On the other hand, both areas show near surface activity (upper 5 km): numerous shallow earthquakes at Uturuncu and ground deformation at Lastarria volcano. During this presentation we will discuss initial results from an international geophysical project to understand the nature of the magmatic activity at Uturuncu and Lastarria as well as the regional and global context of these presumed mid-crustal intrusions.

Using InSAR to Map and Study Deformation of Aleutian Volcanoes

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With its global coverage and all-weather imaging capability, interferometric synthetic aperture radar (InSAR) has become an increasingly important technique for studying magma dynamics at volcanoes in remote regions such as the Aleutian Islands. The spatial distribution of surface deformation data derived from InSAR images enables the construction of detailed mechanical models to enhance the study of magmatic processes. This paper summarizes various deformation processes at Aleutian volcanoes observed with InSAR, including: (1) volcanic inflation and magma intrusion, (2) deformation preceding seismic swarms at several active and quiescent Aleutian volcanoes, (3) persistent volcano-wide subsidence at calderas that last erupted hundreds of years ago, (4) magma intrusion and associated tectonic stress release at active volcanoes, (5) subsidence caused by a decrease in pore fluid pressure in active hydrothermal systems, and (6) lack of expected deformation associated with recent eruptions at frequently active volcanoes. Among the inferred mechanisms are inflation/deflation of crustal magma reservoirs, pressurization/depressurization of hydrothermal systems, tectonic strain, thermal-elastic contraction of young lava flows, etc. Our work demonstrates that deformation patterns and associated magma supply mechanisms in the Aleutians are diverse and vary both in space and time. These findings provide a basis for improved models and better understanding of magmatic plumbing systems in the Aleutians.

Erupting silicic batholiths

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Magma with crystallinity exceeding about 50 vol.% and effective viscosity $> 10^6$ Pa s is generally perceived to stall in the Earth's crust rather than to erupt. There is, however, irrefutable evidence for colossal eruption of batholithic magma bodies and here we analyze four examples from Spain, Mexico, USA and the Central Andes. These silicic caldera-forming eruptions generated deposits characterized by i) ignimbrites containing crystal-rich pumice, ii) co-ignimbritic lag breccias and iii) the absence of initial fall-out. The field evidence is inconsistent with most caldera-forming deposits, which are underlain by initial fall-out indicating deposition from a sustained eruption column before the actual collapse sequence. In contrast, the documented examples suggest early deep-level fragmentation at the onset of eruption and repeated column collapse generating eruption volumes on the order of hundreds of cubic kilometres almost exclusively in the form of ignimbrites. These examples challenge our understanding of magma eruptability and eruption initiation processes. We present an analysis of eruption promoters from geologic, theoretical and experimental considerations. Assessing relevant dynamics and timescales for failure of crystal-melt mush we propose a framework to explain eruption of batholithic magma bodies that primarily involves an external trigger by near-field seismicity and crustal failure. Strain rate analysis for dynamic and static stressing, chamber roof collapse and rapid decompression indicates that large "solid-like" silicic reservoirs may undergo catastrophic failure leading to deep-level fragmentation of batholithic magma at approximately 2 orders of magnitude lower strain rates than those characteristic for failure of crystal-poor magmas or pure melt. Eruption triggers can thus include either amplified pressure transients in the liquid phase during seismic shaking of a crystal-melt mush, decompression by block subsidence or a combination of both. We find that the window of opportunity for the eruption of large silicic bodies may thus extent to crystallinities beyond 50 vol.% for strain rates of $>10^{-4}$ s⁻¹.

Fifteen years of observation of the Montserrat magmatic system

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Soufriere Hills Volcano, Montserrat is only a moderate-sized volcanic system on one of the world's slowest subduction zones - the Lesser Antilles. Yet over the last fifteen years it has produced over 1 km³ of andesite lava. The well observed volcanism of the system over this period provides valuable constraints on the nature of the magma reservoir and its dynamic behaviour. The first-order pattern over fifteen years is of near continuous flux of lava and volatiles through the system. From petrology there is sound evidence for the exchange of heat and mass between a largely crystalline andesite magma body and basalt at depths of about 12 km. From geodesy, island-wide deformation is shown to be elastic with sources from about 6 km to 12+ km depth, but the apparent differential pressure variations in the reservoir only account for a small proportion of the lava flux. Seismic reflection and tomography shows the upper crustal structure, dominated by a NW-trending oblique extensional environment that has controlled some of the shallower processes.

Geophysical Constraints on Magma Emplacement and Storage at Mid-Ocean Ridges

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Mid-ocean ridge volcanoes are not a societal hazard and are expensive to study, but from a geophysical perspective they are an excellent setting to investigate magmatic processes. The magma systems are shallow and are set within a background crustal structure that is well known and laterally invariant. The deep-water setting enables high-resolution active-source seismic imaging which, when coupled with other geophysical techniques, provides detailed constraints on subsurface thermal and magmatic structure. Geodetic observations are difficult on the seafloor but pressure sensors can be used to measure volcanic inflation, and thus infer the rate of magmatic heat input into crustal magma chambers. The presence of focused hydrothermal venting at the seafloor facilitates measurements of crustal heat loss. It should be possible to use the imbalance of heat input and output and repeated geophysical imaging studies to constrain temporal changes in magmatic systems. While sustained monitoring of mid-ocean ridges is challenging, the development of seafloor observatories will support long-term observations at several locations.

The US National Science Foundation's Ridge 2000 program has focused recent geophysical studies at three sites, the East Pacific Rise near 9°50'N, the Endeavour segment of the Juan de Fuca Ridge and the Lau back arc basin, while the Europeans have conducted focused experiments on the mid-Atlantic Ridge. The co-location of geophysical experiments, coupled with synergies that have arisen from complementary petrological and structural studies of ophiolites and present-day ocean crust, has contributed substantially to the development of models for crustal accretion.

In my presentation I will discuss examples of some of geophysical techniques that are being applied to mid-ocean ridges and touch on alternate models for the magmatic accretion of the crust and the controls on magma supply from the mantle. I will conclude by discussing in more detail some recent results from the Endeavour Segment of the Juan de Fuca Ridge. Here the central elevated portion of a 90-km long segment is underlain by a segmented magma lens at 2-3 km depth, which drives five black-smoker hydrothermal systems. Hydrothermal heat flux observations suggest that locally, heat loss significantly exceeds the steady-state level necessary to solidify and cool new oceanic crust. The distribution and focal mechanisms of microearthquakes above the axial magma lens are consistent with the steady injection of pressurized magma into the magma lens beneath the most vigorous vent fields. In conjunction with results from elsewhere and conceptual models of heat transfer, this observation supports the hypothesis that vigorous hydrothermal venting delineates sites of ongoing magma emplacement.

The petrological record of magmatic processes in the Icelandic crust

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Recent geophysical and geodetic monitoring of rifting events in Afar and lower crustal seismic swarms in Iceland have reinvigorated the study of magma storage and transport in rift-related settings. Petrological observations also provide important constraints on the evolutionary path of magma as it rises through conduits and chambers in the crust. These petrological constraints are required for improving interpretation of the geophysical observations.

Thermobarometry based on the composition of basalts, their phenocrysts and cognate cumulate xenoliths indicates that crystallisation takes place at a range of depths in the Icelandic lower crust, possibly in small sills. Simple mass balance calculations can be used to show that this crystallisation generates gabbroic cumulate material that is accreted uniformly with depth into the lower crust. The coupled evolution of the variability in the trace element composition of melt inclusions and the major element composition of their olivine hosts can be accounted for if convection in magma bodies causes concurrent mixing and crystallisation of basalt. These constraints on fluid dynamical behaviour in magma bodies may also allow estimation of their dimensions and comparison with results from geophysical surveys.

While mixing and crystallisation of mantle melts dominates magmatic processing in the lower crust (deeper than 10 km), the shallow Icelandic crust is known to host the generation of rhyolites and the mixing of rhyolitic and basaltic material. A detailed study of the products of the 1783 AD Laki basaltic fissure eruption in SE Iceland also indicates that incomplete mixing between basaltic melt and a crystal mush occurs in relatively shallow magma chambers (~6 km depth) prior to eruption. This mixing event may demonstrate a role for mafic recharge of shallow evolved chambers during the precursory phases of huge basaltic eruptions.

The transit of melt through the crust of the Theistareykir volcanic segment is partly controlled by the physical properties of the magma. Over 70% of the volume of erupted material during the last 100 kyr has magma density close to the density minimum predicted from simple fractional crystallisation models. Dense primitive magmas, such as the Theistareykir picrites, can erupt because they are fed directly from upper mantle/lower crustal magma chambers without being trapped in shallower melt pockets. Eruption of iron-rich evolved basaltic melts from shallow chambers may be triggered by volatile exsolution or by mafic recharge.

Seismicity beneath the Askja volcanic system, central Iceland, indicating multiple centres of melt injection from the mantle in a single spreading segment.

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Over 700 lower-crustal earthquakes (13 – 27 km depth) have been recorded around Askja volcano on the plate spreading boundary in central Iceland, using local arrays of broadband seismometers. The brittle-ductile boundary in the Askja region is well defined by the sharp lower cut-off of upper-crustal seismicity at depths of 5 – 7 km, so the lower-crustal events are well within the normally aseismic and ductile part of the crust. The lower-crustal earthquakes are distinctly different in appearance to the upper-crustal earthquakes with a lower frequency content and generally emergent P- and S- phases. They often occur in swarms lasting several minutes, with hypocentres from a single swarm located close to one another. The lower-crustal events have local magnitudes of 0 to 1.7, which is a smaller maximum size than the upper-crustal events.

In space, these events can be divided into three main clusters, the largest of which is located at the northern boundary of the youngest caldera and adjacent to a geodetically proposed magma chamber, extending along the fissure swarm 10 km to the north east. The second cluster is located 20 km further to the north east, between a shield volcano and a subglacially erupted table mountain. The third cluster is 10 km east of Askja, north of another shield volcano. Earthquakes have been persistent in all three clusters since they were first detected in the summer of 2006, and qualitative evidence suggests that they were occurring during summer 2005. The dimensions and locations of each of the clusters have not changed since we commenced continuous seismic monitoring in summer 2007 and each cluster has a stable upper cut-off depth, possibly the location of a magma body such as a sill.

We propose that these earthquakes are caused by magma movements within the lower crust. They are possibly located at positions of long term magma supply from the mantle. This suggests that the volcanic rift zones are supplied with melt at multiple points along each segment rather than by lateral melt migration fed from a single input.

Anatomy of dyke intrusion at 15–18 km depth beneath Upptyppingar, north Iceland

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An extended sequence over a 12 month period of more than 6,000 microearthquakes at 14–22 km depth near Upptyppingar in the northern volcanic rift zone of Iceland is attributed to the injection of melt into the mid-crust (Jakobsdóttir et al., *Stud. Geophys. Geod.*, **52**, 513–528, 2008). The earthquakes occur in the normally ductile and aseismic region of the crust in response to locally high strain rates caused by melt injection. They enable us to map in detail the dynamics of the progressive intrusion of melt in an inclined dyke with a thickness of 0.4 m and an area of $\sim 50 \text{ km}^2$.

We use data from a detailed array of 20 seismometers deployed by Cambridge University (half from the NERC SEIS-UK facility), supplemented by 6 nearby Icelandic Meteorological Office seismometers to investigate one of the most intense periods of seismic activity during July–August 2007. Over 2000 events were located with magnitudes of 0.8–2.2. Locations of the hypocentres fall on a single inclined plane with a strike of $\sim 080^\circ$ dipping southward at $\sim 50^\circ$. Fault plane solutions show the same orientations and dips. The deformation is dominantly by double-couple mechanisms and is remarkably consistent between events.

The melt injection occurred in swarms of typically 100 detected events, each swarm lasting several hours, with quiescent periods of tens to hundreds of hours between them. Within a swarm we are able to track the melt from an individual injection as it moved upwards and laterally through the dyke over a distance of typically 1 km per injection. Both thrust and normal fault plane solutions occur during the injection swarms, with the P and T axes flipping. We attribute the differing failures to fracturing as melt forces open a channel, alternating with volumetric contraction as the melt freezes or migrates laterally along an open fracture.

Abundant shallow seismicity in the top 7 km of the crust started several months after the termination of the deep seismicity attributed to melt injection. The shallow seismicity occurs where the crust is sufficiently cold to fail by brittle fracture, mostly subsequent to the deeper dyke injection. There is a distinct gap in the depth of seismicity between this upper brittle failure and the deep crustal events, but stress modelling suggests that the shallow seismicity in the brittle layer is responding to stress changes caused by the underlying dyke injection

Eruptive episodes: Interplay between magma movements and storage in shallow elastic crust and at deeper ductile levels

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Magmatic activity at many volcanoes is highly variable, often with unrest periods, shallow magma movements and eruptions clustering in time. An example of this behaviour are rifting episodes at divergent plate boundaries like in Iceland and Afar, extended periods of high eruption frequency over decades separated by less active periods, or extended eruptive activity with intermittent pauses (e.g., like 1995 to present activity at Soufrière Hills, Montserrat). Yet the generation of magma is a steady process. Geodetic imaging of magma transfer in Iceland with GPS, InSAR, levelling, tilt, electronic distance measurements, and borehole strain has revealed magmatic pressure sources both at shallow levels within the brittle crust (about 3 km depth) and deep magma sources below the brittle-ductile transition which occurs typically at 5-10 km depth. These observations and many other suggest a model for volcanic systems where magma accumulates both at shallow and deep levels. Density gradients in Icelandic crust are such that magma is buoyant in the deeper sources. Deep magmatic sources embedded in ductile surroundings can gradually accumulate magma with little increase in surrounding stress, capturing magma over long time that is steadily generated in the mantle. Such sources can therefore expand and accumulate magma over long intervals, until critical conditions are reached and a feeder channel forms towards shallower levels. Once a channel is established buoyancy allows transfer of magma to shallower level, since magma in the deep sources is less dense than the surroundings. Low magma flow rates can drain a large fraction of the deep reservoirs over extended time, with rates limited by the width of channels formed and the amount of underpressure (pressure less than lithostatic) in the deeper source that causes its contraction. If a channel tapping a deep source with sufficient volume of magma hits a shallow magma chamber in elastic upper crust, it will lead to series of injections or eruptions from the shallow source closely spaced in time, with high magma flow rates. If a channel from a deep source reaches the surface without hitting a shallow chamber, a long-lived eruption of low effusion rates may occur, such as those that formed the lava shields of Iceland which are located outside the domain of shallow magma chambers. Interaction of magma storage and transfer in elastic and viscoelastic surroundings, initially in deep ductile lower crust or uppermost mantle, then modulated by magma accumulation in magma chambers in elastic uppermost crust, can explain many features and observations of episodic activity at divergent plate boundaries as well as elsewhere.

Evidence of melt in the crust and mantle beneath the East African Rift system

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The East-Africa rift system is the only place on Earth where all stages of rifting can be observed from initial fracturing in Southern Africa to the formation of new oceanic crust in Afar, Ethiopia. Much work over the last decade has focussed on the transition from continental rifting in the Main Ethiopian Rift (MER) to oceanic spreading in the Red Sea/Gulf of Aden Rifts. Using recently deployed seismic stations and legacy datasets we provide images of the crust and mantle beneath Ethiopia, highlighting how a melt rich crust is connected to the underlying African superplume.

Bulk crustal structure has been determined by H-k stacking of receiver functions. Crustal thickness varies from ~45km on the rift margins to ~16km beneath north eastern Afar. Estimates of Vp/Vs show normal continental crust values (1.7-1.8) on the rift margins, and very high values (2.0-2.2) in Afar and the MER. This supports ideas of high levels of melt in the crust beneath the Ethiopian Rift. Additionally, a common conversion point (CCP) migration technique highlights two regions of low velocity possibly associated with melt rich regions. One exists in the lower crust beneath the southern end of the Manda-Harao volcanic segment. The other is located in the mantle beneath the Erta Ale volcanic segment

Previous studies of anisotropy in the MER have highlighted melt as the most plausible mechanism for generating shear-wave splitting. Finite difference modelling further constrains this anisotropy to a layer extending from the surface to a depth of 90km. This correlates with regions of focussed low velocities seen in seismic tomography, and the suggested region of melting based on geochemistry. Anisotropy in Afar shows similar characteristics to that seen in the MER (sharp changes in fast direction over small lateral distances), but with much smaller delay times. This suggests that melt is not as efficient at generating anisotropy beneath Afar than beneath the MER, possibly due to focussing effects beneath the narrow MER compared to the broad Afar depression.

At sub-lithospheric depths the region of low seismic velocity broadens to cover most of Ethiopia. However, in the transition zone the low velocities become focussed into two regions, one beneath Afar, and the other beneath the Ethiopian plateau. These low velocities are not characteristic of a simple plume like upwelling, rather they indicate a more complicated connection to the large scale upwelling of the African superplume.

Locating magma in Afar, Ethiopia – Magnetotelluric studies

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The electrical resistivity of the Earth's sub-surface is strongly dependent on the presence of fluids or melt. The magnetotelluric (MT) method is an excellent way to probe resistivity over a range of depths from the near-surface to the mantle. It uses naturally-occurring variations in the electric and magnetic fields arising from lightning and solar wind interactions; they induce eddy currents in the sub-surface whose geometry and strength depend on the resistivity structure. To explore the amount and distribution of magma involved in the current rifting event in Afar, Ethiopia, we have collected MT data along two profiles – one across the active Dabbahu magmatic segment and one across the inactive Hararo segment, in both cases approximately perpendicular to the segment axis. After briefly summarising the data processing, we show that the results are broadly consistent with a two-dimensional (2D) interpretation, and present 2D models of both segments. The data are strongly contrasting – beneath the active Dabbahu segment we infer extensive volumes of low resistivity material, including a large sub-crustal (centred on ~20km depth) very low resistivity body, whereas resistivities are generally much higher beneath the Hararo segment. The sub-crustal body beneath the Dabbahu segment, which we interpret to be a magma chamber, is located to the west of the dykes that have been injected over the last 4 years, but coincides with the geomorphological rift axis, in agreement with inSAR, GPS, surface deformation and geological observations. There are indications of a low resistivity feature continuing from it towards the location of the dykes, but the data sensitivity at upper crustal depths is inadequate to image reliably a shallower magma chamber inferred from petrological studies, or the dykes themselves. The 2D assumption is most in error at depth beneath the rift axis, so in addition we have used three-dimensional modelling to interpret departures from the 2D model. This indicates that the depth to the top of the sub-crustal conductor is a maximum beneath the profile, reaching much closer to the surface to its north and south. This is consistent with other data, including seismicity, suggesting that the current dyking episode has been fed from the Dabbahu-Gab'ho and Ado-Ale volcanic complexes. We will compare the Dabbahu results with a preliminary inversion of the Hararo segment data.

Geodesy reveals deep lateral magma flow and complex magma plumbing in Ethiopian spreading centre

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The chain of volcanoes that runs through Afar in Ethiopia marks a subaerial spreading centre separating the Nubian and Arabian plates. In September 2005, a major dyke intrusion ruptured the 60-km-long Dabbahu segment of this plate boundary. The 4-8m-wide dyke was fed laterally from two shallow magma chambers at the north end of the segment and an inferred deeper source near the segment centre. A rapid deployment of ground-based geodetic instruments, and frequent satellite radar passes, have allowed tracking of the temporal and spatial pattern of surface deformation occurring since the major dyke intrusion - the first time this has been possible for a major rifting episode. Since that first intrusion a number of smaller dykes have been intruded in the same segment. Here we show that the post-intrusion response of the magmatic system reveals a magmatic plumbing system that is more complex than previously thought. In addition to the shallow chambers previously identified, a third, mid-segment chamber is present in the mid-crust. Furthermore, a broad subsiding area to the south-east of the rift segment can be explained only by the lateral flow of magma away from a reservoir in the lower crust towards the active rift segment - a distance of at least 60 km. Our results suggest that models of mid-ocean ridge magma systems may be too simple, and especially that transport of magma from sources away from the spreading axis may play an important role.

Magma emplacement and storage at ocean ridges

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Many ocean ridge segments have a systematic bathymetric form of shallower depths at segment interiors, with progressive deepening towards segment “edges.” Because of this characteristic, ridges have often been viewed as akin to central volcanoes on Iceland, with magma emplaced from the mantle at segment centers, and distributed through the crust and upper mantle from center to edge, often by dike propagation. Alternatively, there has also been the argument that ridges are a continuous two dimensional crack and magma can be emplaced from depth all along the length of the ridge segment, rather than centrally. These are the “central supply” and “multiple supply” models of ocean crust formation.

Recent data provide greater complexity to these simplified points of view. The style of segmentation and magma emplacement depends in part on the spreading rate. The slowest spreading Gakkel Ridge has no major transform offsets but has distinct volcanic edifices along strike, showing that the distribution of melt emplacement can be controlled by mantle processes rather than surface segmentation. In general, the extent of focusing seems to increase as spreading rate declines. Along the mid-Atlantic Ridge, almost half the segments away from hot spots do not form by the classical model of symmetrical crustal accretion, but by detachment faulting. Such segments clearly do not fit simple volcano models of ocean crust formation. The small amount of available data suggest that segments with detachment faults are associated with melts derived by lower degrees of melting that fractionate at higher pressure., and are generally more primitive.

Detailed petrological studies of individual segments provide important data on all these issues. In investigating the spatial aspects of magma emplacement, gradients around hot spots are particularly useful. Are the gradients smoothed out by homogenization within a segment? We have collected new high precision data from all the available samples from the FAMOUS segment to look in detail at segment scale variations. The southern half of the segment has a rather coherent magma series suggesting some homogenization through melt emplacement. In contrast, the northern half shows an astonishing variety of magmas requiring diverse sources and processes. There is a slight increase in isotope and incompatible element enrichment from south to north, suggesting the Azores gradient is able to manifest at the segment scale. At the same time both enriched and depleted samples appear to be concentrated to the segment center. On a larger scale, there is a remarkably regular gradient of MgO content with axial depth south of the Azores, suggesting that increased magma supply at constant spreading rate is associated with increased crustal processes so that erupted lavas have lower temperatures.

Along the East Pacific Rise, distinct geochemical offsets can occur at the smallest (1km) scale of discontinuity, showing that magma is emplaced at multiple points along the ridge axis. Some segments also have diversity in radiogenic isotopes at a very small scale even distant from transform faults showing that magma is emplaced in small batches without lengthy storage and homogenization.

Basalt Storage and Differentiation in the Lower Crust and its Relationship to the Seismic Moho

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Arrest and differentiation of mantle-derived basaltic magmas as sills within Deep Crustal Hot Zones [1], in a wide variety of tectonic settings, has a number of testable implications for crustal structure. The liquidus phase of almost all mantle-derived (primitive) basalts is olivine \pm spinel. Most erupted basalts are related to their primitive parents by appreciable olivine fractionation, while more evolved magmas (e.g. andesite, trachyandesite) require additional pyroxene \pm amphibole fractionation. Thus the cumulate residues generated over this fractionation interval are ultramafic rocks with physical properties very similar to mantle rocks, from which they will be seismically indistinguishable. The arrival of plagioclase, which has significantly lower seismic wave velocity than olivine or pyroxenes, as a liquidus phase is very sensitive to the dissolved H₂O content of the parent basalt. High H₂O suppresses plagioclase appearance to lower temperatures. Experimental data show that the onset of plagioclase crystallisation is dramatic for almost all basalt magmas, such that once saturated the modal proportion of plagioclase increases sharply. This leads to a marked drop in the bulk seismic wave velocity of cumulate rocks once plagioclase is stabilised. We propose that this marked drop in seismic wave velocity corresponds to the seismic Moho, which lies at much shallower depth than the petrological Moho in a wide range of tectonic settings. The Moho depth depends on the geothermal gradient and the H₂O content of the parent magmas. For a given geotherm, wetter basalts yield a shallower Moho; for a given H₂O content, lower geotherms yield a deeper Moho. Thus Moho depth and heat flow are potential basalt hygrometers. In areas of very high heat flow, such as active rifting, temperatures may never be low enough for appreciable plagioclase crystallisation leading to the absence of a Moho. Vertical migration of the Moho is predicted to occur as crustal heat flow waxes and wanes. The eclogite transition, where plagioclase is transformed completely to dense, seismically fast garnet, places a maximum seismic Moho depth of ~80 km irrespective of geothermal gradient. Our proposal is consistent with geophysical and petrological observations in Afar, Lesser Antilles and a large number of active margins for which heat flow and Moho depths are available [2].

[1] Annen et al. *J Petrol* 47: 505 (2006); [2] Zellmer, *Geol Soc London Spec Pub* 304:15 (2008)

Controls of the width of a propagating dyke

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We study deformation in upper crustal rocks due to a vertically propagating dyke using a numerical code that solves for elastic deformation of host rocks, magma flow and fracturing at the tip. With a volatile-free magma, a dyke fed at a constant rate into a uniform medium adopts a steady-state shape and rises at a constant velocity. Deformation is enhanced in the nose region below the tip. Dyke width is poorly sensitive to host rock properties and is $\approx 1\text{-}2$ m for typical input rates and viscosities of basaltic magmas. Large amounts of deformation can be achieved in low density upper crustal layers and/or if magma is volatile-rich.

In low density host rocks, the negative buoyancy of magma hampers dyke ascent and the nose region swells to accomodate the flux of magma that continues to be fed from deeper crustal levels. The characteristics of penetration are determined by a local buoyancy balance in the nose, independently of the total buoyancy of the magma column extending from source to tip. A large internal overpressure develops in the nose region and acts to widen the dyke. Such overpressure in the swollen nose region may generate a horizontally propagating sill. In this case, the dyke may not reach Earth's surface and there is no eruption. For this to occur, the thickness of low density layers must exceed a threshold value in a range of 1-2 km.

With volatiles present, the volume flux of magma increases due to decompression-induced volatile exsolution and gas expansion. With no fragmentation, this enhanced flux leads to the thinning and acceleration of the dyke. The opposite behaviour is observed for magma that contains sufficient amounts of volatiles and undergoes fragmentation. The sharp drop of head loss that occurs in low density gas-rich fragmented material acts to increase pressures within the dyke and hence to enhance host-rock deformation. As a consequence, the mixture of gas and magma flows through a widening aperture and the dyke decelerates. In this case, enhanced deformation is not due to a change of magma buoyancy but to a change of rheological behaviour.

Lateral transport of magma in long, wide dykes: the Palaeogene dykes of northern England

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The Palaeogene dykes of northern England extend for over 400 km laterally from the Palaeogene Mull volcano of western Scotland. They form a diffuse swarm that broadens away from Mull to a width of about 20 km close to Glasgow and as much as 100 km at the extreme end of the swarm in the North Sea. Several of the dykes in the swarm are 15 – 25 m wide, while others are as narrow as 2 m. Seismic reflection profiles indicate that the dykes extend to depths of around 10 km. The chemistry of the dykes ranges from basaltic (with about 50% silica) to much more evolved rocks with up to 58% silica, indicating a considerable variation in viscosity of the magma. At the present level of exposure, most of the dykes are divided into short en-echelon segments, while other dykes have been seen only in deep coal mines. The dykes are likely to be continuous at depth, sending segments upwards to intrude at shallower levels. Propagation of the dykes is likely to have been by hydrofracturing. The excess magmatic pressures in the source volcano cannot have been high enough to contribute significantly to the propagation, or the magma would have been erupted instead of being intruded. The topographic driving pressure gradient from the lateral slopes of the volcano would not have extended far enough to contribute to the lateral extent of intrusion. Hydrofracturing runs into difficulties with the great width of some of the dykes. The challenge is to find a model that explains the full complexity of these and other far-propagating dyke swarms containing dykes wider than a few metres.

A simple analytical solution for the coupling of magma chambers and dykes

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In the past decades volcano seismologists and geodesists have collected many observations that current models of dike propagation do not explain. The cause of this failure has been already identified by several authors in the assumption that magma chambers can maintain their pressure constant while feeding dikes. This assumption collides e.g. with the convex upward shape of the volume evolution during the 1997 dike intrusion at Kilauea, as noted by Owen et al. [2000] and Segall et al. [2001]. Segall et al. [2001] described the flow of the magma from a chamber to a dike with an ordinary differential equation for the unknown pressures of chamber and dike. The feeding of dikes is there associated to a pressure drop in the magma chamber, controlled by magma bulk modulus and elastic compressibility of surrounding rock. My model develops on that intuition, and makes use of mass conservation (instead of volume conservation) as a constraint for pressure as magma flows from the chamber to the dike. This ansatz allows to solve the problem analytically. The model predicts that chamber and intrusion volume change exponentially with time as $V(t) = V_{\infty} [1 - \exp(-t/\tau)]$. Intrusion velocity is found to change as $v = v_0 \exp(-t/\tau)$, where v_0 is the initial dike velocity. The asymptotic volume V_{∞} and the time scale τ are expressed in terms of rock, magma, chamber and dike parameters and of the initial pressure conditions. Fitting volume or velocity curves can provide independent constraints on parameters difficult to retrieve otherwise. I validate my model with the best observations available for lateral dike propagation: the volume history of chamber and dike during the 2000 Miyakejima intrusion (Japan), dike velocity during the 1978 Krafla event (Iceland) and during some intrusions following the 2005 event in Afar (Ethiopia). The fit between model and observations is excellent. This paper confirms and extends the results of a previous study [Rivalta and Segall, 2008] that explained the volume imbalance found during some dike intrusions. The final ratio between dike volume and the volume withdrawn from the chamber was found to be $rV = 1 + 4\mu\beta/3 > 1$, where μ is the host rock rigidity and β is the magma compressibility. This invalidates the most intuitive assumption (and implicit boundary condition) on magma exchange that the volume gained by the intrusion equals the volume lost by the chamber(s). Here, I demonstrate that the formula for rV holds at any time, not just at equilibrium. My model confirms that some magma chambers behave as stiff magma-tanks, able to inflate large dikes as balloons, and demonstrates that this is unlikely to occur if the chambers are simply shaped as sills.

Thermal implications of magma emplacement geometries and emplacement rates

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Field observations, geophysical studies, geochronological data and conceptual reasoning suggest that many large igneous bodies result from the agglomeration of smaller magma pulses and that these magma pulses often take the shape of low aspect-ratio sheets. The thermal evolution of a magma body that grows slowly by accretion of sills or dykes differs fundamentally from the thermal evolution of a large body that is instantaneously emplaced. In all cases, the initial temperatures and the thermal conductivities of both injected magma and country rocks influence the thermal evolution of the magma-country rock system, but in the case of incremental emplacement the distribution of magma sheets relative to each others and their emplacement rate also exert a strong control on temperature distributions. When a magma body grows by accretion of sills, each sill can be intruded above the former one (over-accretion), below the former one (under-accretion), or the sills can be randomly distributed. The country rock that is the closest to the locus of intrusion reaches higher temperatures in comparison to the country rock that is insulated from new magma by former intrusions. The top thermal aureole is larger than the bottom aureole in case of over-accretion but the opposite is true in case of under-accretion. Similarly, the extent of magma contamination by crustal melts depends on the respective fertility of country rocks below and above the growing magma body and which is the closest to the level of injection. The size of thermal aureoles and the extent of crustal contamination also depend on the magma emplacement rate. In addition, emplacement rates control melting degrees. If the emplacement rate is high enough, a large part of the growing intrusive body can be a magma reservoir, but if the emplacement rate is too low, the size of any magma chamber is restricted to the size of a single magma pulse. In the latter case, the small magma chamber will be short-lived whereas the former case will lead to longer-lived magma chamber.

Lateral emplacement of granitic magma: laccolithic as opposed to cauldron subsidence in the Palaeogene Mourne granites, N. Ireland

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This contribution considers the significance of lateral magma flow based on physical emplacement models of the Palaeogene Mourne Granite Centres, NE Ireland. The implications concern the sighting and emplacement of igneous centres and the controls on ascent and emplacement. Field observations and anisotropy of magnetic susceptibility (AMS) measurements of oriented blocks from the Western Mourne granite pluton indicate the presence of a weak fabric. Visible fabrics, determined from the preferred alignment of feldspar phenocryst long axes in outcrop, trend between NNE and north. The texture of the granite shows little evidence for plastic strain suggesting that the fabric observed delineates magma flow. AMS fabrics define sub-horizontal foliations, parallel to gently dipping margins and gently plunging lineations that trend SSW-NNE and diverge northward. These data so far point to an emplacement model for the Western Mourne granite that describes a laccolith, fed laterally from the SSW. This parallels the NNE directed lateral emplacement of the adjacent Eastern Mourne granite (Stevenson *et al.* 2007, *J Geol Soc Lond*, **164**, 99-110) suggesting that these two centres share a common feeder zone outside the Mourne area to the SSE, coincident with a 50mGal peak gravity anomaly close to the coast (GSNI data). Contemporaneous mafic dykes that crop out along this stretch of coast exhibit xenoliths of mafic cumulate that, together with the gravity anomaly, suggests there may be an unexposed mafic pluton in this area. Given the genetic links between mafic and felsic magmas in this region, the coincidence of the projected Mourne granite feeder zone and the possible buried mafic centre, leads to a model in which the Mourne granites were emplaced SSW to NNE as a gently dipping sheet, up dip, from this unexposed mafic centre. This model raises the possibility that the other Palaeogene igneous centres in NE Ireland (Slieve Gullion and Carlingford) may be laterally linked in the subsurface. Significant lateral movement of magma in the upper crust means that the location of the igneous centres in the upper crust or volcanic edifice at the surface may not necessarily reflect the point at the base of the crust where the magma was generated.

Cone sheet emplacement in sub-volcanic systems: a case study from Ardnamurchan, NW Scotland

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Inclined concentric sheet intrusions (ring dykes and cone sheets) are key elements of the intrusive framework of sub-volcanic systems (central complexes). The nucleus of volcanic centres are often identified by the focus of inward dipping cone sheets based on a fundamental assumption about how the general geometry and disposition of the sheets relates to a (central) source. We aim to test the implications for magmatic plumbing (magma flow and linkage) that is generated by this model and thereby examine this fundamental assumption of sub-volcanic systems. Here we present preliminary evidence for magma flow and emplacement dynamics from the cone sheets of Ardnamurchan, NW Scotland, using anisotropy of magnetic susceptibility (AMS) measurements and structural field observations.

AMS data from over 100 oriented block samples from the Ardnamurchan cone sheets reveals magnetic lineations that are consistent with visible magma flow indicators, such as step and broken bridge axes. Flow directions vary from strike parallel to dip parallel and cannot be traced back in a simple way to a source. Field observations show host rock behaviour during cone sheet emplacement can be linked to lithology; magma fingers (ductile) occur in Palaeogene volcanic and volcanoclastic rocks, broken bridges (brittle-ductile) occur in Mesozoic sediments, and angular xenoliths (brittle) occur in Proterozoic psammites. In well exposed coastal sections, cone sheets intruding Mesozoic sediments are observed parallel to bedding, transgressing up the sedimentary sequence and may be described as transgressive sills. At Mingary Pier (NM 493 626) the transgression appears to be controlled by host rock fractures.

Given that there is little compositional variation between different cone sheets, the host rock lithology and structure needs to be considered before grouping them into separate geometric suites related to volcanic centres. Flow direction data does not support a centralised source model and in fact reveals a general NW-SE trend suggesting an alternative source.

POSTERS

InSAR Observations of Magmatic Processes in the Eastern Branch of the East African Rift

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In the early stages of continental rifting, extension takes place by normal faulting, while in mature continental rifts dyke intrusion dominates. Little is known about the nature of the transition between fault-controlled and dyke-controlled extension or about the processes in an intermediate setting. Here we present observations of the temporal and spatial evolution of surface displacements resulting from magmatic processes in the Eastern Branch - an immature section of the East African Rift.

A seismic swarm occurred in Northern Tanzania from July 14 to August 4 2007. Using InSAR images from Envisat (IS2 and IS6) and ALOS, we show that the seismic swarm was accompanied by 1) subsidence that can be attributed to ~40 cm of normal motion on a NE striking fault, 2) the intrusion of ~2.4 m wide dyke, 3) deflation of a point source magma chamber and 4) collapse of a shallow graben. The large number of available SAR images allows us to examine the sequence and time-dependent behaviour of these processes.

A systematic InSAR survey detected geodetic activity at four of the eleven central rift volcanoes in the Kenyan sector of the East African Rift. Subsidence of 2-5 cm occurred at Suswa and Menengai during 1997-2000, ~9cm of uplift at Longonot in 2004-2006 and ~21 cm of uplift at Paka during 2006-2007. The deformation is episodic, and no deformation was observed at these volcanoes during other time-periods. The best-fitting source models for each episode is inflation or deflation of a horizontal lensoid at a depth of 2-5 km. The episodic nature of the activity, its lack of correlation with seasons, and the preferred source geometry are all consistent with activity in the volatile-rich cap to a crystal-rich magma chamber beneath each of the 4 volcanoes.

Imaging magmatic intrusion into the upper and lower crust beneath the Ethiopian rift using receiver functions

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Controlled-source seismic, receiver function and gravity data have revealed strong evidence for upper and lower crustal magmatic intrusions beneath the Ethiopian rift and its north-western flank. Upper crustal magmatic intrusion beneath the northern main Ethiopian rift (NMER) axis is focussed in a ~25 km-wide zone at depths of greater than 10 km and, based upon modelled seismic velocity and density values, is interpreted to contain more than 40 % of frozen gabbroic material. The base of the crust beneath this axial magmatic zone is poorly defined, with little evidence of a Moho discontinuity, suggesting that ongoing magmatic addition obscures the transition from crust to mantle. A 6-18 km thick high V_p (>7.3 km/s) and V_p/V_s (>1.85) layer is imaged beneath the Ethiopian Plateau to the north-west of the NMER, commencing at a depth of ~30 km. This layer is most likely gradational and its velocity characteristics imply it could consist of either: i) a high proportion of solidified gabbro; or ii) varying amounts of intruded gabbro and metamorphosed original lower crust. A small proportion of partial melt may also be present. We forward and inverse model isotropic and anisotropic receiver function signals originating from the magmatic lower crustal layers to provide constraints on composition, extent, internal structure and mode of emplacement. We link these results to the two major magmatic episodes of the NMER region – the 30 Ma flood basalt event and the 11 Ma to present day rifting.

Two-Dimensional Numerical Heat Flow Modelling from Multiple Dyke Injection Events in Afar, Ethiopia.

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The mechanism of magma transport through cold lithosphere and crust, and the distance over which it travels, controls the presence and type of resultant surface volcanism as well as the rate of spreading of the crust. As a result, in the Afar province in the north east of Ethiopia the East African rift is slowly spreading via the process of dyke injection and normal faulting to form a new ocean. The region is an ideal setting to study the processes of multiple and shallow dyke injection, and how these can lead to the splitting of the crust.

In this study, numerical modelling through the finite difference method has been applied to the geological setting of an actively spreading rift, and a solution for the two-dimensional heat flow equation is computed according to the explicit method. The initial temperature profile is set up by the crustal geotherm, and a constant temperature boundary condition for the domain is assumed. We also assume that the physical and chemical properties of the crust can be simplified to be homogeneous over the intruded depth, so that the thermal diffusivity of the crust can be treated as being independent of depth and temperature. Dykes of a basaltic composition are intruded sequentially at a constant rate. Each one is instantaneously intruded into the crust at a constant temperature, and the model computes how heat is dissipated over time throughout the depth of the crust. The resultant temperature profile is used to calculate a profile of melt fraction and from this the distribution and quantities of melt within the crust are predicted.

The model is used to investigate how the size and frequency of dyke intrusions affect the distribution of melt within the East African Rift. Changes in the initial conditions such as increased temperature, altered geothermal gradient or intrusion frequency and spacing can also affect the resultant melt fraction and ultimately the presence or absence of an accumulating magma body. The results could be compared with previous tomographic and petrological studies conducted in the region providing constraints on the degree of fractionation and composition of the melt present in the crust. This thermal modelling of the crust beneath Afar develops our understanding of the nature and frequency of magma intrusions in the East African Rift System, and the conditions for the creation and evolution of the magmas that are seen at the surface.

Magma ascent by gravitational instability constrained from field observations in the San Rafael desert, Colorado Plateau, Utah

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Geological and geophysical observations of a small volume basaltic outcrop in the San Rafael subvolcanic field indicate that magma initiated the ascent from a shallow intrusion by gravitational instability (Diez et al., 2009). The domes and plugs mapped on the upper contact of the underlying sill-like intrusion are interpreted as diapiric structures that formed after the mechanical alteration of the overlying wet porous wall rocks by sudden pore fluid expansion and subsequent effective stress reduction. The density contrast, with magma of lower density, and a significant yield strength reduction leading to liquefaction and fluidisation triggered the ascent of magma by Rayleigh-Taylor type instability. These observations motivated the derivation of a multilayer linear stability model to explore the time and spatial scales involved. This model is complemented with first order sill growth calculations and other models, such as i) a pressure propagation model to address the extent of wall rock that is mechanically altered by pore fluid expansion and, ii) a cooling and crystallisation model to constrain the time scales permitted before developing a thick solid margin of magma in contact with comparatively colder wall rocks. The time scales constrained by these models are compared with those from the linear stability model to assess the physical and geological consistency of the gravitational instability mechanism invoked.

InSAR observations of the Central American Volcanic Arc between 2006-2009

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The Central American Arc presents an ideal test ground for studying active volcanism because of its high density of active volcanoes and their diversity of character. Both open and closed systems, passive and explosive degassing and a range of magma types from basic to silicic are found in a relatively small area. Only since ALOS PALSAR started providing L-band coverage of Central America in 2006 has it been feasible to conduct a large-scale InSAR survey of the region, since C-band radar is unable to penetrate dense, tropical vegetation.

We have produced all possible interferograms from ALOS data for the Central American Arc, which stretches from the Mexican border with Guatemala in the North through El Salvador and Nicaragua down to Costa Rica. There are over 70 Holocene volcanoes in this region, of which 26 are historically active. Just over 50% of all volcanoes surveyed showed no deformation, including five volcanoes that were actively erupting during the period of the survey. The remaining volcanoes were dominated by atmospheric signals that we analyse in terms of their relationship to seasonal variations in water vapour.

We present a selection of results from the Central American Survey, including observations of slope collapse related subsidence at Arenal, Costa Rica.

Resurfacing a rift: recent basaltic volcanism in Afar

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Basaltic volcanism along rift zones is responsible for forming ~65% of the Earth's surface. However, as the vast majority of this activity occurs in submarine settings the typical characteristics of rift related eruptions (frequency, duration, volume etc) and the relations between intrusive and extrusive magmatism, particularly at the scale of a single eruption, are not well known. A currently ongoing phase of magmatic rifting along a subaerial section of the Red Sea system in Afar, Ethiopia, presents an exceptional opportunity therefore to provide constraints on the volcanic component of crustal growth and to examine intrusive-extrusive relationships. Here we begin to catalogue the volcanic aspects of this ongoing event by characterising the two basaltic fissure eruptions (August 2007 and June 2009) that have occurred thus far in the Afar rifting cycle. Comparing these with the Icelandic Krafla rifting episode we provide a preliminary evaluation of the role and significance of volcanism to episodic rifting process. Both recent Afar eruptions were short period events (36-72 hours) with bulk lava volumes of $4.4 - 18 \times 10^6 \text{ m}^3$, erupted from a fissure system 4 - 6.5 km in length. Supplementing field observations with data from a range of satellite borne instrumentation (i.e., MODIS, OMI, ASTER, ALI) was critical to both the identification and subsequent analysis of these eruptions. Compositionally, both erupted basalts are very similar and lie towards the evolved end of the regional trend. Combining data from these eruptions with geophysical models of the intrusive activity in Afar we assess the partitioning of magma between intrusion and volcanism for the Afar rifting phase thus far. By comparing this to data from the Krafla rifting cycle we examine the likely evolution of intrusive - extrusive magma relations as the Afar activity progresses. The current activity in Afar (since Sept. 2005) has an intrusive to extrusive magma volume ratio of ~180:1. This is similar to the equivalent stage of the Krafla cycle, which had a final volume ratio of 3:1. Comparing the temporal trends of intrusive and extrusive magmatism and the physical features of volcanism (fissure length, duration, volume) between Krafla and Afar we expect that, should the Afar activity continue, the volcanic output will increase significantly and will be accommodated by eruptions of increasingly large size, rather than by more frequent but small magnitude events.

Crystal sedimentation: analogue and numerical modelling.

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A series of crystal settling experiments in a system composed of natural two pyroxene - gabbro is conducted in order to understand the relations between cumulus texture and the evolution of chemical composition at grains boundaries during the crystals-melt settling in a magma chamber. The settling experiments were conducted in a centrifuging furnace at 1235°C under atmospheric pressure during 6 hours and with an acceleration range between 1g to 1000g of partially molten gabbro samples with the grain size 100µm (Dorfman, Bagdassarov, Dingwell). Crystals during the centrifuging process have been segregated according to their buoyancy: plagioclase crystals floated to the top and magnetite crystals sank to the bottom of container.

The chemical evolution of melt, vertical and horizontal distribution of crystals and melt in the experiments at 100g and 200g is similar. The segregation realized in experiments at 500g and 1000g revealed much worse separation of heavy and light crystals and the melt phase. The vertical evolution of the major and trace elements in the melt phase shows that close to the cumulate layer (between 0 to 2 mm from the bottom) the variation of these elements depends on the distance from the container wall, and becomes constant in the interior of sample. The horizontal evolution shows some variations which appear close to the walls of the capsule and which are due to the wall effect during the centrifuging runs.

The numerical modelling of the crystal sedimentation process has been done in order to describe the compaction evolution with time. Comparing the numerical and laboratory modelling of crystal sedimentation, the numerical results agree quite well with the stratification of the compacted crystal layers in the centrifuge runs. Finally the calibrated numerical model can predict the evolution of the compaction in a time scale of several years. Applied to the centrifuge experiments, the numerical modelling shows a stable density stratification of compacted crystals in the time scale from 1 to 10 years at 1 g.

The chemical evolution takes place only in the experiment at 1000g (which is equivalent to the first 8 months of sedimentation in natural conditions) and it will not progress, if the crystal-melt separation will continue further.

The centrifuge experiments and numerical modelling demonstrate that the correlation between magma chamber cumulate textures and the evolution of chemical composition at grain boundaries of cumulus crystals occur during the first stage of the compaction, and ceased out when the maximum compaction is reached.

Emplacement of crystal-rich magmas: insights from the Snap Lake kimberlite intrusion (NW Territories, Canada)

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The Cambrian Snap Lake kimberlite intrusion (Northwest Territories, Canada) is a complex segmented diamond-bearing ore-body. Detailed geological investigations suggest that the intrusion is a multi-phase body with at least four different magmatic lithofacies. In particular, olivine-rich (phlogopite-poor) and olivine-poor (phlogopite-rich) varieties of hypabyssal kimberlite have been identified. Key observations are that olivine-rich lithofacies (ORK) has a strong tendency to be located where the intrusion is thickest and that there is a good correlation between intrusion thickness, olivine crystal size and crystal content. Accordingly the olivine-poor lithofacies (OPK) tends to be most abundant where the intrusion is thinnest. Complimentary studies demonstrate that the lithofacies are geochemically distinct, and are characterised by different diamond abundances and size distributions. Our data and observations suggest that the ORK and OPK represent different magma phases that have experienced different processes during transport and emplacement. Heterogeneities in the kimberlite lithofacies are attributed to variations in intrusion thickness and structural complexities. Auto-xenoliths of ORK within the OPK suggest that the magmas are closely related in time and have clearly exploited the same fracture system during intrusion, resulting in various degrees of intermingling. The geometry and distribution of lithofacies points to magmatic cointrusion, and flow differentiation driven by fundamental rheological differences between the ORK and OPK phases. The presence of such low viscosity, crystal-poor magmas may explain how extremely crystal-rich kimberlite magmas (> 60 vol.%) are able to reach the surface and erupt in kimberlite diatremes. We envisage that the low viscosity OPK magma acted as a lubricant for the highly viscous ORK magma; such rheological segregation is a common feature in other magmatic systems. The Snap Lake intrusion provides important insights into the architecture and dynamics of magmatic plumbing systems at high crustal levels, particularly in settings where sheet intrusions feed into point-source diatreme-vent systems. The study also has implications for predicting diamond distributions at other kimberlite intrusions where different magmatic lithofacies can be identified.

Crustal structure and melt supply variability in the presence of oceanic core complexes: the Mid-Atlantic Ridge at 13°N

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Between the Fifteen-Twenty and Marathon fracture zones, the Mid-Atlantic Ridge displays two very distinct styles of seafloor morphology. The segment centre and area bounding the Marathon FZ are typical of lineated abyssal hill terrain which formed at relatively robust levels of magma supply to the ridge axis. Adjacent to these areas are large swathes of irregular seafloor which are believed to have formed when melt supply fell below some critical value, necessitating an increased component of tectonic extension on long-lived (~1 Ma) detachment faults, forming oceanic core complexes (OCCs).

Here, we present the results of a combined deep-towed sidescan sonar and magnetic survey with shipboard gravity and extensive seafloor sampling across active OCCs in the region between 13°N and 14°N. Sidescan sonar data have been mapped to reveal variability in the width of the neo-volcanic zone (NVZ), which is entirely absent opposite active OCC formation. Furthermore, the youngest volcanic material (identified from sidescan and magnetic data) exists in close proximity to the axial valley-wall faults, suggesting these faults may capture upwelling melt at depth and transport it away from the ridge axis. In some instances there is a mismatch between the location of the NVZ and central magnetic anomaly high, which can be explained by temporal variations in the locus of melt emplacement. Geomagnetic polarity transition widths show this zone of emplacement to vary along-axis between 2 and 5 km wide. Magnetisation data have also been used to confirm that OCC formation is synchronous with asymmetric plate separation (as has been observed across other OCCs). The magnetic pattern is generally poorly developed as a result of reduced melt supply and increased tectonic disruption of source material.

The gravitational residual mantle Bouguer anomaly (RMBA) indicates that OCCs are associated with high density (~2900 kg.m⁻³) material at shallow depth. The overall RMBA structure is remarkably similar to that which is observed at Kane Massif and Fuji Dome. In addition, circular lows are observed within the RMBA along the ridge axis, suggesting discrete centres of melting. On the flanks conjugate to active OCCs, RMBA highs are observed which show that significant reductions in melt emplacement are recorded on both plates.

Melt movement along a dyke at Upptyppingar, north-east Iceland

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In summer 2007, the Upptyppingar region of north-east Iceland exhibited intense periods of seismic activity in the middle of a 12-month long episode of over 6000 microearthquakes interpreted as a dyke intrusion in the mid-crust [Jakobsdóttir et al., *Stud. Geophys. Geod.*, **52**, 513–528, 2008]. The events occurred between 14–22 km depth, mainly in bursts as swarms of approximately 100 events. Here we focus on the precise locations of events within several swarms during July 2007 that indicate the progressive movement of melt along the dyke. Hypocentral locations of individual events within swarms migrate over distances of typically 1–2 km, over time periods of several hours.

Data was collected by a network of twenty 3-component seismometers deployed by Cambridge University, supplemented by a further six permanent seismometers deployed and operated by the Icelandic Meteorological Office. Earthquake hypocentral locations were refined by a combination of precision time-picking and double-difference earthquake location methods. This enables us to constrain whether the inferred dyke intrusion remained confined to a narrow plane or caused widespread (~2 km) deformation adjacent to the intrusion. This has implications for the morphology and dynamics of melt intrusions at depth in the crust.

Probing the interior of an active volcano: 3D seismic tomography at Montserrat

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The island of Montserrat, in the Lesser Antilles, has been the subject of a seismic tomography experiment with the main aim of studying the magmatic system of the active Soufriere Hills Volcano (SHV). A two-dimensional inversion of a subset of the data collected has provided a first image of the structure of the crust beneath Montserrat. It has revealed the presence of high-velocity intrusive complexes forming the cores of the main volcanic edifices, but was unable to confirm or rule out the presence of a magma chamber. We present the results of the three-dimensional travel-time inversion of the full dataset, including wide-angle refractions and reflections and multi-channel reflections. The ray coverage of the 3D inversion is denser and allows a more detailed resolution of the subsurface. The presence of high-velocity cores beneath the three volcanic centres is confirmed and their extent is now better constrained. The high-velocity regions extend from the surface to a depth of at least 8 km beneath the two extinct volcanic centres in the north, but only to a depth of about 5 km beneath SHV. A low velocity zone is observed beneath SHV at depth between 6 and 10 km, and is interpreted to correspond to the presence of partial melt, i.e. to a magma chamber possibly representing the source of the current eruption. The overlying high velocity region is interpreted to correspond to a system of solidified intrusions. Our results are in agreement with petrological and geodetic constraints and will provide new insights into the magmatic processes at Montserrat and other island arc volcanoes.

The emplacement of saucer-shaped sills: the role of host rock fluidisation and the formation of magma fingers

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The Golden Valley Sill, South Africa, like many similar structures imaged on 3D seismic, is saucer-shaped with a transgressive rim. This rim exhibits 10's – 100's m wide fingers radiating from a central axis and forming the outer dipping rim. We have compared the thermal stability of magma intrusion along fingers with intrusion as sheets, and investigated the mechanics of finger formation. Localised fluidization of the host rock is observed close to the margins where the fingers occur, suggesting a causal link between fluidization of the country rocks and finger formation. We relate the large scale formation of fingers to host rock fluidization caused by flash-boiling of pore fluids following the tensional failure of the roof of the inner dish at a maximum radius. Once fluidization has occurred by this method, the mechanical heterogeneity controlling the propagation of a concordant sill is broken and the intrusion can transgress. This work emphasises the importance of understanding the coupled nature of magma intrusion on host rock lithology, and in particular the ability of host rock lithology to behave in a brittle or non-brittle manner during magma intrusion. The observation of numerous saucer-shaped sills ~ 1-3 km beneath the paleosurface on 3D seismic in the North Atlantic Igneous Province indicates that these processes are widespread and likely of fundamental importance in the emplacement of magma into sedimentary basins.

Imaging the magma chamber under Krafla, NE Iceland.

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The Krafla volcanic system within the Northern Volcanic Zone (NVZ), north-east Iceland, was the centre of a rifting episode in 1975–1989 that activated an approximately 100 km long segment of the divergent plate boundary. This volcanic and tectonic episode was characterised by inflation/deflation cycles regulated by magma pressure within a shallow crustal magma chamber beneath the Krafla caldera and by tectonic stress at the plate boundary. Magma accumulated in a shallow magma chamber during inflation periods and was intruded into the transecting fissure swarm or extruded in basaltic fissure eruptions during brief deflation events. The last deflation event took place in September 1984 during which an eruption occurred along a 9 km-long fissure extending north from the centre of the caldera. In June 2009, the Iceland Deep Drilling Project (IDDP) well at Krafla encountered rhyolitic melt at a depth of 2104m under the Krafla caldera.

In August 2009, we deployed a network of 23 Gralp 6TD broadband three-component seismometers in and around the Krafla caldera to monitor local seismicity, supplemented by six borehole seismometer stations. Local and regional events will be used to investigate the seismic structure and map the distribution of melt beneath Krafla, with the IDDP drilling results allowing us to 'ground-truth' our results. We anticipate that investigating seismic anisotropy will also provide information on fracture networks in the area.

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