EUG XI

Symposium VPP5

Rates of Melting and Melt Extraction in the Mantle and Continental Crust

Convenors

Nick Petford
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Tuesday AM Session

VPP5 : TUam01 : G4
Melt Generation and Segregation in the Lower Crust of the Alboran Domain: The Evidence from Xenoliths in the Neogene Volcanics

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Xenoliths enclosed in the Crd-Grt-bearing lavas of the Neogene Volcanic Province of SE Spain retain evidence of partial melting and relevant information on the mechanisms and P-T conditions of crustal anatexis, preserved by rapid exhumation and cooling during eruption. The main type of xenoliths has a marked restitic composition (low SiO_2, high Al_2O_3 and FeO), is made of Bt-Pl-Sil-Grt-graphite (±Ilm, Crd, Her, Qtz), and contains abundant glass of peraluminous felsic rhyolitic composition (leucogranite). Glass occurs as melt inclusions, thin films at grain-boundaries, foliation-parallel layers, and pockets in strain shadows. Mass balance calculations among glasses, xenoliths and probable metapelitic protoliths from the basement of the Betic Cordillera indicate degrees of melting in the range of 35-60 wt.%. Microstructures show that anatexis was accompanied by foliation development, implying that the xenoliths represent portions of a deforming crystalline basement, partially molten before being enclosed in the dacite. Deformation during foliation development assisted melt extraction, and melt escaped mainly by flow along foliation planes, at least on lengthscales of tens of centimetres. Crustal anatexis occurred at 5-7 kbar, 850±50ºC, and was followed by a further melting stage at T>900ºC, as indicated by textures of incipient, incongruent melting of biotite in both Qtz-present and Qtz-free assemblages. The main stage of anatexis took place under fluid-present conditions, whereas further melting of biotite to hercynite or orthopyroxene was probably fluid-absent and took place when the xenoliths were already incorporated into the host lava. Primary glass inclusions in all minerals indicate that the whole restite assemblage crystallised in the presence of melt, which is only possible by a disequilibrium melting mechanism due to very rapid heating rates. Calculated pressures approximate the actual Moho depth in the region (ca. 21 km), and suggest that partial melting of the xenoliths occurred close to the crust-mantle boundary. The very high temperatures, the absence of HP relicts, and the syn-anatectic pseudomorphs of sillimanite after andalusite observed at Mazarr-n, are difficult to reconcile with a model of decompression melting, and rather suggest regional scale (isobaric) heating related to emplacement at shallow depth of asthenospheric mantle and/or mantle derived magmas. These xenoliths are an unique example of anatectic crustal fragments not affected by recrystallisation during cooling. They allow 'in situ' characterisation of HT processes and melting mechanisms in their various aspects, and constitute an ideal link between experimental and field studies of migmatite formation.

VPP5 : TUam02 : G4
Some Thermal Constraints on Crustal Assimilation by Hydrous Mantle Magmas in Calc-Alkaline Batholiths

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Closed-system thermal models constrain the maximum extent of assimilation of stoped crustal rocks by fractionating hydrous mantle magmas. Fractional crystallisation causes the melt to evolve from picrite - gabbro - tonalite/granodiorite - granite and is accompanied by increasing water content in the progressively smaller melt volumes. The relative masses of the evolving melt are calculated based on chemical modelling the differentiation of calc-alkaline rock suites and the corresponding temperatures are based on experimental data of liquidus temperatures. The influence of the melt fraction in the crustal rocks (assimilate) is tested for several fertilities based on approximental data. The AFC-process has been modelled stepwise by mixing the heated assimilate with the slightly supercooled mantle melt; crystallisation then occurs until the hybrid melt reaches the liquidus composition. The heat released during the cooling of the fractionating mantle magma depends on the shape of the liquidus curve (i.e. water content of the magma). The most limiting parameters for assimilation are the initial temperature of the mantle magma, the ambient country rock temperatures and their fertility. The rate-limiting steps for natural assimilation are governed by time-dependent cooling of mantle magma and heating of xenoliths.

VPP5 : TUam03 : G4
Crustal Melt Segregation: The Deformation Predicament

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We present a numerical model of melt segregation under variable deformation types (pure and/or simple shear) and rates. The model, which is Lagrangian in its description, requires an initial melt content and two thresholds that allow melt connection and melt escape. Deformation is a necessary melt-segregating factor, with pure shear being more efficient than simple shear. A coefficient of melt extraction, defined as the ratio of escaping melt to the initial melt content, is proposed. Melt segregation shows a transient state before reaching a stationary state of constant extraction. The coefficient of melt extraction varies linearly with parameters such as initial melt percentage, thresholds or deformation, which are tested separately. During each single run, the coefficient of melt extraction goes through a transient state characterised by an exponential spike whose amplitude is also a function of the initial conditions (initial melt content, threshold, deformation rate). Because melt extraction is discontinuous and irregular with time, we suggest that detailed chemistry does not properly describe the melt evolution in migmatites. Because of its irregular values with spikes depending on initial conditions, we suggest that the coefficient of melt extraction is analogue with the friction coefficient defined in stick-slip motion experiments. However, the departures in melt extraction volume from average values are damped when initial conditions are changed continuously, reflecting a memory effect. We suggest that melt extraction relates to a pinning - depinning process, which also controls friction.

VPP5 : TUam04 : G4
An Experimental Approach for Quantitive Melt Segregation

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Field evidence from natural partial molten systems like migmatites indicates a close relationship between melt segregation and deformation. To study this phenomena we conducted experiments with rock analogues consisting of mixtures of $LiNO_3$ and KNO_3 as a melting component and crushed baryte featuring as a non-melting framework. Four sets of experiments with strain rates from 10^{-5} to $5x10^{-4}$ at melt contents between 4.4%, 8.8%, 17.7% and 26.6% have been performed. Hot isostatically pressed cylindrical samples of 35 mm diameter and approx. 60 mm height have been sintered and uniaxially deformed at 133.5°C to strains of 30-40% with instantaneous record of strength. With this setup we enable an efficient voluminous spatial melt segregation.

From stress-strain relationship and textural indications we infer granular flow as major deformation process in our viscoelastic samples. Bulk strength decreases with lower strain rate and higher melt content, but shows no rapid decrease at critical melt contents as inferred from literature (Arzi, 1978). Especially at high melt contents some experiments showed pseudo-brittle deformation which we interpret as high melt pore pressures leading to rapid segregation in shear zones with contemporary decline of bulk strength.

The development of texture and melt distribution is quantified by image analysis of micrographs made from the polished section of deformed samples. Melt distribution is pervasive at high strain rates and develops distinct structures with decreasing strain rate and higher melt content. In samples deformed at very low strain rates and high melt content segregation is most efficient with enrichment in ductile shear zones up to four times the initial volume. Higher melt content leads to expulsion of melt.

With this model we have shown that deformation is an efficient way to segregate melt from isolated interstials to interconnected structures by producing new conduits.

Arzi, AA, *Tectonophysics*, **44**, 173-184, (1978).

VPP5 : TUam05 : G4
The Transition from Pervasive to Segregated Melt Flow in Ductile Rock

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No convincing explanation has been offered for the transition from pervasive to segregated melt transport in ductile rocks. In the simplistic extreme, pervasive processes exploit existing porosity, whereas segregated melt transport is a mechanism in which the melt moves through a void space that propagates or grows dynamically. In the case of dikes, it is recognized that although the latter mechanism may be realized as self-propagating melt-filled cracks, the critical crack length is too long to permit the cracks to initiate spontaneously from a matrix in which melt is pervasively distributed. Porosity waves are an intermediate mechanism capable of bridging the extremes between percolative and segregated transport, but the popularity of the porosity wave model has declined because of the perception that pervasive melt transport is too inefficient to be significant on the time and spatial scales relevant for melt segregation and transport. This failing in large part can be attributed to oversimplification of the rheological models used to evaluate the relevance of the porosity wave mechanism. Realistic rheological models reveal a spectrum of compaction generated flow instabilities, manifest as both sill- and dike-like self-propagating high-porosity structures, that is much broader than hitherto anticipated. We develop an elementary mathematical treatment of the equations governing percolative melt transport in a porous compacting media to establish whether such structures are themselves likely to be the dominant mechanism for melt transport or if they may be the precursors of segregated melt transport and catchment. The analysis shows that the flow instabilities are capable of growing indefinitely so that the melt can be completely segregated from the rock matrix. The chief factor controlling whether segregation occurs is the magnitude of the melt source, if this source is treated as an excess flux, order of magnitude flux variations are more than adequate to cause melt segregation. Our solutions define a continuum of the hydraulic regimes recognized in asthenospheric rocks. In order of increasing flux these are (i) periodic oscillations about the background porosity; (ii) dike-like solitary porosity waves; (iii) fluidized channels; and (iv) fully segregated melt flow.

VPP5 : TUam08 : G4
Ultra-Fast Source to Surface Movement of Magmas at Island Arcs from Global $^{226}Ra/^{230}Th$ Systematics

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U-series disequilibria provide important constraints on the physical processes of element transfer within the Earth. We show that lavas from island arcs around the world have near ubiquitous excesses of ^{226}Ra and ^{238}U over ^{230}Th which were not produced during partial melting. The largest ^{226}Ra-excesses are in the most primitive lavas suggesting a mantle origin. ($^{226}Ra/^{230}Th$) decreases with increasing differentiation which must take ~ 8,000 years if it is controlled by crystal fractionation and even faster where mixing is important. Globally, ($^{226}Ra/^{230}Th$) is positively correlated with Ba/Th suggesting the ^{226}Ra-excesses reflect addition by fluids from the subducting plate within the last few 100's years. Assuming that these fluids were added to the base of the melting column to initiate melting, a combination of moderate matrix upwelling and low porosity followed by rapid melt segregation and transport is required to preserve the fluid-induced ^{238}U- and ^{226}Ra-excesses yet simultaneously generate ^{231}Pa-excesses by melting and melt transport processes. Thus, the total magma transit time from source to surface at island arcs is less than 8000 years demanding rapid melt segregation and channelled magma flow at rates probably exceeding 100 metres per year.

VPP5 : TUam09 : G4
The Chemical Signature of Dunite Melt Channels- Implications for Melt Transport in the Mantle

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The migration of melt from its source under ocean ridges to the oceanic crust is thought to be traced by dunite bodies. The dunites may either mark the wall rocks to open conduits or the porous flow channels themselves. In principle, porous flow channels should be marked by a long time of formation, a diffuse, if any, internal chemical variation and a high melt flux. Dunites formed as wall rocks adjacent to open conduits should form rapidly, be symmetrically zoned at least for compatible elements, and record only a low melt flux. In terms of time, a theoretical evaluation (Suhr, 1999) suggests that m-scale dunites take at least hundreds, if not thousands of years to form, thus favouring a porous flow regime. In terms of the chemical variation, dunites with both symmetrical internal zonation (rare) and with very subtle or non-existent variation (more common) have been found. Concerning the melt flux in the dunite, NiO in olivine should be useful. Homogeneously low value ranging from 0.33 to 0.35 wt.% NiO in olivine characterise the weakly or irregular zoned bodies. These values are lower than the likely mantle equilibrium value of 0.36 to 0.38%. In general, low NiO values can be explained by the additional formation of olivine at the expense of orthopyroxene during the reaction harzburgite ⇒ dunite along the melt channel. However, for a high melt flux (melt:rock ratio ~10), we expect that the NiO values be reset to equilibrium mantle values. Melt:rock ratios for porous flow dunites under an ocean ridge are expected to be high, between 8 and 200 (Kelemen et al., 1997). Since full equilibration with mantle olivine values appears not to be the case, a relatively low melt flux through the channel is indicated. This is corroborated by the occurrence of relict orthopyroxene grains within mantle dunites. The current study thus neither clearly favours open conduits nor reactive porous flow channels. It may, however, indicate, that melt transport switches between both regimes in time and space. Which of these modes is more relevant remains unresolved.

Suhr, G, *J. Petrol*, **40**, 575-599, (1999).
Kelemen, Pet al, *Phil. Trans. R. Soc. Lond. A*, **355**, 283-318, (1997).

VPP5 : TUam10 : G4
Melt Extraction Rates and (Dis)Equilibrium Melting in Migmatites

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Melt extraction rates can be inferred mainly from (i) geochronological constraints; (ii) physical models for melt escape and melt percolation; and (iii) the degree of (dis)equilibrium reached between melt and source rocks. The first method is restricted by the time resolution of isotopic techniques (commonly U-Pb) and therefore generally yields time scales >1 Ma. Results from the second, more theoretical approach depend heavily on assumed melt viscosity, percolation path tortuosity and type of flow, but suggest rapid melt segregation (< 100 years: Brown et al., 1995). The third method yields similarly rapid segregation (Sawyer, 1991), but its reliability depends on the knowledge of element diffusion rates in minerals and melt, and on the correct recognition of (dis)equilibrium. In this talk, the evidence for disequilibrium melting in migmatites is questioned on the basis of (i) textural arguments and numerical modelling; (ii) the mathematical treatment of trace element modelling.

Disequilibrium melting in migmatites is generally inferred from observed trace element distributions in migmatites, coupled with experimental data on trace element solubilities. For example, relative enrichment of trace elements in melanosome (‘restite’) and their relative depletion in leucosome (‘crystallized melt’) have been used as arguments for disequilibrium melting (Whitney & Irving, 1994) and rapid (< 100 years) melt segregation (Sawyer, 1991).

These and other datasets allow a different interpretation, based on a four-stage migmatization model (Kriegsman, 2001): (i) partial melting and small-scale segregation; (ii) partial melt extraction; (iii) partial back reaction between in situ crystallizing melt and restite; (iv) crystallization of remaining melt at the solidus, releasing volatiles. In this model, incompatible elements are enriched in the melt during partial melting. When segregation is incomplete, subsequent back reaction during cooling leads to mass transfer and element partitioning: trace elements are concentrated in accessory phases in melanosome and, by implication, depleted in leucosome. This model is supported by textural observations, zoning of accessory phases and numerical modelling.

Mathematical models designed for the prediction of trace element distribution between source rocks and fully segregated melt are commonly applied to migmatites. However, it is shown here that trace element models for three migmatization scenarios (1. subsolidus migmatization; 2. disequilibrium melting; 3. equilibrium melting followed by restite-melt back reaction) are mathematically equivalent. Hence, evidence reported to support disequilibrium melting (Sawyer, 1991) or subsolidus migmatization (Chavagnac et al., 1999) can be reinterpreted in terms of equilibrium melting followed by retrograde reequilibration during in situ melt crystallization (Fourcade et al., 1992). This model implies much longer melt residence times and lower cooling rates.

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Chavagnac V, Naegler TF & Kramers JD, *Lithos*, **46**, 275-298, (1999).
Fourcade S, Martin H, De Bremond d’Ars J, *Lithos*, **28**, 43-53, (1992).
Kriegsman LM, *Lithos*, **56**, (2001).
Sawyer EW, *J. Petrol*, **32**, 701-738, (1991).
Whitney DL, Irving AJ, *Lithos*, **32**, 173-192, (1994).

VPP5 : TUam11 : G4
Contrasted Tectonic and Magmatic Rates and Transport of Granitic Magma

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The structural, petrographic and isotopic information recorded during magma transport through the crust requires consideration of the time duration. The strain pattern within a pluton, for example, will not have the same meaning if the time of crystallization is 10 ky, 1 My, or significantly longer. A short recording time provides information on instantaneous strain, whereas a longer time of emplacement will form fabrics which should be interpreted in terms of finite strain, which will act to smooth the trend. Our recent studies indicate that the duration of magma transport (ascent + emplacement) for similar plutons located in a given geodynamic environment could vary from one to three orders of magnitude (from 1 ky to 1 My for example). In faster plutons, which are characterized by active transport mechanisms, internal magma pressure controls the transport and, if rapidly frozen, the fabrics record an infinitesimal strain. The latter occurs because the process is so rapid that tectonic strain has no time to be recorded. Thus, actively transported magma may appear to be anorogenic although they are transported within an actively deformed crust. In the slowest plutons, which seems to be more characterized by tectonically-controlled passive transport, the fabric record a finite strain. Many plutons are probably the result of a combination of these two end-members processes, which vary spatially and temporally. Our analysis suggests that if regional deformation is considered as steady-state for the considered time-scale, then: 1) Magma pressure is the critical parameter which governs the emplacement mechanism; and 2) A cyclically build-up of melt pressure, due to variations of the magma production rate at the source, will control the history of ascent and emplacement.

VPP5 : TUam12 : G4
U-Th-Pa Systematics and Melting Processes in the Azores Region

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Magmas generated beneath ocean islands are generally thought to be derived from enriched portions of the mantle. These could either be enriched (‘metasomatized’) peridotite or more mafic rocks such as pyroxenites. The distinction between the two types of source should be reflected in the trace element fractionations that are found in ocean island basalts (OIB). This should also be true for U-series disequilibria measured in lavas as these tracers are sensitive to the mineralogy of the mantle source. It has been advocated that enriched sources should be characterized by high Pa and Th excesses relative to their parent nuclide. If the MORB lavas are derived from mixing of a depleted N-MORB source and an enriched source then they should plot on a mixing line between these two endmembers in a ($^{231}Pa/^{235}U$) versus ($^{230}Th/^{238}U$) diagram. If, on the other end, the melting process (temperature and pressure of melting column) also controls the fractionation in the U-decay series, then more complex relationships are expected.

In this study, we have analyzed lavas from the Azores islands and the nearby mid-Atlantic ridge in an attempt to assess the relative importance of source variations versus melting processes. The lavas were analyzed for ^{230}Th-^{238}U (Turner et al. 1997, Bourdon et al. 1996) and ^{231}Pa-^{235}U disequilibria. Our preliminary results for the Azores islands show that the ^{231}Pa excess (20-70%) are at the low end of the trend found for other OIB (Pickett et al. (1997) and Bourdon et al. 1998) and fall on a positive correlation in a $^{231}Pa/^{235}U$ versus $^{230}Th/^{238}U$ diagram. In contrast, preliminary results for lavas from the nearby Mid-Atlantic ridge are characterized by higher (231Pa/ ^{235}U) activity ratios for similar ($^{230}Th/^{238}U$) ratios.

These data do not indicate a simple mixing trend between an N-MORB and an enriched component in a $^{231}Pa/^{235}U$ versus $^{230}Th/^{238}U$ diagram . Clearly, the dynamics of melting must have played a role in generating larger ^{231}Pa excesses beneath the Mid-Atlantic ridge. This study will allow us a direct comparison of melting processes for MORB and OIB and should provide information about the role of the lithosphere during melt migration. In particular, the significant ^{231}Pa-^{235}U for the lavas on the Azores islands indicate relatively rapid transport through the lithosphere.

Turner et al, *Chem. Geol*, **139**, 145-164, (1997).
Bourdon et al, *Earth Planet. Sci. Lett*, **142**, 175-190, (1996).
Pickett et al, *Earth Planet. Sci. Lett*, **148**, 259-271, (1997).
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VPP5 : TUam13 : G4
Melt Migration in a Deforming Mantle: The Role of Non-Dilatent ‘Vug-Wave’ Propagation

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We investigate a simple physical model for melt migration through a deforming mantle. Previous studies have mostly concentrated on melt migration through a static mantle, focussing on the role of melt buoyancy in driving tensile crack propagation. However, mantle deformation can provide a significant driving force for melt migration if the propagation of melt-filled ‘dislocation’ significantly reduces the local strain-energy of the deforming mantle. The driving energy release favoring the propagation of such a melt-filled ‘vug-wave’ are the strain energy reduction within the surrounding deforming mantle and the gravitational energy release associated with buoyant melt ascent. Propogation-resisting energy ‘sinks’ include the strain-energy associated with crack growth and the viscous dissipation from migrating melt. These dynamics are initially being explored in a particularly simple form: their 2-D non-dilatent (or ‘shear-crack’) limit. To analyze this we couple a 2-D dislocation-discontinuity boundary element method for crack-like propagation of a vug-wave to a Poiseuille flow description of melt transport within the moving vug-wave. The (C-$L^{0.5}$) dependence of regional strain-energy reduction favors the formation of long, thin cracks while viscous dissipation within the crack ($speed^2$xMVx length/width) favors shorter squatter ones. An intriguing initial aspect of this work is that the resulting mantle average viscosity will be highly anisotropic and extremely weak in shear-deformation parallel to the direction of melt propagation. This mechanism for migration will also tend to focus melt along the planes of maximum shear, which point towards a spreading ridge axis and towards the center of a symmetrically upwelling plume.

VPP5 : TUam14 : G4
Consequences of Diffuse and Focused Porous Melt Transport on U-Series Disequilibria in MORB

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Magmas erupted at mid-ocean ridges (MORB) are not in major or trace-element equilibrium with abyssal peridotites, indicating that at least during the final stages of ascent to the surface, there is little interaction of melt with the surrounding mantle and that melt must somehow organise into channels that chemically isolate it from the surrounding matrix. There have been several mechanisms proposed for the formation of these channels, but there is debate as to whether melt is efficiently extracted and transported through unreactive channels on very short time scales <~1600 yrs, or whether there is a significant component of slower, reactive transport via porous flow that occurs on time scales of several thousand years. A key observation at the centre of this debate is from uranium-series disequilbria observed in MORB. Excess ^{226}Ra in MORB indicates that melt is transported from the melting region on time scales less than ~1600 years. But ^{226}Ra excess can be generated both at the bottom of the melt column, during the onset of melting, or at shallow levels if melt transport occurs via porous, equilibrium flow. Determining the depth at which ^{226}Ra is generated is critical to interpreting the rate and mode of upward migration of magma. A recent compilation of high quality U-series data suggests that ^{226}Ra excess is generated independently of ^{230}Th excess and that the negatively correlated array of U-series data is a result of mixing of melts that have travelled either through reactive, low-porosity pathways, or unreactive, high-porosity pathways. We present the results of calculations of the effect of porous melt migration on U-series disequilibria where high-porosity, unreactive porous channels can form in a background, low-porosity zone that is undergoing melting. The results show that the low-porosity region is quickly depleted of incompatible elements as melt is transferred to the high-porosity channels, in which ^{226}Ra excesses decay on timescales that are short compared to the time for melt to reach the top of the melting column. ^{226}Ra excess maintained in the low-porosity region at shallow levels has negligably small concentrations and cannot be the source of ^{226}Ra excesses observed in MORB. However, reaction between enriched magmas from deep in the melting column with depleted peridotite near the top can cause ^{226}Ra excess with comparatively high concentrations. Mixing of deep melts which avoid this shallow reaction process with those that undergo shallow reaction in various proportions produces a negative correlation of ^{226}Ra and ^{230}Th excess with the slope and magnitude observed in MORB.

Tuesday PO Session

VPP5 : TUpo01 : PO
The Time Factor of Magmatic Melt Crystallization in Conditions of Intrusion Emplacement

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A transition of a substance from liquid to solid is accompanied by a considerable heat release on the boundaries between different phases. The calculation have shown that the quantity of latent heat during the crystallization of pyroxene and olivine makes up more than a third of heat contents within the range from melt temperature to standard condition (for plagioclase, this value is about two time lower). The quantity of heat liberation from the crystallization system of a magmatic melt (in every moment of time) is determined by the correlation of crystallization velocity and the rate of heat removal into the rock that hosts the liquid phase. The space-time dependence of heat effects in the studied process is manifested in slowing-down, break-off or increase of the crystallization velocity of a magmatic melt. As soon as the phase change from liquid to solid is completed, the heat release from the formed intrusive massif will be determined only by the rate of heat dissipation into the environment through the rocks surrounding the intrusion. For description the temperature (time) dependence of crystallization process of magmatic melt the equation was reception, as a exponential function. The coefficients of this equation to take account of heat release and heat removal into the rock. Crystallization processes of a magmatic melt are of interest in the context of the fact that the nature and conditions of extremely large quantities of released heat and the associated fractionation of liquid phase components, were crucial factor in the formation of such layered intrusions as Bushveld, Stillwater and other complexes.

VPP5 : TUpo02 : PO
Melt and Fluid Inclusions Study on Quartz Xenoliths from the Aeolian Islands Arc (Southern Italy): Evidence for Crustal Contamination

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Silicate-melt and CO_2 fluid inclusions have been discovered inclusions in quartz-rich xenoliths hosted in early stages basaltic lavas and late stage rhyolites from several volcanic centres on the islands of Vulcano, Salina, Filicudi and Alicudi. Study xenoliths consist mostly of rounded to polygonal quartz grains, often surrounded by a crystobalite overgrowth with glass films. Silicate-melt inclusions have irregular to negative-crystal shape, with sizes ranging from <3 to 50 µm. No daughter minerals have been found inside the inclusions. Homogenisation temperatures of the trapped melt ranges from 980 to 1120°C with a peak at 1090°C.

Early pure CO_2 fluid inclusions, coexisting with silicate-melt inclusions were studied at Vulcano Island and show densities ranging between 0.89 and 0.52 g/cm^3. This indicates that trapping of silicate melt occurred at pressures from 3.3 kbar (13 km) to 5.6 kbar (21 km) corresponding to intermediate-lower crust.

Quenched melt inclusions were analysed through EMP and SIMS techniques. Major elements chemistry is quite homogeneous in all investigated Islands and is consistent with the composition of a HK rhyolite (SiO_2 = 69 - 84 wt%; K_2O = 2.4 - 6.2 wt%). Ca-Fe-Mg correlate differently with Al in the different Islands and show positive correlations at Alicudi, Filicudi and Salina, while negative correlations are present at the Vulcano Island. Inclusions have high Cl (< 0.8%) and F (< 0.3%) contents. Trace elements SIMS analyses of selected inclusions from all the studied islands revealed the occurrence of different patterns of incompatible elements. In particular, various degree of enrichment in REE and in HFSE, are observed in the analysed inclusions. These data are consistent with the occurrence of several melting events, in presence of free CO_2 fluids, affecting the lower metamorphic basement with the progressive extraction of silicic melt trapped as inclusions into the restitic quartz grains forming the sampled xenoliths. Multi-stage melting mainly of the quartz feldspate and mica components of these crustal rocks caused the generation of high-K rhyolitic melts and left a quartz-rich granular restite. The bearing of these data on models of interaction between Aeolian arc magmas and the continental crust is discussed. Based on this data, it is suggested that crustal contamination of magma in the Aeolian arc was an important process, which, however, was unable to modify the first-order petrological and geochemical characteristics of magmas, whose origin were inherited.

VPP5 : TUpo03 : PO
Possible Constraints on the Rates of Crustal Melting within Thermal Aureoles

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The role of crustal melting is fundamental to the evolution of the continental lithosphere yet there remain few empirical constraints on the rates of melt formation, segregation and emplacement. Chemical disequilibrium between melt and protolith provides a potential insight into the mechanisms and rates of process involved during crustal melting. Disequilibrium melts are most likely to be preserved where melts result from rapid advective heating rates. We have investigated two examples of granitic melts associated with the aureoles of gabbroic intrusions.

The Ranomandry Complex, West-Central Madagascar, is comprised of a gabbroic boss surrounded by a biotite granite annulus intruding metasediments that are locally migmatised along the SW margin of the granite. Both granite and gabbro yield coeval zircon ages (~792 Ma) and initial mapping of the complex suggested that the granite is sourced from the metapelitic migmatites in the aureole. However, deformed plagioclase-free migmatite leucosomes ($Qtz+Or_{85}$) contrast strongly with biotite granite compositions (~30% An_{25}), arguing against a source within the exposed metasediments. This is confirmed by contrasting initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios for metasediments and granite. Subsequent modelling of major and trace elements from the granite suggests a derivation from a garnet-bearing, low Rb/Sr source at temperatures of 880-940°C, with little residual feldspar. Comparison with experimental compositions suggests formation by fluid-absent biotite breakdown from a metagreywacke protolith at pressures of 1.0 to 1.5 GPa. Ascent of the gabbroic magma is likely to have provided the advective heat required for melting within a tectonically thickened lower crust.

The north east aureole of the Bushveld Complex, South Africa, is characterised by anatectic sillimanite-grade metapelites resulting from emplacement of the Rustenburg layered suite. Two melt types are observed; 1): fine-grained, quartz-rich deformed veins that are locally transgressive to the main fabric within the host metagreywacke; and 2): coarse-grained pods of tourmaline-mica granite within cordierite-biotite-sillimanite gneisses. Type 1 veins result from early mobilisation of melt+crystal mixes. Type 2 melts result from fluid-present melting of metapelites, localised within vertical EW dilatational zones that are probably sag fractures in floor of the overlying intrusion. Elemental and isotopic data will be presented to identify the source of the melts more precisely and disequilibrium characteristics will be interpreted in terms of melt rates within the aureole.

VPP5 : TUpo04 : PO
Mantle-Crust Interactions in a Post-Collisional Granitoid of Sierra de San Luis, Argentina

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Shear zone related high aspect ratio and concentrically zoned ellipsoidal batholiths, crystallisation ages of which overlap within errors (Sims et al., 1997) made up the Late Devonian (Early Carboniferous?) post-collisional granitoids of the Sierra de San Luis. The former are biotite granites with extensive mylonitization (Sims et al., 1997) whereas the latter are porphyric biotite or biotite-hornblende granodiorites/monzogranites and equigranular biotite monzogranites mainly with magmatic fabrics as exemplified by the Renca Batholith (López de Luchi et al., 2000). Quartz syenitic to monzonitic mafic microgranular enclaves, synplutonic dykes and stocks in the Renca batholith define a Mg-K magmatic association. These units are compositionally similar to vogesites and durbachites in close petrogenetic relation with the minette dykes that intrude the country rocks next to the contacts (López de Luchi and Rossello, 1999). Lamprophyres are preferentially emplaced in a broadly WNW fracture system that parallellizes the major axis of this pluton.

In the Renca Batholith, major and trace-element contents are similar for the most mafic enclaves and the lamprophyres. Correlation between Cr, Ba, Mg, REE indicate that a subduction related enrichment could be responsible for the LIL enrichment. (La/Yb)n ratios indicate different melting percentage coupled with a progressive shallowing of the source. Lamprophyre magmas would be in equilibrium with a phlogopite±garnet bearing lherzolithic mantle whereas enclave melt would be in equilibrium with the same mantle at shallower depth since Ho/Yb is lower.

Post collisional uplift could favour decompressional paths. Although the enriched lherzolithic mantle is a plausible source for the basic precursors of the enclaves and the lamprophyres, underplating of these mantle derived magmas could in turn promote melting of the lower crust that would be source for high K calc-alkaline magmas. Mixing and mingling of these two end member generate the whole spectrum of rocks that constitute the ellipsoidal batholith. Amphibole and sphene fractionation controlled the evolution of the hybrid granites as indicated by trace-element patterns.

Ascent of the mantellic magmas together with the crustal derived magmas to higher levels of the crust would be channellised by coeval shear zones that controlled the high aspect ratio batholiths. In areas of high strain rate deformation overlast emplacement therefore no record of mixing process are recognized but when strain rate is lower, mingling and mixing process, evidencing the mantle-crust interaction are favoured together with the predominance of magmatic structures during emplacement.

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VPP5 : TUpo05 : PO
Isotope Equilibrium in Felsic Magmas: Evidence Against Rapid Melt Generation and/or Rapid Magma Ascent ?

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Various processes, such as magma mixing/mingling and wall rock assimilation, can cause heterogeneity in granitic rocks on a variety of scales. Such heterogeneity is likely to be preserved implying high viscosity contrasts, fast cooling rates, and moderate magma convection at middle to upper crustal levels. The existence of chemical and isotopic heterogeneity in magmatic systems is well documented. In addition, recent field and experimental studies show that local isotope heterogeneity may result from incomplete melt-residue equilibration during crustal anatexis. Very slow elemental and isotopic diffusion during partial melting and within magmas are likely to prevent large-scale equilibration. Nevertheless, numerous monotonous granitic bodies exist with very homogeneous element and isotope composition. Can models of fast crustal melting with instantaneous melt extraction and ascent explain the generation of such felsic magmas in volumes >1000 km^3? In the South Bohemian Weinsberg granites three voluminous (together >40,000 km^3) and homogeneous magma batches can be identified. These rather tabular shaped plutons were emplaced at about 7-17 km depth and extend together over an area of 80x120 km. Each magma batch has different initial $^{87}Sr/^{86}Sr$ (0.7080, 0.7094 and 0.7104) but all equilibrated at around 328-329 Ma, perhaps slightly before monazite crystallisation (328-324 Ma; Friedl et al. 1996). Their elemental and isotopic compositions imply variable source compositions, chemical differentiation subsequent to magma homogenisation, and probably melt/residue equilibration during anatexis. Convection during diapiric ascent (e.g. Weinberg, 1997) may facilitate chemical and isotopic homogenisation within each magma type. However, because solidification rates are fast and viscosity increase, the rapid ascent of subsequent melt batches in dykes or conduits implies the presence of a homogeneous magma pool in the deeper crust. Thus, magma homogenisation must have occurred mainly during melt formation and accumulation in the deeper crust. A relatively uniform source region may have allowed this, but slow heating during crustal thickening was probably critical. In contrast, rapid crustal heating and instantaneous melt extraction should generate an extremely inhomogeneous magma compositions.

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VPP5 : TUpo06 : PO
Interaction between Mantle and Continental Crust Liquids in the Bocca di Tenda Gabbroic Complex, Northern Corsica

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The post-Variscan gabbroic complex of Bocca di Tenda was dated by single zircon lead evaporation at 273 ±23 Ma (Rossi et al., 1992). The complex consists of: (i) olivine-gabbronorites, locally showing high amounts of olivine (Fo78-72), (ii) gabbronorites and pyroxene-bearing quartz-diorites, commonly containing significant amounts of ilmenite, (iii) hornblende-bearing tonalites. The complex is enclosed by coarse-grained granitoids, mainly granodiorites to monzogranites with pertithic alkali feldspar, hornblende and biotite. An original contact zone, mostly composed of micro-tonalite showing back- and net-veining phenomena, is preserved. Bodies of undeformed coarse-grained granitoids are also present within the gabbroic complex and in places show dykes of micro-tonalite with granitoid xenocrysts.

The gabbroic complex is characterized by diffuse dykes of different composition and age. Mafic bodies of micro-gabbronorite to micro-diorite, locally crosscutting at high angle the igneous layering of the gabbroic rocks, intruded the gabbroic complex when it was not completely solidified. Dykes of two-mica, peraluminous micro-granites commonly contain mafic ovoid enclaves and quartz-feldspar micrographic intergrowths. Later dykes with chilled margins are represented by: i) basaltic dolerites locally displaying miarolitic cavities filled with calcite; ii) peralkaline rhyolites with phenocrysts of perthitic alkali feldspar, quartz and aegirine, and trachitic to spherulitic groundmass.

The Bocca di Tenda gabbroic complex shows the intrusion of rather primitive basalts at middle-upper crustal levels. The trace element compositions of the liquids in equilibrium with the clinopyroxenes from the olivine-rich gabbronorites are similar to T-MORB and continental tholeiites. The gabbroic complex formed by a differentiation process controlled by fractional crystallization, most likely coupled with assimilation of crustal material. In particular, quartz-diorites and tonalites point to reaction of cumulus minerals with SiO_2- and H_2O-rich melts of likely crustal origin. The process of crustal assimilation is consistent with the trace element clinopyroxene variations and the compositions of coarse-grained granitoids and micro-granites. To unravel the role of crustal contamination in the igneous differentiation process, oxygen isotope analyses by laser fluorination technique are presently in progress.

The late dyke injection documents the uplift of the gabbroic complex to shallow levels. Trace element compositions of micro-gabbronorites, basaltic dolerites and calculated parental liquids of the gabbroic complex are similar. Trace element data indicate that basaltic dolerites and rhyolites could be related through a process of crystal fractionation. The rhyolites are chemically comparable to the peralkaline granites of the Corsica batholith, which were dated at about 245 Ma by Rb/Sr and Sm/Nd methods (Bonin et al., 1978; Poitrasson et al., 1995). The whole magmatic evolution of the Bocca di Tenda gabbroic complex is most likely related to post-collisional lithospheric thinning.

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VPP5 : TUpo07 : PO
A Simple Episodic Model of Melt Extraction for Plumes

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One of the major outstanding problems of melting processes in the mantle is the understanding of melt segregation and extraction within rising plumes. Here a simple extraction model is proposed, which is based on two-phase porous flow within the partially molten region, combined with only three extraction parameters. The equations of conservation of mass, momentum and energy are solved for a two phase material (melt - matrix) (Schmeling, 2000). As a rising hot mantle region (plume) reaches the asthenosphere, decompressional melting occurs, and the melt begins to percolate with respect to the matrix. Accumulation layers form which might be the locus in which melt might focus within subvertical melt channels feeding dykes. However, buoyancy driven propagation of magma filled dykes requires a minimum length of the dyke (Dahm, 2000). From these findings one might speculate that the extraction of melt out of the accumulation layers may be controlled mainly by three parameters d_{ex}, ϕ_1, and ϕ_2, where d_{ex} is the critical thickness of a partially molten layer, in which a critical melt fraction ϕ_2 is exceeded. If this condition is met within a certain region of the melt source region, melt might be extracted from that region in the form of one or several propagating dykes, leaving behind a region of residual melt fraction ϕ_1.

This simple extraction model is tested in 1D for a rising hot mantle flow. Depending on the chosen extraction parameters multiple extraction events are observed with a characteristic episodicity. The extraction events occur at different depths within the ascending flow. Although the rising velocity is assumed to be constant in time and space, any of these melt extraction pulses leaves behind a region with reduced melt fraction, which acts effectively as a permeability barrier for melts immediately beneath. By this mechanism new accumulation layers are formed, which subsequently are the source of new extraction pulses. A characteristic saw tooth distribution of the melt fraction evolves. Exploring the parameter space shows, that small values of d_{ex} and ϕ_2 result in multiple extraction depths and short extraction cycles, respectively. For values of d_{ex} and ϕ_2 of a few km and a few%, respectively, typical extraction cycles have the order of 10^4 years and they extract melt volumes per surface area of the order of 100 m each (rising velocity of the mantle flow = 10 cm/a, mantle excess temperature = 300 K). Such episodicities are observed e.g. on Iceland as fluctuations of the volcanic activity within neovolcanic rift zones. Applied to a 2D rising plume model, significant heterogeneities of the melt fraction are observed within the asthenospheric part of the plume. Such heterogeneities might be observable by seismic methods.

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VPP5 : TUpo08 : PO
Melt Generation, Segregation, and Crust Formation in a Plume-MOR Setting

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The evolution of a mantle plume ascending from the 660 km discontinuity beneath a spreading mid-oceanic ridge and the generation and migration of melt is modelled for the case of temperature-dependent mantle viscosity. The interactions between melt generation and mantle convection are taken into account by simple models for the effect of latent heat on temperature and for density reduction in the melting mantle due to depletion and melt retention of the matrix. The latter results in a noticeable increase of the upwelling velocity particularly in the central region of the plume. An attempt is made to assess the importance of mechanisms related to rock matrix deformation on the direction of melt flow. Furthermore, a simple model for the formation of oceanic crust from the melt extracted from the plume head resp. the sub-MOR mantle is included to get estimates of crustal thicknesses. The thickness of the crust above the plume turns out to be very sensitive to its excess temperature and can vary over more than one order of magnitude in a temperature range of a few tens of degrees.

VPP5 : TUpo09 : PO
Inferred Differences in Mantle Upwelling Rate between the Reykjanes Ridge and Iceland from U-Series Disequilibria Data

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U-series disequilibria have had a profound impact on mantle melting models, providing information on rates of melt generation and the nature of melt extraction processes. We present new U-series data on Reykjanes Ridge MORB and Iceland lavas in order to assess mantle processes beneath a slow-spreading, plume-influenced mid-ocean ridge, and how proximity to a plume affects mantle upwelling. Samples from the southern Reykjanes Ridge at ~58°N, identified as < 8 ka from measured ^{226}Ra-^{230}Th disequilibria, define a sub-horizontal trend on the equiline diagram. Correlations between (^{238}U/^{232}Th) and (^{230}Th/^{232}Th) can be explained by mixing between melts derived from heterogeneous mantle sources, with enriched sources having lower U/Th than depleted sources, and Lundstrom et al. (1998) showed that the slope of these trends should depend on the spreading rate:, data from the Reykjanes Ridge (half-spreading rate; 10 mm/yr) are predicted to have a slope of 0.0-0.1 in this model, consistent with the observed data. The local importance of source heterogeneities within this 150 km ridge section, is evident from the observation that samples north of ~58.3°N have lower U/Th, and higher Th, ^{230}Th/^{238}U, Nb/Zr, ^{3}He/^{4}He, and ^{206}Pb/^{204}Pb than those to the south. Only one sample from the northern Reykjanes Ridge ~62°N is < 8 ka (i.e. ^{226}Ra-^{230}Th disequilibrium), and it plots with the southern Reykjanes Ridge samples on the equiline diagram. In contrast, post-glacial lavas on the Reykjanes Peninsula show broadly similar U/Th to the Reykjanes Ridge samples, but with significantly lower (^{230}Th/^{232}Th) (~1.15 vs. ~1.30), and thus lower (^{230}Th/^{238}U). The higher potential temperature and elevated water content relative to ambient upper mantle inferred for the Iceland plume mantle will act to increase the depth of melt initiation which should lead to greater ^{230}Th-^{238}U disequilibrium which is not observed. Instead, the distinction is more likely due to differences in mantle upwelling rate (note that the spreading rate is the same on Iceland and the Reykjanes Ridge): a higher upwelling rate associated with the plume will produce lower ^{230}Th-^{238}U disequilibrium for a given U/Th due to the reduced opportunity for ^{230}Th in-growth in the melt column. This active upwelling cannot extend far along the Reykjanes Ridge (<<200 km). As U and Th are highly incompatible elements, they are stripped rapidly from residual mantle, and thus ^{230}Th-^{238}U disequilibria likely reflects variations in mantle upwelling within low melt productivity regions below the dry solidus.

VPP5 : TUpo10 : PO
Magma Transfer Time beneath the Southern Volcanic Zone, Chile, as Inferred from U-Series Disequilibria

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Radioactive disequilibria between short-lived nuclides in the decay series of U and Th can, in principle, yield constraints on rates and time scales of magmatic processes. The quality of such time information, however, depends on how well the mechanisms of fractionation between different elements in the U-series are understood.

Studies of U-series nuclides in arc lavas often reveal linear correlations on the (^{230}Th/^{232}Th)-(^{238}U/^{232}Th) isochron diagram. Such a correlation from historical lavas in the Southern Volcanic Zone (SVZ) of Chile was interpreted as an isochron reflecting the time elapsed between a U addition by fluids to the mantle source and magma eruption, being ~20 000 years. This interpretation was supported by a fair correlation between excess ^{238}U over its radioactive equilibrium value with ^{230}Th and ^{10}Be/Be, which strongly suggests that ^{238}U-excesses are related to slab input into the mantle source. However, new results show that the same lavas have ^{226}Ra-excess over ^{230}Th ranging from 15 to 45% (half-life of ^{226}Ra is 1600 years). The only exception comes from the volcano San Jose, which is built upon a thicker and older crust, and probably has been affected by crustal contamination leading to (^{226}Ra) = (^{230}Th) in its lava sample.

The enrichment of Ra in the SVZ lavas coincides with those of U and ^{10}Be. This is evidenced by (^{238}U/^{230}Th) - (^{226}Ra/^{230}Th) and ^{10}Be/Be - (^{226}Ra/^{230}Th) correlations. The latter correlation strongly suggests that high (^{226}Ra/^{230}Th) are inherited from the subducted oceanic crust and that ^{10}Be and Ra, as well as U, are added to the SVZ magma source with a fluid phase. Moreover, the correlation between excesses of U and Ra over Th clearly indicates that the fluid addition is both a very recent and an unique event beneath SVZ. Indeed, fluids generated by dehydration of hydrous minerals are likely to always bring both U and Ra together. The fact that (^{226}Ra/^{230}Th) correlates with (^{238}U/^{230}Th) and ^{10}Be/Be which both are modified by radioactive decay on a significant longer time scales, also implies that magma chamber residence time is likely to be of the same order of magnitude for individual SVZ volcanoes. If the observed Ra-excess is indeed generated during dehydration which produces the fluid phase, then the transfer time from the subducted crust to surface during eruption is constraint to be significantly shorter than 8000 years