

EUG XI



Symposium FMF6

Mechanisms of Fluid Flow in Metamorphic and
Igneous Environments

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Convenor

Marian Holness

Sunday Poster Session

FMF6 : SUpo01 : PO
Mass Balancing in Shear Zones Cutting
Granitic Rocks: Quantitative Studies of
Accessory Zircon vs Geochemical Calculation
Methods

Robert Sturm & Hans Peter Steyrer

Zircon crystals are considered as minerals showing high resistance during low- to medium-grade metamorphic events. The preservation of well-defined crystal shapes even under extreme mechanical deformation has made the mineral an important tool for proofing the consanguinity between protolith and mylonite in shear zones cutting magmatic, especially granitic rocks. In this study, the value of zircon for mass balancing investigations is introduced regarding a shear zone in the western part of the Tauern Window. This shear zone is characterized by a rigorous transformation of a high-Si tonalite into a subsilicic, high-Mg-Fe garnet-chlorite schist under low amphibolite-facies conditions. Extensive geochemical studies of the protolith and the highly deformed mylonite resulted in remarkable, fluid-induced element transports with losses of e.g. Si, P, Ca, Na and gains of e.g. Mg, Fe³⁺, Fe²⁺. According to these data, the volume of the mylonite is affected by a loss of c. 30% with respect to the tonalite. As an alternative method, zircon crystals were separated quantitatively from defined volumina of both the protolith and its appropriate mylonite. The comparative study was based on the hypothesis that passive enrichment of crystals within a reference volume during the shearing process points to volume loss, whereas depletion of zircons within the reference volume corresponds to volume gain. The amount of a volume change during deformation can be easily calculated from the quotient of the normalized zircon number in the mylonite and the normalized zircon number in the protolith. The method could be applied successfully to the shear zone of this study. The analysis of ten tonalite samples and ten samples of the mylonite resulted in a volume loss of 32 + 10% during mechanical deformation. Quantitative zircon separation is rather time-consuming, but it reveals good results in rocks affected by low- to medium-grade metamorphic events, where geochemistry-based calculations are inaccurate due to the many variables involved. Further studies will investigate the suitability of this method for shear zones formed under high-grade metamorphic conditions.

FMF6 : SUpo02 : PO
Stress-Shear Metamorphic Differentiation as
the Paradigm for Origin of the Kola Banded
Iron Formation

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Geological, isotopic - geochemical data, mass-balance recalculations show that Banded Iron Formation of the Kola peninsula (Baltic Shield) were derived from the stress-shear metamorphism of primary highly ferruginous basic volcanites in situ, the gain-loss of the substance being of inferior significance in scales of the ore-bearing Kola series as a whole. Metamorphic differentiation is the process restricted in its manifestation by diffusion rates of the components. As shown in a number of the works by V.E.Panin, a combination of stress and shear can lead to the transition of the substance to the atom-vacancy state (AVS) with a drastic increase of the diffusion rates (up to ten orders of magnitude). This promotes the occurrence of the metamorphic differentiation processes at scale levels up to hundreds of meters. A simplest model of the process in question is as follows: the iron oxidizes in the zones traversed by a fluid flux with the formation of magnetite; accordingly, ferrous iron becomes deficient and therefore starts diffusing from the regions surrounding the active zone; the rest of the rock-forming elements, in accord with the mass-balance, are forced out and lost, in doing so aluminium as the most inert element in the metamorphometasomatic process deposits in the direct vicinity of the forming ore bodies and forms aluminosilicate gneisses framing ferruginous quartzites lens. The fluid is, herewith, regarded not as a transport agent (the solid-phase process of the substance to the AVS is being assumed) but as an oxidant for ferruginous minerals. In this case, more intricate synergetic effects associated with a nonlinear interaction of the components in the system are possible. We have performed a numerical modeling of the system describing

extraction of iron from ferrosilicate (Fs) and redeposition in the form of magnetite (Mt). We shall designate all the complexes incorporating the block [Fe²⁺2Fe³⁺] as X, [Fe²⁺Fe³⁺] as Y, Fe²⁺ as Z, Fe³⁺ as R. Model scheme of the reactions, with the kinetic constants of the direct/reverse (if there is) reactions, respectively: Fs= Z (k₁) Z= R (k₂/k₃) Z+R= Y (k₄/k₅) Y+R= X (k₆/k₇) X= Mt (k₈) X= 3R (k₉) Mt= Z+2R (k₁₀) Assuming that all the complex formation reactions are equilibrium ones, we shall write the following kinetic equations (kinetics proportion to the degree 2/3 reflect surface-to-volume ratio):

$$\begin{aligned} dM/dt &= [k_{11}ZR^2 - k_{10}Mt^{2/3}] / dFs/dt = -k_1Fs^{2/3} \\ dZ/dt &= k_1Fs^{2/3} - k_2Z + k_3R - k_{12}ZR^2 - [k_{11}ZR^2 - k_{10}Mt^{2/3}] / D_{ic2}\Delta Z - u(\delta Z/\delta x) \\ dR/dt &= k_2Z - k_3R + k_{12}ZR^2 - 2[k_{11}ZR^2 - k_{10}Mt^{2/3}] / D_{ic2}\Delta R - u(\delta R/\delta x), \end{aligned}$$

where

$$\begin{aligned} k_{11} &= (k_4/k_5)(k_6/k_7)k_8; \\ k_{12} &= (k_4/k_5)(k_6/k_7)k_9; \\ u &= \text{speed of the fluid flux.} \end{aligned}$$

In the digital calculation of the system the stationary periodic structure of R and Z concentrations forms from the initially homogeneous distribution of all the variables that leads to the wave-like character of distribution of the magnetite being formed.

FMF6 : SUpo03 : PO
Fluid Flow Pathways along the Glarus
Overthrust Deduced from Stable and
Sr-Isotope Patterns

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In the Eastern Helvetic Alps, the Glarus thrust puts Permian Verrucano siltstones over Mesozoic carbonates in the south and Tertiary flysch in the north with an intermediate thin layer (<1-5 m thick) of intensely deformed calc-mylonite. The oxygen isotope composition of this carbonate layer shows a very pronounced regional trend. δO^{18} values are lowest in the south (11‰ SMOW) and increase rapidly northward to reach a plateau with values of around 20‰, still significantly lower than Mesozoic marine carbonates found in the footwall (south) and the hangingwall (north). Minor regional scale variations occur also along strike. Vertical isotope profiles at selected sites have been measured for δO^{18} , δC^{13} and Sr⁸⁷/Sr⁸⁶ in calcite.

In the south, the δC^{13} profiles display a very sharp gradient at the contact. On the δO^{18} vertical profiles, the footwall carbonates show isotopic shifts to lower values up to ten meters below the thrust. In the hangingwall, δO^{18} of calcite are in disequilibrium with Verrucano only in the first meter above the thrust before reaching a constant value of 12‰. Vertical profiles for Sr⁸⁷/Sr⁸⁶ have a very steep gradient of 0.01 over a few cm immediately below the Verrucano-calc-mylonite contact.

In the north, δC^{13} and δO^{18} vertical profiles display the same features. In the footwall, the gradient is very steep with values in equilibrium with the flysch since the first centimeters below the contact with the calc-mylonite (δO^{18} =20‰; δC^{13} =-2‰). A shallow gradient upward is observed in the hangingwall: altered values are observed within the Verrucano at up to 30 m above the contact. We interpret these isotopic patterns as follows: strong alteration of calc-mylonites and footwall carbonates in the south require massive isotopic exchange with either hangingwall Verrucano and/or O¹⁸ depleted, basement derived fluids with low XCO₂, expelled along the thrust from deeper levels further south. In either case, a relative component of downward infiltration into the footwall is required. In northern localities, calcite saturated fluids expelled from the Tertiary flysch in the footwall dominate the isotopic signature of the calc-mylonite; massive alteration of the Verrucano in the hangingwall requires a significant component of fluid infiltration upward. A smooth isotopic gradient along the thrust in N-S direction is used as an argument for the expulsion of O¹⁸ depleted fluids along the thrust, although given the extremely high strains within the mylonite zone, a similar trend could possibly be achieved through purely mechanical stretching.

Simulations using a finite element model combining fluid flow and isotopic exchange reactions, between different rock masses of well-defined initial isotopic composition are undergone in order to test these assumptions. The first simulations tend to confirm our hypothesis, especially the intervention of a large amount of fluids flowing upwards from the flysch.

FMF6 : SUpo04 : PO
Isotopic Evidence for Large-Scale Fluid Flow
during Collision in the External Crystalline
Massifs and Penninic Nappes (Swiss Alps)

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In orogenic belts, dating different deformation phases is important to understand the tectono-metamorphic history, as well as burial and exhumation rates. In deformed rocks, the isotopic record is frequently difficult to interpret because the behaviour of the isotopic system depends of many factors such as deformation, grain size reduction, fluid circulation, temperature, mineralogy, and the presence of relics. Using two case-studies in late Variscan granites, we examine the influence of localised fluid flow on the behaviour of Rb-Sr and ³⁹Ar-⁴⁰Ar systematics within Alpine shear zone networks during the evolution of the Tertiary collision.

Isotopic results on white micas were obtained in HP (400-450°C, 12-9 kbar) ductile D1 shear zones in the Rofna metarhyolite of the Suretta nappe (upper Penninic domain). Only white micas in the schistosity preserved the chemical composition of the HP D1 deformation (Si = 3.39-3.49 p.f.u.). These micas give reliable ³⁹Ar-⁴⁰Ar in situ UV laser and ³⁹Ar-⁴⁰Ar stepwise heating ages corresponding to the D1 deformation phase around 46 Ma. Local metamorphic reactions occurring in C-planes resulted in the formation of phengites with Si = 3.20-3.33 p.f.u. We believe that formation of a new white mica generation is certain evidence for (localised) fluid circulation. These lower-Si micas are younger than those preserved in the schistosity and give ³⁹Ar-⁴⁰Ar laser spot ages scattering from 41 to 25 Ma, and stepwise heating end-member ages around 25 Ma. Rb-Sr phengite-whole rock ages cluster around 26-23 Ma.

Two ductile shear zones related to the Miocene greenschist-facies deformation (450°C, 6 kbar) were selected in the Aar granite and the Grimsel granodiorite of the Aar massif (External Crystalline Massifs, ECM). Biotite and white mica ³⁹Ar-⁴⁰Ar ages cluster around 19 Ma and white mica-, biotite - feldspar Rb-Sr ages in mylonite are around 12-10 Ma.

These isotopic results are interpreted as recording a sequence of fluid circulation events during the evolution of Tertiary orogenic processes. Deep fluids expelled during continental subduction partially reset the Rb-Sr isotopic composition in networks of fine-grained shear zones in the hanging-walls of the main thrusts. In the Suretta nappe, the HP deformation is dated at 46 Ma and low-Si mica crystallization due to fluid circulation is recorded around 25 Ma during early subduction of the ECM. In the ECM itself, the ductile deformation is dated at about 19 Ma; large-scale fluid flow, recorded in abundant fluid inclusions, occurred at the time of Jura formation around 10 Ma, when the European plate was underthrust below the ECM and partly dehydrated.

FMF6 : SUPo05 : PO
Hydrothermal Alteration, Fluid Flow and
Volume Change in Shear Zones: The Layered
Mafic-Ultramafic Kettara Intrusion
(Jebilet Massif, Variscan Belt, Morocco)

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In the layered Kettara intrusion (Jebilet, Morocco), focused fluid flow associated with heterogeneous ductile deformation converted mafic and ultramafic metacumulates into centimetric to metric interconnected shear zones. The inner parts of the shear zones are ultramylonites mainly composed of chlorite and tremolite. The relative abundances of chlorite and tremolite along the shear zones vary from approximately 0% to approximately 100% but these proportions don't depend on the nature of the host rock deformed. Rather, they are correlated with volume change during shearing.

Chlorite-rich ultramylonites correspond to volume-loss shear zones while tremolite-rich ultramylonites correspond to volume-gain shear zones. Equal proportions of chlorite and tremolite indicate iso-volume type shear zones. All these types of shear zones are characterized by the immobility of Ti, P and V.

Volume-loss shear zones exhibit gains in Fe, Mn, Ga, Zn, Cu and losses in Si, Ca, Na, K, Mg, Sr, Rb. - Volume-gain shear zones exhibit gains in Fe, Mn, Ga, Zn, Si, Mg, Ca, Sr, and losses in Y, Rb, and Cr. - Iso-volume shear zones exhibit gains in Fe, Mn, Ga, Zn, Al, Ca and losses in Rb, Ba, Cu, Mg and Sr.

The gains in Fe, Ga, Mn and Zn in all the three types of shear zones indicate interaction of gabbros with an evolved fluid. Moreover, the positive correlation which exists between the budget of Si and the volume change indicates, in accordance with data on mylonitization of granitoid rocks, that the principal cause of volume variation in these shear zones is the variation in Si content.

REE are mobile; their concentrations are not correlated with volume change, they reflect REE concentrations in chlorite and tremolite.

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FMF6 : SUPo06 : PO
Age of Hydrothermal Alteration Leading to
Garnetite and Kyanite Pseudo-Quartzite
Formation in the Khizovaara Segment of the
Late Archaean Keret Greenstone Belt,
Russian Karelia

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The rocks in the Khizovaara segment of the late Archaean Keret Greenstone Belt are dominated by sub-aqueous rhyodacitic to andesitic volcanites and volcanoclastic sedimentary rocks that are intersected by comagmatic sub-volcanic intrusives, formed in an island arc setting. The volcanic sequence shows widespread signs of bedding-parallel to structurally controlled hydrothermal alteration, which now appears as kyanite-, garnet-, staurolite- and/or quartz- rich lithologies. Several prominent, 100-500 m wide, garnetite-dominated metasomatic zones of regional significance are developed along structural discordances in the sequence. One of these, the Khizovaara zone, contains an up to 100 m wide and 1 km long unit of kyanite-, staurolite-, garnet- and/or hornblende-bearing pseudo-quartzites. The pseudo-quartzite unit contain unaltered bodies of trondhjemitic orthogneisses and meta-pyroxenites and are enveloped by a halo of deformed quartz-kyanite veins intersecting dioritic orthogneisses with inclusions of garnetites and basaltic

meta-volcanites. These veins are in turn cut by meta-tonalite dykes. Both the dykes and the alumina-rich assemblages have been deformed and subsequently upgraded during a second episode of acid-leaching, leading locally to the formation of nearly monomineralic kyanite and fuchsite rocks. Zircons from a kyanite pseudo-quartzite, a hornblende-staurolite pseudo-quartzite and a meta-tonalite dyke have been dated using the NORDSIM ionprobe in Stockholm. The morphology of zircons in the kyanite and hornblende-staurolite pseudo-quartzites corresponds to their formation by fluid-rock interaction. The zircons yield nearly concordant U-Pb isotopic ages at 2.77-2.76 Ga whereas those in the tonalitic dyke are more heterogeneous, but give ages in the range 2.78-2.76 Ga. Recent U-Pb dating shows that acid to intermediate volcanism forming the island arc assemblage in the Keret belt occurred at c.2.78 Ga. Our data suggest that the formation of siliceous and aluminous protoliths occurred during the island arc volcanism. They are interpreted as the result of sub-seafloor alteration related to hydrothermal convection and fumarolic activity above sub-volcanic intrusives that partly truncate early formed alteration zones. The altered rocks were transformed into kyanite-, staurolite- and garnet-rich assemblages during a subsequent tectonothermal event of unknown age. The kyanite pseudo-quartzites are related to alteration of felsic and intermediate volcanites whereas the staurolite-, garnet- and hornblende-bearing assemblages evolved from dominantly mafic precursors, which is confirmed by extremely low U-contents in zircons from the latter rocks. The second episode of fluid migration and associated acid-leaching, which caused progressive replacement of hornblende, garnet and staurolite by kyanite-rich assemblages, is also undated.

FMF6 : SUPo07 : PO
The Geology & Genesis of the "Kandemwa"
Emerald Deposit in Zimbabwe, Africa

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Introduction

The Kandemwa emerald deposit is located about 25 km to the south-west of the village of Odzi in the eastern part of Zimbabwe. The Kandemwa area is a hill-shaped area in the southern extension of Odzi-Mutare Greenstone Belt. The general geology of the study area is composed of Shamvaian granitoids and pegmatites of the Wdeza- and Chilimanzi Suite (2.65-2.57 Ga). The fault bounded emerald bearing pegmatite is located in a greenstone lenses (size 500x200 m) which is intruded in Wdeza Suite Gneisses. The pegmatite contains a central zone of feldspar and a quartz- feldspar paragenesis. The marginal zone of pegmatite consists of massive mica which is between 30-70 cm wide. The emerald (Be₃Al₂(SiO₃)₆) occurs along the contact zone between the mica zone and the feldspar zone.

Emeralds deposits

There are three types of formation of emeralds. 1. Intrusion of emerald bearing pegmatitic fluids in metasediments or metavolcanics with the growth of emeralds during a metasomatism in the contact zone (Grundmann and Morteani, 1989) (e.g. Habachtal, Austria). 2. Carbonatation of serpentinized ultramafic protoliths in quartz-carbonate rocks (Arif, Fallick and Moon, 1996) (e.g. Pakistan). 3. Intrusion of emerald bearing pegmatitic fluids in chlorite-tremolite-magnetite schists with a biotite-phlogopite contact zone (Emerald Mine Investment Group, 1998) (e.g. Sambia).

Methods

Results from field work and from investigations by several analytical methods have led to the following results: *Cathodoluminescence*: several zoned emeralds and a fenitization of feldspars during an alkaline metasomatism, *SEM*: diopside-olivine ultramafite with clouds of chromite, sodium dominated feldspars, *Fluid inclusion studies*: sodium-calcium dominated fluid system with temperatures of 200-300°C of quartz and emeralds, temperature increasing during emerald growing, *Thin section*: unstable pressure conditions as derived from deformation textures, temperatures of 300-550°C as derived from secondary alteration assemblages.

Discussion & Conclusions

The principles of emerald formation are similar in most types of deposits. It necessitates a chromium and beryllium source and the interaction between both. Difference between the formation type lies in the composition of the interacting rocks. The occurrence of pegmatite fluids implies that the Kandemwa emerald deposit is of the third type of known deposits. On basis of the data gained so far, the following genetic model is suggested: Granitoid magma intruded in local country rocks including an ultramafic xenolith. Pegmatitic fluids migrated along faults through the ultramafic body. Temperature and pressure increased through serpentinization of ultramafics. Contact metamorphism and alkaline metasomatism of immediate wallrocks followed. Source of beryllium are pegmatitic fluids, source of chromium are olivine in ultramafic rocks. Subsequently Be-bearing fluids entered the system and crystallized in the contact zone between the ultramafic rocks and the pegmatite. For further works, it would be interesting to check the surrounding ultramafic lenses for emerald occurrences.

FMF6 : SUPo08 : PO
Geostatistical and Hydraulic Characterization
of a Mineralized Stockwerk: Application to the
Rosia Poieni Porphyry Copper (Apuseni Mts,
Romania)

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Hydrothermal mineral deposits form as result of focused flow of large volume of fluid. In such environment, permeability required for observed rates of hydrothermal outflow must be related to high fracture density, because non-fractured rock has intrinsically low bulk permeability. The mineralized stockwerk of the Rosia Poieni porphyry copper (Apuseni Mts, Romania) has been chosen for a geostatistical and hydraulic characterization in order to understand how mineralized vein system evolve and grow. A 1D sampling of the stockwerk has been realized on 2000 fractures distributed on five levels of the open pit (910, 940, 1000, 1045 and 1060 m). Application of geostatistical analyses show that, in all level, the thickness distribution is fractal. The fractal dimension D increase from the deeper to the highest level and show strong correlation with the copper grade. The spacing distribution are different according to levels: the 910 m profile is characterized by a fractal distribution whereas the others show log-normal distribution. Calculation of Cv values indicate clustering for all the levels. Cv values for the 910 m level decrease with the increase of the threshold thickness (typical of a fractal spacing distribution) whereas the other levels show constant Cv values. Heterogeneity in the characteristics of the stockwerk are thus observed at the open pit scale. Precise studies realized on the 1000 m level shows that heterogeneity can equally be shown at the profile scale. Eight zones were distinguished according to the density and the nature of the filling. Geostatistical analyses applied in each zone show that the thickness distribution is always fractal and that D is variable, linked to the copper grade. The majority of the spacing distribution are log-normal except in the more mineralized zones where they tend towards a fractal distribution. Cv values are variable, always >1 in the more mineralized zones implying a clustered organization of veins. The more mineralized zones seems thus to be characterized by a fractal distribution of both thickness and spacing linked to the presence of thick veins and a clustered spatial organization. Estimation of hydraulic conductivities developed by veins has been realized. The mineralized and fractured rock has been considered as an impermeable mass cut by planar discontinuities of infinite extension. The hydraulic properties of the stockwerk depend thus only of the geometric properties of the mineralized veins. The mean permeability developed by all the veins on each profile decrease from the deeper level (910 m) to the highest level (1060 m). High permeabilities developed on the 910 m profile are linked to the presence of major drains and the clustered organization of veins. The level 1060 m, characterized by numerous and thin veins with a homogeneous spatial repartition, develop a more pervasive permeability.

FMF6 : SUpo09 : PO
Trace Element Mobility in Contact Metamorphic Rocks: Baddeleyite-Zirconolite-(Zircon) Veins in Olivine-Bearing Marbles from the Stubenberg Granite Contact Aureole (Styria, Austria)

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The occurrence of accessory phases like baddeleyite and zirconolite has long been recognized to be related to metasomatic activity during contact metamorphism/metamorphism of carbonates. The Stubenberg Granite belongs to the Austroalpine basement nappe system of the Eastern Alps. A Rb-Sr whole rock isochron suggests a Permian age of the intrusion. During subsequent Eo-Alpine metamorphic overprint, the assemblage garnet + biotite + muscovite + albite ±K-feldspar formed. Garnet has a composition of $Alm_{53}Pyr_7Gro_{42}Sp_{53}$. The unusually high Cl-contents in biotites of up to 1.3 wt.% are thought to be an inherited primary igneous feature. Preliminary thermobarometric calculations yield temperatures of 530-600°C and pressures of 12-15 kbar and a high $a(H_2O)$ of 0.90. Contact metamorphism during emplacement of the granite into sedimentary country rocks led to the formation of marbles, amphibolites and minor calcisilicates. The marbles contain the assemblage olivine (For_{95}) + calcite + Ti-clinohumite (* 8 wt.% TiO_2) ±phlogopite ±chlorite. Small calcisilicate lenses occur at the contacts between marbles and amphibolites and are characterized by the assemblage wollastonite + vesuvianite + garnet + zoisite + biotite + titanite. During the Eo-Alpine event, the marbles underwent localized deformation, resulting in the development of a pronounced foliation along with shear bands of up to 2 cm in width. These shear bands show a mineralogical zoning with an Mg-rich ilmenite + baddeleyite + zirconolite + apatite + calcite + chlorite ±magnetite ±pyrrhotite assemblage in the center, followed by calcite + chlorite and olivine + Ti-clinohumite + calcite + phlogopite assemblages towards the rims of the shear bands. Baddeleyite is always replaced by zirconolite, suggesting a reaction baddeleyite + 2 geikielite + 3 calcite + CO_2 = zirconolite + 2 dolomite. Zirconolite shows strong oscillatory zoning with U-rich rims. In a few cases, baddeleyite has been replaced by zircon and uraninite (UO_2), indicating an increase in the activity of $a(SiO_2)$ relative to the ZrO_2 -ZrSiO₄ buffer during the Eo-Alpine overprint. Aside from the shear bands, Mg-rich ilmenite + baddeleyite + zirconolite + apatite were also found in narrow, foliation-parallel layers within the marbles. Textures suggest that the HFSE- and REE-rich assemblages formed during Permian emplacement of the Stubenberg granite and attendant contact metamorphism/metamorphism of carbonate country rocks. As a result of the subsequent high-P Eo-Alpine metamorphic overprint, HFSE- and REE-elements were locally re-mobilized.

FMF6 : SUpo10 : PO
Occurrence and Origin of Cl-Rich Amphibole and Marialitic Scapolite in the Central High Atlas (Morocco)

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The Central High Atlas (CHA) is a Cenozoic intracontinental fold belt. Its sedimentary formations are essentially Mesozoic with firstly Triassic silt, evaporates, and tholeiites; secondly Liassic to Bajocian carbonates and marls; and finally Bathonian to Low-Cretaceous sandstones. In its axial zone, the Triassic to Bajocian formations are intruded by numerous Jurassic NE-SW magmatic plutons comprising various petrographical facies (troctolites, gabbros, syenites). The intrusions are overlaid by Cretaceous sandstones. Their emplacement was accompanied by a hydrothermal activity, which gave rise to heterogeneous transformations in the intrusions and their host rocks. In the intrusions, the hydrothermal alteration led to formation of numerous secondary minerals comprising hornblende, actinolite, scapolite, talc, epidote, chlorite,

albite, sphene, serpentine, prehnite, analcime, calcite, and quartz (Zayane, 1992; Laville et al., 1994; Zayane et al., 2000).

The hornblende and scapolite are essentially present as fractures-filling minerals which cross cut the intrusions. The scapolite ($Na_{2.7}Ca_{1.1}Al_4Si_{7.6}O_{20}Cl_{0.7}$) is close to marialite while the hornblende $K_{0.5}Ca_2(Mg_{0.2}Fe^{2+}_{0.8}Al_{0.8})Al_{1.45}Si_{6.55}(OH)_2$ is paragasitic and chlorine rich (2%). Chlorine rich amphiboles have been described in oceanic gabbros where they correspond to dashkesanites (Honnorez and Kirst, 1975). The paragasitic hornblendes of the CHA are however distinguished from dashkesanites by their richness in K_2O (2.3%) and poverty in Na_2O (0.4%).

The content of Cl in the amphibole - scapolite association or in Cl-rich amphibole is controlled by the ratio aCl/aOH of the fluid phase in equilibrium with the mineral phases. Because the Cl content of the magmatic minerals as well as the Cl content of the magmas is too low, the origin of the fluid phase cannot be magmatic (Mével, 1987). The Cl content of the amphiboles in equilibrium with seawater is weak (about 0.2%) (Vanko, 1986), then the CHA amphiboles were probably formed in equilibrium with a highly saline fluid phase. The source of Cl in the CHA is probably to find in the Triassic evaporates which generally outcrop at the contact with the magmatic intrusions.

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FMF6 : SUpo11 : PO
Mechanism of the Fluid Flow Through the Feldspar- A CL-EMS Study

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The use of Cathodoluminescence (CL) combined with electron microprobe analyses (EMP) is an advanced method enabling to identify and quantify rock and mineral textures, which are unobservable using other, conventional techniques. Feldspars are common objects of such studies (e.g. COX et al. 1996, STIRLING et al. 1999, GOETZE et al. 2000). We used this technique to identified possible fluid migration pathways in feldspars, which are responsible for their secondary alteration. Plagioclase and K-feldspars from acid magmatic rocks and high-grade gneisses were analyzed using cathodoluminescence equipment with hot cathode. Carbonatization is abundant alteration, which affect plagioclases rich on An component, including those enclosed in K-feldspar megacrysts. We identified very narrow microveins penetrating K-feldspar host and plagioclase inclusions as well. The carbonate microveins are clearly visible in the CL, where the bright orange CL of carbonates contrast with bright blue CL of feldspars. These veins follow preferably crystallographical plains (e.g. twinning or cleavage) or grain boundaries. But some veins penetrate the crystal without any dependence on crystallographical orientation, indicating that fluid migration related to carbonatization occurs after the brittle deformation. The boundaries between the vein and K-feldspar or biotite are sharp. The reaction appears only if the mineral contains a significant amount of calcium (e.g. plagioclase or Ca-hornblende). The carbonatization influenced therefore the An rich zones only, the Ab rich zones remains unaffected.

Albitization is further widespread alteration affecting plagioclases. Some primary An rich plagioclases are totally replaced by secondary albite. The fluids, responsible for this kind of alteration, used preferably the crystallographical plains too. The twinning plains seem to be a main path for these fluids. In the CL, green, primary An rich plagioclase is replaced along these plains by dark blue luminescent albite. If the twinning plain intersect the cleavage, the secondary albite replaces the former plagioclase along this plain too, and consequently, the whole grain may be replaced by homogenous albite.

Slightly different type of fluid migration was observed in the extremely radioactive alkali-feldspar-syenites. The radioactive elements are concentrated in strongly metamict zircon. The change in volume during the metamictization is responsible for the origin of very thin cracks, which penetrate the whole rock. Some K-feldspars exhibit a change in luminescence along such cracks, which was induced by circulation of radioactive fluids.

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FMF6 : SUpo12 : PO
High-Temperature Fluid Circulation as a Cause for the North Pyrenean Metamorphism?

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Lithospheric scale shear zones act as drains for fluid circulation. Upwards movement of fluids is an efficient mean of heat transport. Fluid circulation in large vertical shear zones or faults may thus give rise to temperature anomalies centered on these structures. On the other hand, high temperature metamorphism may be located close to a major deformation zone without being the consequence of fluid circulation ; it is particularly the case for detachment zones which juxtapose high grade rocks from to syn-tectonic sedimentary basin.

The North Pyrenean Metamorphic Zone (NPMZ) in southern France is 5 km wide and is composed of Mesozoic metasediments. It is limited in the South by the North Pyrenean Fault (NPF), a 400 km long vertical structure which was active during the rotation of the Iberian plate to the East as a consequence of the opening of the Gulf of Biscay (mid-Cretaceous). Pull-apart basins are created during this transtensive sinistral context in the North of the NPF and are filled with a thick Albo-Cenomanian flysch. Ultramafic bodies and alkali basalts emplaced in this context and in the same time (110-85 Ma).

Metamorphism has been dated at 98-87 Ma (Golberg and Maluski, 1988). Some authors argue that the extreme thinning of the crust below the extension zone and the consequent uprise of the crustal isotherms are the cause of the thermal anomaly. Others favor the role of fluid circulation as a vector of heat transfer, considering that the localized anomalies cannot result from a diffusive process alone (Dauteuil et Ricou, 1989). Fluid circulation is indeed well documented in the zone by hydrothermal breccias and talc-chlorite hydrothermal deposits. The latter have been dated at 112-97 Ma (Schärer et al., 1999). Thus, fluid circulation, metamorphism and faulting are nearly synchronous.

We test this last hypothesis that considers high temperature fluid circulation as the main cause for the North Pyrenean Metamorphism. For this, we present the C and O stable isotope compositions of metacarbonates of the NPMZ, as well as results on hydrothermal breccias and talc-chlorite deposits.

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FMF6 : SUpo13 : PO

Fluid Regime and Metamorphism during Continental Collision: An Example from the Micaschist-Marble Complex, Eastern Alps, AustriaAna-Voica Bojar¹, Harald Fritz, Zachary David Sharp², Hans-Peter Bojar³ & Jurgen Loizenbauer⁴¹ Dept. of Geology and Paleontology, Heinrichstrasse 26, A-8010, Graz, Austria² Dept. of Earth and Planetary Science, Northrop Hall RM 141, Albuquerque, USA³ Landesmuseum Joanneum, Raubergasse 10, A-8010 Graz, Austria⁴ Dept. of Geology and Paleontology, Heinrichstrasse 26, A-8010 Graz, Austria

The aim of this study is to reveal deformation and fluid regime within the Middle Austroalpine (MA) Nappe complex during the Cretaceous tectono-metamorphic events. For this purpose collaborative P-T data from coexisting mineral assemblages, stable isotope and fluid inclusion studies have been obtained from a major tectonic unit: the Micaschist Marble complex (MMC). During Cretaceous closure of the Meliata-Hallstadt ocean, progressive continental shortening was accompanied by top-to-the-north to top-to-the-west nappe stacking within the M.A. units (Fritz, 1988; Dallmeyer et al., 1998; Neubauer et al., 2000). Cretaceous peak metamorphic conditions of the MMC, which is composed of micaschists, quartzites, marbles, amphibolites and calc-silicate rocks, are around 600°C and 6 kbar (Bojar et al., submitted). The period of nappe stacking was followed by N-S shortening and coeval E-W extension that led to exhumation of the Gleinalm core complex along large-scale normal faults and sedimentation of the Kainach Gosau basin. During the Late Cretaceous extension, the MMC as well as the adjacent Paleozoic of Graz were overprinted by greenschist facies metamorphism, concentrated along a sinistral wrenching corridor and westward dipping normal faults (Neubauer et al., 1995). Detailed oxygen isotopic data across a marble layer within the pelitic schists show modification from the initial step function shape during prograde Late Cretaceous metamorphism. The shape of the isotope profile is compatible with predicted curves calculated for advective-diffusive transport in a fluid phase. Advective fluid transport modified the oxygen signature of marble beds in the scale of 30 cm which implies a component of upwards fluid flow. For the pinned boundary solution (Bickle and Backer, 1989), the calculated time integrated fluid fluxes are 0.3 m³/m². Flow along a stable interconnected porosity took place over a total duration of 0.3 Ma. Fluid inclusion from the quartz veins display shifts from early CO₂ dominated fluids with moderate densities to H₂O ± NaCl (equiv.) dominated low density fluids. Associated isochores support progressive isothermal decompression followed by isobaric cooling. Our data suggest that: a) Major contribution of heat transfer by fluid advection can be excluded for Alpine metamorphism; b) The first fluid event occurred during prograde metamorphism and resulted in the development of asymmetric isotope profiles along marble-pelitic contacts. The second was associated with the development of retrograde veins during progressive exhumation of the Gleinalm dome.

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FMF6 : SUpo14 : PO

Hydration and Fluid-Induced Recrystallization of Alpine Type Peridotites (Almklovdaalen, Western Norway)Olga Kostenko (olga.kostenko@geologi.uio.no)¹, Bjorn Jamtveit (bjorn.jamtveit@geologi.uio.no)¹ & Håkon Austrheim (hakon.austrheim@nhm.uio.no)²¹ Department of Geology, University of Oslo, P.O.B. 1047 Blindern 0316 Oslo, Norway² University of Oslo, Mineralogical-geological, museum, Sars'gate 1, N-0562 Oslo, Norway

Retrogressive metamorphism is to a large extent controlled by the coupled action of fluid flow and deformation. Here we will describe an example of fluid-induced recrystallization of mantle-derived peridotites from the Almklovdaalen

ultramafic massif (Western Gneiss Region, Norway). The Almklovdaalen alpine-type peridotite massif is comprised mostly by dunites with interlayered bands of garnet-bearing peridotites (harzburgites and lherzolites), and eclogite lenses, which occur near the contacts with surrounding gneisses. The compositional layering of the massif is parallel to the contacts with the gneisses. Chemical data, including oxygen isotope compositions, are in the accord with the rocks being mantle derived. The mineralogy and internal fabric of the ultramafic rocks indicate several periods of deformation and metamorphism, including periods of retrogression and hydration.

Field observations in the central north part of the massif reveal sharp transitions from grey-colored tough dunite to green-colored recrystallized ('sugar-grained') dunite associated with crack systems concentrated in several meters wide pipe-like structures. The green dunite in the pipes has experienced significant grain coarsening and large olivine porphyroblasts (up to 10 cm) are often observed within the green dunite.

Microscopic observations show that the grey-coloured dunite has a strained deformational fabric with seriate-interlobate texture and undulose extinction. Deformation lamellae and olivine grains with plucked irregular grain boundaries are common, indicating stress-induced recrystallization due to grain boundary migration and grain boundary rotation. The microfabric of the green dunite is almost strain-free, shows recovery, and often display equigranular-polygonal (foam) textures. These observations are consistent with static recrystallization of green dunite in areas of fluid infiltration and low effective stresses.

Oxygen isotopic compositions: $\delta^{18}\text{O} = 4.4\text{-}5.2\text{‰}$ for grey dunite, and $5.1\text{-}5.7\text{‰}$ for green dunite and olivine porphyroblasts, are consistent with introduction of external fluids into the dunites, during recrystallization and porphyroblastesis. These observations contribute to the understanding of the coupling between fluid infiltration, deformation and microstructural changes during periods of retrogressive metamorphism and hydration of high-grade metamorphic rocks.

FMF6 : SUpo15 : PO

Application of 3D Streamline Methodology to Model Geothermal Circulations in the Soutz Fractured ReservoirJean-Charles Voillemont (jean-charles.voillemont@ensg.inpl-nancy.fr)¹, Pascal Audigane (pascal.audigane@ic.ac.uk)² & Jean-Jacques Royer (royer@ensg.inpl-nancy.fr)³¹ LIAD-CRPG-CNRS-ENSG, 15 rue ND des Pauvres, BP. 20, 54501 Vandoeuvre-Les-Nancy, France² Center for Petroleum Studies, T.H. Huxley School, Imperial College, Prince Consort Road, London, SW7 2BP, England³ LIAD-CRPG-CNRS-ENSG, 15 rue ND des Pauvres, BP. 20, 54501 Vandoeuvre-Les-Nancy, France

The Soutz Hot-Dry-Rock project aims at recovering the heat contained in the Rhenish granite basement by circulating a cool fluid between two wells drilled at 5000 m depth. The reservoir was hydro-fractured to increase its permeability and connectivity to improve fluid circulation between injection and production zones. During these stimulation tests, several seismic events with a small magnitude (< 4) were induced by shear displacement. Studying the evolution in time of this induced microseismicity gives information about the spatial distribution of the diffusivity and permeability into the reservoir (Shapiro et al., 1999). A 3D model of the reservoir was built using GOCAD. Then, using a single phase Darcy approach, a 3D flow velocity model was computed for several scenarios of exploitation assuming that the reservoir is isolated from the far field as observed during the stimulation tests. In each case, the cooling time of the geothermal reservoir was estimated using a thermo-convective streamline approach calculated from the velocity field (Batycky et al., 1997). The underlying idea of the streamline approach is to decouple the resolution of the thermal problem from the modelization of fluid circulation. The streamline concept is justified because the characteristic times of the thermal and fluid problems differ from several orders of magnitude. The proposed methodology consists in resolving independently a 1D thermal equation along each streamline connecting injection and production zones. The streamlines are calculated from the velocity field by determining a coarse path using a tracking algorithm on a 3D gridded mesh followed by a refinement of the streamline trajectory using a

smoothing DSI constraint. Several geometric configurations of the injection and production wells have been investigated including a triplet system constituted of a central injection well and two deviated lateral production wells. Assuming an injection flow rate at 100 l/s and a production flow rate at 50 l/s per well, this approach gives an estimation of the total available energy at 30 MW decreasing to 10 MW during the first 30 years (Audigane, 2000). These preliminary simulations are very encouraging for such type of installation and gives rise to further geothermal research works in similar geological contexts. This study shows that the streamline approach is an easy way to estimate cooling time of complex geothermal reservoirs in which several processes are coupled. Despite of its limitation, this method can be applied to larger segment of the lithosphere.

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FMF6 : SUpo16 : PO

Deep Percolating Meteoric Waters in the Central AlpsJosef Mullis (josef.mullis@unibas.ch)¹, Torsten Vennemann (torsten.vennemann@uni-tuebingen.de)² & James O'Neil (jro@umich.edu)³¹ Mineralogisch-Petrographisches Institut, Universität Basel, Bernoullistrasse 30, CH-4056 Basel, Switzerland² Wilhelmstrasse 56, Universität Tübingen, 72074 Tübingen, Germany³ U.S. Geological Survey, 345 Middlefield road, Menlo Park CA 94025, USA

In order to investigate the origin of mineralizing fluids that have precipitated fissure and vein quartz in the northern Penninic Alps and the southern Gotthard Massif, the quartz hosts and their included fluids were examined for their stable isotope and fluid inclusion geochemistry.

Two distinct groups of quartz could be differentiated on the basis of their occurrence, textural appearance, and composition of included fluids: (i) Tessin-habit quartz formed from a CO₂-dominated fluid in small SE-NW striking Alpine fissures at 450 to 410°C and 3.5 to 2.5 kbars and (ii) needle-like and split-growth quartz precipitated between 320 and 200°C and *1 to 0.7 kbar in large SE-NW striking, nearly vertically dipping vein systems. Wall rock alteration is well developed in early formed Alpine fissures, but not observed in the younger large vein systems.

The early CO₂-bearing fluids in Tessin-habit quartz have δD values of -19 to -37 ‰ (relative to VSMOW), measured by thermal decrepitation and isotopic analyses of the included water, and $\delta^{18}\text{O}$ values of +21.9 to -1.3 ‰, calculated from measurements of the isotopic composition of the quartz host. These δD and $\delta^{18}\text{O}$ values suggest a metamorphic fluid with some dilution by meteoric fluids. The CO₂-rich fluids were generated by dehydration and decarbonation reactions, including decomposition of organic matter, in the enclosing metasedimentary rocks.

In contrast to the CO₂-rich fluids in Tessin-habit quartz, stable isotope compositions of water-rich fluids in needle and split-growth quartz have δD values between -73 and -143 ‰ and $\delta^{18}\text{O}$ values between -1.1 and -13.7 ‰, indicating increasing dominance of meteoric water. To allow the precipitation of large amounts of young vein quartz from fluids dominated by meteoric water, a topographic high is postulated as a high-altitude catchment for the meteoric water. According to recent results on dating and tectonics of the Central Alps, the necessary conditions were given during the Mid-Miocene in the Pennine area and adjacent Gotthard-Massif, with the southern part of the Penninic nappes experiencing a greater uplift during the Mid-Miocene than the frontal part. The southern Penninic part could, therefore, have served as a hydraulic head. Infiltrating meteoric waters must have moved through permeable north-dipping rocks or vein systems. At temperatures above 320°C and depths exceeding 10 km silica was dissolved. Stable isotope compositions and trapping conditions of fluids at 320 to 200°C and *1 to 0.7 kbar indicate precipitation of needle and split-growth quartz from ascending meteoric fluids within extensional vein systems.

FMF6

Mechanisms of Fluid Flow in Metamorphic and Igneous Environments

FMF6 : SUpo17 : PO Disequilibrium Fluid Migration Pathways in a Contact Aureole

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Contact aureoles provide a natural link between experimental studies of high temperature fluid behaviour in rocks and complex natural hydrothermal systems. Many current models for grain-scale fluid pathways in contact aureoles rely heavily on equilibrium fluid distributions, yet evidence is accruing that reaction rates in the aureole, and the rate at which fluids are expelled from the solidifying pluton, may exceed the rate at which fluid-bearing rock can attain textural equilibrium. A non-equilibrium, crack-dominated, pore network has been suggested for the aureole of the Ballachulish Igneous Complex in Scotland, based on consideration of the comparable amounts of water-fluxed melting in lithologies with very different values of the quartz-H₂O dihedral angle (Holness and Clemens, 1999). Here we present new microtextural data which demonstrate the importance of cracks in controlling the fluid distribution in Appin Quartzite.

Small degrees of water-saturated melting in the Appin Quartzite are discernible up to 500 m from the contact. Cathodoluminescence imaging shows that the aqueous fluids responsible for this melting migrated along a fracture network dominated in the lower temperature part of the aureole by intergranular microcracking along pre-existing grain boundaries. Intragranular fracturing occurs in rocks at 0.1 m from the contact. Infiltrating aqueous fluids were associated with grain growth during the prograde path. Melt occurs as thick films surrounding sub-angular to angular grains of residual quartz. Present-day grain boundaries between restitic quartz grains now lie within melt-derived quartz, showing that simultaneous growth of the adjoining quartz grains occurred during solidification. Our results confirm the importance of microfractures in controlling grain-scale migration of both melt and aqueous fluids in high temperature, low permeability systems.

Holness, MB & Clemens JD, *Contrib. Min. Pet.* **136**, 154-168, (1999).

FMF6 : SUpo18 : PO 3-D Finite Element Modelling of Free Surface Komatiite Lava Flows

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3-D Finite element computer simulations of free surface komatiite lava flow over ledges and hollows, which are taken to be embayments, show that back eddies develop behind the upstream ledge. These eddies very effectively mix sulphides with melt and hence would very effectively scavenge Ni from the lava. These back eddies are therefore anticipated to be zones of deposition of massive sulphides. The more vigorous the flow, the more vigorous the back eddy and the more efficacious the scavenging of Ni from the melt. The particulate matter gathered in the eddy tapers off down stream which conforms to field observation of some Ni deposits. The middle portions of the eddy are stagnant, therefore little mixing takes place there and it is expected that these portions would be relatively barren zones as is seen in the field. Flow over hollows reveals similar structure except that if the flow is fast enough, the eddy fills the whole hollow. If the flow is too fast, it skips over the hollow with little eddy formation in it. This implies that if the flow is too deep or too fast or both, there will be little deposition of massive sulphides in embayments. Therefore, although a thick flow would be conducive to a large R factor, if the slope down which it plunges is too steep, material might not collect in the embayments. On the other hand, the implication is that thin flows down steep slopes may still yield payable reserves. Inclusion of temperature dependent viscosity indicates little likelihood of thermal erosion of underlying substrate. This conforms to the observation that lava flows do not thermally erode tar roads in Hawaii. A quench surface is laid down which armours the road from the lava. The komatiite thermal erosion paradigm arose from experiments which poured hot water on waxy material that was at room temperature: well above the freezing point of water. Theoretical support arose by neglecting heat transfer in the vertical. Both approaches

have no relationship to reality as lava is injected into an environment approximately 1000 degrees below its freezing point and neglecting heat flow in the vertical holds forever the substrate at the mean flow temperature of the lava when in fact its temperature should come to about half-way between that and ambient which calls for the formation of a quenched margin instead.

FMF6 : SUpo19 : PO Heterogeneous Permeability Deduced from Microseismicity: Application to the Soultz Geothermal Reservoir

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The Hot Dry Rock (HDR) project at Soultz-sous-Forets aims to recover the heat contained in a fractured granitic reservoir by circulating fluid between wells hydraulically connected by a fracture network. A cool fluid injected from the surface at depth is warmed in contact with the hot rocks during its percolation, and pumped at the surface where the heat is extracted to produce electricity. To reach temperatures around 200°C, a reservoir was created by hydrofracturing at 5000 m depth during the year 2000. This work aims at estimating the permeability of the geothermal reservoir using the induced microseismicity recorded during the stimulation tests at high pressure (about 15 MPa). During the fluid injection phase, the pore pressure perturbation propagates at a velocity depending on the diffusivity of the medium (Biot, 1956). Moreover, from the theory of slow wave in poroelastic medium, the hydraulic diffusivity D and the first arrival time t of the micro-earthquakes can be related according to: $r^2 D^{-1} r = 4\pi t$ where r is the distance at time t of the moving wavefront from the pressure source (Shapiro et al., 1999). Assuming that the hydraulic diffusivity varies slowly into the medium, the derivative $D(r)$ can be neglected compared to the velocity of the front wave. Then, the heterogeneous isotropic diffusivity can be deduced at each location. Finally, using the spatio-temporal distribution of the micro-earthquakes, it is possible to estimate an isotropic equivalent permeability of the stimulated area. This method has been applied on several geothermal reservoirs including Soultz (France), Fenton Hill (USA) and Ogachi (Japan) (Audigane, 2000). At Soultz, the estimated diffusivity ranges from 0.02 to 0.2 m²/s indicating a permeability comprised between 2.7 10⁻¹⁷ to 2.2 10⁻¹⁶ m² depending on the assumed porosity of the granite (around 0.3%) (Audigane, 2000). Compared to Soultz, the injection pressure requested to induce microseismicity at Ogachi (Japan) is similar in magnitude (20 MPa), but is five time less than the one requested at Fenton Hill (USA) (50 MPa). These observations suggest that the hydrofracturing mechanisms involve a reactivation of the pre-existing fracture network rather than a break-down of the granite. This approach provides a unique methodology to derive, at the reservoir scale, the heterogeneous diffusivity from the micro-seismicity evolution in space and time. The proposed methodology can be applied at larger scale to other lithospheric segments, especially to active seismic areas.

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Shapiro S, Audigane P and Royer J-J, *Geophys. J. Int.* **137**, 207-213, (1999).

FMF6 : SUpo20 : PO Partial Melts: Self-Organised Critical Systems?

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The process of melt accumulation from a partially molten rock is traditionally viewed as a case of Darcian flow through permeable media. A prerequisite for such flow is that the melt-filled porosity is connected, which is the case above a critical melt fraction or percolation threshold. Although partially molten rocks are soft ductile materials, melt-filled hydrofractures can easily form if high melt pressures cause melt-induced embrittlement, which enhances connectivity. Still, melt fractions need to be at least several percents to achieve full percolation and flow towards influx sites of dykes that propagate upwards.

We argue that there is no critical melt fraction, as melt can start to flow and accumulate locally if there is only local connectivity. This reduces the melt fraction at some sites and increases it at other sites. Hydrofractures can move by propagation at one end and simultaneous closure at the other end under an applied stress gradient. This way, batches of melt can even move without any permanent local connection. The movement and accumulation of some melt can trigger chain reactions of movement and accumulation ("avalanches"). One can imagine that melt accumulation occurs in scattered bursts between periods of quiescence. The mobility of melt is most likely enhanced by deformation.

Such a system was experimentally simulated in analogue materials and with a numerical model. In the numerical model, small volumes of melt were added to the system and allowed to move and merge with others, while accumulated volumes above a certain size were extracted. A dynamic steady state quickly developed. The melt fraction in the source remained on average constant and very low (1 to 2.5%), but with strong fluctuations. The numerical and experimental systems developed towards a self-organised critical state, characterised by the emergence of scale invariant or fractal structures, such as the size distribution of melt batches, avalanches and escaping melt batches. This scale-invariant structure links the smallest leucosomes to the largest batholiths or volcanic outpourings. If the fractal dimension is high (end-member fractal dimension 3, low strain rate), melt does not accumulate and segregate well. If the fractal dimension is low (end-member fractal dimension 2, high strain rate), melt accumulation is very efficient and 50% of all melt ends up in the single largest melt volume. Only a very small fraction of all melt is expected to remain in the source.

The above necessitates a new approach to the description of the dynamics of melt accumulation, as classical Darcian differential equations for continuous melt flow are insufficient. This not only applies to the segregation and accumulation of melt, but also to extraction of hydrocarbons and metamorphic fluids from their source.

FMF6 : MOpm21 : F4 The Behaviour of Excess Argon in Fluid Rich and Fluid Poor Systems

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K-Ar and Ar-Ar dating techniques are commonly applied to igneous and metamorphic rocks which have experienced both high fluid flux and to rocks which contained little free fluid and probably experienced no fluid flow. Although most ages produced reflect the time at which the minerals cooled and became closed to argon diffusion, minerals in both fluid rich and fluid poor systems occasionally produce ages older than geological criteria or other isotope geochronological measurements suggest. Such samples are deemed to contain 'excess argon' and are often rejected. However, new solubility data for argon in minerals and

existing data for solubility in fluids and melts can be used to understand the incorporation of excess argon, in both fluid rich and fluid poor systems and provide valuable insights into the environment in which the samples cooled to their argon retention or 'closure' temperature. Argon escaping from minerals above their closure temperature is assumed to enter an 'infinite reservoir', leaving minerals free of radiogenic argon. The dilemma in this scenario is that studies of ground waters, fluid inclusions and many natural volcanic glasses demonstrate that hydrous fluids and magmas at all depths in the crust contain argon. The reason why all minerals do not contain significant quantities of excess argon, indeed the reason why the K-Ar and Ar-Ar dating techniques work at all, is that argon is extremely incompatible. Taking K-feldspar as the example, it is possible to show that in an open system, although the concentration of excess argon is never zero, it is more than 2 orders of magnitude below detection limits in most cases. The extreme incompatibility of argon means that the grain boundary fluids do indeed act as an infinite reservoir. In natural open systems, excess argon does occur and this can usually be traced to local sources of high argon concentrations such as basement rocks being reworked in later shear zones. In low fluid systems, the composition and salinity of the fluid is critical, but the mineralogy of the rocks, the amount of free fluid in the rock and the age of the system play crucial roles. Extremely fluid poor systems will always exhibit excess argon but even small amounts of fluid can effectively remove excess argon from commonly analysed minerals. Treating argon as a trace element with variable solubility explains the occurrence of excess radiogenic argon in rocks which contain little fluid but it also shows that excess argon attributed to fluid ingress in some systems may in fact be due to salinity changes or simple cooling.

FMF6 : MOPm22 : F4

How Fluids Get into and Out of Rocks during Metamorphism

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The mechanisms of fluid introduction to rocks during retrogressive metamorphism and fluid expulsion from rocks during progressive metamorphism are poorly understood. Both processes involve the coupled action of mineral dissolution and precipitation, fluid migration and deformation, and both processes are sensitive to anisotropies in the external stress field. Furthermore, any fluid-consuming or -producing metamorphic reaction generally causes a significant perturbation of the local stress field and porosity due to its associated volume change. We have developed a series of models that can simultaneously describe: (1) local rock deformation (including fracturing), through a spring network representation of the rock matrix, (2) fluid pressure variations and thus fluid flow through a continuum description, and (3) local heterogeneous reactions. These models are applied to some simplified geological scenarios, that illustrate some of the generic effects. We also apply the models to a natural example of retrogressive metamorphism at high pressure conditions, where the morphology of the fluid infiltration front and the pattern and thus the 'pervasiveness' of fluid rock interactions heavily depend on the coupling between externally (tectonically-) imposed stress fields and local stress perturbations caused by metamorphic reactions.

FMF6 : MOPm23 : F4

Attempts to Date Retrogression and Quantify Fluid Infiltration into Granulite-Facies Basement within the Grampian Orogenic Belt in the Irish Caledonides

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Retrogression of high grade assemblages in the lower crust is limited by availability of water and low permeabilities under these conditions. Metabasite pods are a minor but common constituent of most gneiss terrains and appear to

be relatively impermeable to judge by partial preservation of dry assemblages. In contrast, metasedimentary lithologies of suitable mineralogy often exhibit thorough retrogression.

Within the Caledonian orogenic belt, the Sliswood Division of NW Ireland is an exotic lower crustal block which, together with various arc terranes and ophiolites, collided with the Laurentian margin causing the Grampian orogeny. The Sliswood Division comprises metasediment, metabasite and tonalite and locally preserves high-pressure granulite-facies metamorphic assemblages within metabasites and psammites.

Ar-Ar and Rb-Sr mineral dating (Flowerdew et al. 2000) combined with new U-Pb zircon ion microprobe analyses can be used to constrain the timing of fluid infiltration but it is difficult to quantify fluid flow with any confidence. Attempts to do so using field and petrographic assessment of fracture permeability and hydration volumes will be discussed.

The high-grade assemblage is characterized by grt-cpx-plut-ilrn in the metabasites. The earliest fluid infiltration is manifest by epitaxial replacement of clinopyroxene by hornblende and growth of zircon both dated at c. 480 Ma. Later static biotite, titanite and epidote partially to completely replace the high-grade assemblage while wholesale amphibolitisation accompanied by ductile deformation. Retrogression continued during and after main deformation (at c. 460 Ma) when fluid infiltration was strongly controlled by fracturing and late pegmatite intrusion at c. 455 Ma. Fluid infiltration thus spanned a maximum of c. 25 Ma.

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Geological Magazine, 137, 419-435, (2000).

FMF6 : MOPm24 : F4

How Time-Integrated Fluid-Flux should Constrain the Hydrothermal Mineralization Potential of a Faulted Rock Volume: A Comparison between 3D Fluid Flow Simulations and Measured Gold Content at the Sigma Mine, Quebec, Canada

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The spatially variable time-integrated flux of a metal-transporting fluid through a fractured rock assemblage places an upper bound on its potential hydrothermally-induced metal enrichment. Since permeability varies spatially, fluid flux can vary accordingly, affecting this metal-enrichment potential. However, a high paleo-permeability does not automatically imply a high time-integrated fluid flux through the corresponding lithology or structure, because flux magnitude depends on the orientation of the highly permeable feature relative to the far-field fluid pressure gradient and on the structure's position relative to other high-permeability domains. Furthermore, in a hydrothermal system with arrays of highly permeable zones, these interact, inducing complex spatial variations of the fluid flux.

We have numerically simulated hydrological interaction patterns of permeable faults using a fault dilatancy- and structural observation-based permeability model for a central portion of the Sigma goldmine, Quebec, Canada. The simulated spatial variations of fluid flux are compared with the observed gold-grade variations along the planes of the faults in the mine and so are the mass-flux and gold-grade spectra, respectively.

Our modeling predicts that the highest time-integrated fluid fluxes occur where faults intersect and in rock bridges between faults which terminate very close to one-another. High fluid fluxes also occur in the central portions of isolated faults oriented parallel to the far-field fluid pressure gradient. However, where faults occur close to parallel interconnected faults or form short branches of faults with larger dimensions, they are largely bypassed by the flow. At the Sigma mine, the highest gold grades occur at near-vertical fault branchlines and at fault intersections. Isolated faults still contain quartz but lack gold mineralisation. These observations are in very good agreement with our model predictions.

The important result for exploration and mine development is that our numerical simulations yield a new hydrological criterion to discriminate mineralized from barren structures. If the fault geometry is constrained before the onset of mining, as is possible via 3D high-resolution seismic data, this approach offers a faster recognition of the high-grade zones and permits more selective underground mining.

FMF6 : MOPm25 : F4

Fluid-Rock Interactions at the Brittle-Ductile Transition: Pressure-Temperature-Salinity Effects

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Most recent rheological models of lithospheric extension consider conduction heat transfer as the main factor of cooling during exhumation of metamorphic core complexes. Nevertheless, systematic hydration reactions occurring in the vicinity of an extensional detachment attest to the existence of intense fluid circulation, which must have an effect on the thermal regime of late-stage exhumation. In this study, we use a combination of structural geology, oxygen stable isotope and fluid inclusion analysis to constrain the temperature, pressure and fluid chemistry evolution along a crustal scale detachment of Tinos island (Cyclades, Greece). Best record of the temperature gradient attending the brittle-ductile transition is given by quartz/calcite/chlorite veins formed during the retrograde path. Preliminary $\delta_{18}O$ thermometry on quartz/calcite and quartz/chlorite pairs has revealed a temperature shift of almost 350°C on a 90 m thick cross section normal to the contact. Such a drastic cooling is best interpreted as the result of massive fluid discharge along the footwall of the detachment. Detailed cathodoluminescence analysis of individual quartz-calcite veins allowed identification of at least two generations of quartz/calcite pairs in isotopic equilibrium. High resolution $\delta_{18}O$ thermometry of each generation using SIMS technique allowed characterising the cooling history in a single vein and in different veins collected along a profile normal to the contact. Microthermometry on fluid inclusions trapped in quartz and calcite shows a decrease of salinity towards the detachment from 11 weight% NaCl equivalent in blueschist rocks, to almost pure water (3 weight% NaCl equivalent) in the highly retrogressed shear zones. These results argue for the dilution of a saline-rich brine of metamorphic origin by "downward" meteoric water or seawater infiltration along the detachment. Pore fluid estimates are inferred from oxygen fractionation temperatures projected on model isochores of fluid inclusions in a P-T^o diagram. This allows a comparison of hydrostatic pressure vs lithostatic pressure. These results represent the first complete data-set of fluid pressure, temperature and composition along a crustal scale detachment, which are of crucial importance for constraining the role of fluid advection on the thermal regime.

FMF6 : MOPm28 : F4

Tectonic Contacts as Fluid Channels for Fluids Released during Subduction of the Zermatt-Saas Zone

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Massive zones of talc-schists along the borders of serpentinite bodies, and chlorite-schists bordering eclogites, are found in the Zermatt-Saas Zone. To convert serpentinite to talc-schist, increase of SiO₂ (16.5/100 g) with small losses of Al (1.5 g) and MgO (1 to 6 g) occur at near constant volume. To convert eclogite to chlorite-schist, loss of SiO₂ (16/100 g), CaO (5 g), Na₂O (5 g), with gains of MgO (31 g) and H₂O, occurs with 30% volume increase. The conversion of eclogite to chlorite-schist experienced elemental losses that were not compensated by gains of the talc-schist. This mass loss suggests an advective component to the metasomatism. Mass-balance indicates advective addition of SiO₂ some 6 to 10 times larger than the diffusive amount added. Structural and stable isotope arguments are presented to constrain the timing of dehydration fluids released during subduction of the Z-S Zone. The rising fluid triggers metasomatic formation of talc-schist as a "whitewall", and chlorite-schist as a "blackwall", at the contact between metabasalts and serpentinites, and then subsequently migrate upwards along tectonic contacts.

**FMF6 : MOpm29 : F4
Influence of Deformation and Fluid Flow on Ar/Ar and Rb/Sr Systematics in the Aar Massif Shear Zones (External Crystalline Massifs, Switzerland)**

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The aim of this study is to test the isotopic behaviour of two radiogenic systems within ductile shear zones open to fluid circulation. We focused our attention on biotite and white mica ³⁹Ar-⁴⁰Ar and Rb-Sr systematics because they are classically used to constrain regional cooling history. The late Variscan Aar metagranite and Grimsel granodiorite belong to the External Crystalline Massifs (ECM) in the Central Swiss Alps. They underwent Oligo-Miocene heterogeneous deformation under greenschist facies conditions (450°C, 6 kbar).

The P-T-t path of the ECM was modelled using geological and metamorphic constraints without considering data based on mineral ages. Taking the beginning of overthrusting at 33 Ma, this model shows that the P peak and the T peak are reached at 23 Ma and 18 Ma, respectively.

In two pluri-decimetric shear zones, we selected a weakly deformed metagranite, an orthogneiss, and a mylonite exhibiting different grain sizes, in each shear zone. Biotites and phengites were separated and analysed by ³⁹Ar-⁴⁰Ar stepwise heating and Rb-Sr. ³⁹Ar-⁴⁰Ar biotites and white micas ages give results (21-16 Ma) close to the calculated T peak conditions irrespective of their mineral grain size while Rb-Sr whole rock-mineral ages scatter from ages corresponding to T peak conditions to young ages around 10 Ma in the deformed samples. The similarity of ages on the different micas and the lack of systematic grain-size / age relationships argue that volume diffusion was a negligible process. Instead, they provide evidence for the strong influence of late fluid circulations in the high-strain zones. Temperature is not the main limiting parameter of the isotopic closure; fluid circulation provides more rapid exchange and therefore plays a greater role in isotopic resetting. Furthermore, this study shows that the ³⁹Ar-⁴⁰Ar method allows to date the last stage of ductile deformation, i.e. temperature peak, and that on appropriate minerals it may be less sensitive to late fluid circulations than the Rb-Sr method.

Dating the D1 deformation at 23-18 Ma gives new indications on the Oligo-Miocene tectono-thermal evolution of the ECM. These new results emphasise large fluid circulations through the ECM at around 10 Ma, correlated with the occurrence of late fluid inclusions in quartz veins. This late fluid flow could correspond to deep fluid expelled during the underthrusting of European continental crust below the ECM at the time of the Jura formation.

**FMF6 : MOpm30 : F4
High Grade Fluid Metasomatism on both a Local and Regional Scale: K-Feldspar-Quartz Grain Boundary Reaction Textures as a Product of Solid State, Fluid Induced Dehydration of Amphibolite Facies to Orthopyroxene-Bearing Granulite Facies Rocks**

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During the granulite facies metamorphism of metaigneous rocks, hornblende and biotite break down, in the presence of quartz, into orthopyroxene, clinopyroxene, feldspar, and a fluid phase. Vapour-absent melting has been proposed as the principle force behind these dehydration reactions. However, what ultimately induces these minerals to break down is apparently not always a matter of pressure, temperature, and subsequent spontaneous partial melting. Solid state dehydration, induced by pervasive high grade fluid flow, without any direct evidence of a melt being present, has been shown to be a distinct reality, at least on a limited scale. Geological evidence exists that on a scale of centimetres to a few meters, localised, CO₂ induced dehydration zones in metaigneous rocks can be generated under granulite facies conditions (Todd & Evans, 1994). Other

workers have proposed that, on a more regional (km) scale, low H₂O activity, concentrated or supercritical Cl-rich brines could play a major role in the dehydration of hornblende- and biotite-bearing gneisses to orthopyroxene-bearing granulites (Newton et al., 1998). In a number of these dehydration zones, both local (Todd & Evans, 1994) and regional (Harlov & Wirth, 2001), K-feldspar reaction textures (micro-veins) along quartz/plagioclase and plagioclase/plagioclase grain boundaries as well as replacement anti-perthite have been proposed as evidence for the presence and passage of these "dry" fluids. Modal mineral analysis suggests that the K⁺ required for these features, principally came from the localised, fluid induced, solid-state breakdown of hornblende to orthopyroxene ±clinopyroxene in the presence of quartz.

The limited infiltration range (< 2 m; Harris & Bickle 1989) of CO₂ to penetrate rock along grain boundaries is due to its very high wetting angles. This has been confirmed in grain boundary experiments at 1000 MPa and 950-1200°C along the CO₂-H₂O join by Watson & Brenan (1987). In distinct contrast to CO₂, grain boundary experiments at 1000 MPa and 950-1150°C, involving both concentrated Cl and F brines, indicate that they have both a low viscosity and a low wetting angle (Watson & Brenan, 1987). This allows them to form a highly interconnected network along grain edges, thus allowing for the possibility of fluid transport by porous flow over relatively large distances. Experimental evidence also indicates that at granulite grade pressures (> 4 kbar) and temperatures (> 600°C), the activity of H₂O approximates the H₂O fraction squared or higher as opposed to simply the fraction of H₂O present (Aranovich & Newton, 1997). The implication is that fluid induced dehydration of amphibolite facies rocks to orthopyroxene-bearing granulite facies rocks could still occur at relatively high fractions of H₂O as well as over relatively large distances compared to CO₂.

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**FMF6 : MOpm31 : F4
Heterogeneous Fluid Distribution during Prograde and Retrograde Evolution in the Pointe Géologie Gneissic Basement (Terre Adélie- East Antarctica)**

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In Pointe Géologie area (66°40'S - 140°00'E)(Terre Adélie - East Antarctica), the paleoproterozoic basement mainly consists in a migmatitic complex of metasedimentary origin. The metasediments underwent a thermal event leading to the high-grade amphibolite facies assemblages bt-crd-sill ±gt and to dehydration melting reactions at 3.5-5.5 kb and 650°-750°C conditions. Retrogression in greenschist facies followed at 450°C±1 kb. Field observations, mineral chemistry and petrological analysis are consistent with heterogeneous water distribution from early anatectic peak to retrogression. In most of the archipelago, anatectic sill = cd ± gt ± kfs ± bi assemblage in Kfs rich-migmatites (KFG). Locally, along EW north deeping decametric bands of nodulose gneiss (NG), partial melting is restricted to a few plg-q ± kfs leucosomes. These bands are systematically limited upward by granitic layers. Pseudosection calculated for peak conditions including melt composition for both KFG and NG, show that they underwent partial melting to different extent. Commonly, the retrograde imprint facies in migmatites and anatectic granites, is quite weak and expressed by an overall bi-mu ± and ± gt equilibrium assemblage whereas it is more developed along the EW bands with mu-bi ± gt ± chlorite paragenesis suggesting more extensive rehydration. Such differences suggest that partial melting and retrogression occurred at different H₂O contents between NG and KFG. At 450°C, a pseudosection shows that hydrated assemblage (bi-mu nodules) in NG requires at least 10-20% more H₂O

than KFG (cd-mic-sill-and). K₂O and Al₂O₃ contents in the bulk rock composition have no significant influence on pseudosection geometry. Therefore, H₂O appears to be the main variable and pseudosection geometry suggests that the heterogeneous distribution of water was effective before retrogression, i.e. during the partial melting event. The particular orientation of EW north deeping bands of NG, underlined by anatectic bands suggests that partial melting and water distribution was driven by early extensive structures related to the regional early extensive tectonic stage in the archipelago. Before the anatectic peak, shear zones act as drain collecting fluids and dehydrating adjacent zones. During retrogression, fluids circulate preferentially in the NG where anisotropy was preserved. Consequently, bands of nodulose gneisses are interpreted as paleochannels more extensively retrogressed.

Such a schema contrasts with those generally found in the literature where fluids circulation appears to be mainly controlled by late tectonic structures such as shear zones. In Pointe Géologie, geometry of the channels is inherited from early tectonic structures of the gneissic basement.

**FMF6 : MOpm32 : F4
Reaction-Induced Microcracking during Pyrometamorphism, Isle of Mull, Scotland**

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The Loch Scridain area in the south of the Isle of Mull has been intruded by a Tertiary swarm of gabbroic sills. One of the largest of these sills outcrops at Traigh Bhan na Sgurra, where it intrudes garnet-grade pelites and psammities of the Moine Schist and varies in thickness between 1.5 m and 6 m. In places, the flow of magma within the sill was turbulent, with no chilled margins and a wide contact aureole. Petrographic analysis was undertaken of a detailed sampling traverse away from the lower contact of the sill within a psammitic horizon.

The lowest temperature evidence for contact metamorphism is the development of inter- and intra-granular cracking due to thermal decompression, some 4 m from the contact. At about 3.5 m from the contact, muscovite breaks down via a metastable melting reaction to a fine-grained mixture of biotite, mullite, spinel, corundum and melt. The solidified melt phase occupies a set of fine-scale cracks radiating away from the reacted muscovite grains. Observations of the cracks using cathodoluminescence show that many of these melt-filled cracks re-use an earlier set of healed, quartz-filled cracks related to the regional metamorphic event.

Upgrade from the muscovite breakdown, the interphase boundaries between quartz and feldspar grains are replaced by a fine-grained granophyric intergrowth as melting occurs in the system Qtz-Ab-Or±H₂O. These melt sites also have granophyre-filled cracks emanating from them.

The melt in the contact aureole is confined entirely to the sites of reaction and the crack networks formed during the melting event either by thermal decompression or by internal overpressuring. No evidence is seen for melt segregation or textural adjustment in response to minimisation of internal energies.

Thermal modelling of the aureole, using a simple two-stage model with an early stage during which the contact is held at the magmatic temperature and a later stage during which both the intrusion and the aureole cool by conduction, can be constrained by the profile of maximum temperature obtained from the observed reactions. The model is consistent with a magma flow episode lasting 5 months. This is longer than the duration of experiments during which full textural equilibrium is achieved, demonstrating that the rate of melt production during reaction is a critical factor in determining whether melt distribution is controlled by reaction or textural equilibrium.

FMF6 : MOPm33 : F4**Observations of Melt Localization in Deforming Two-Phase Rocks****Benjamin Holtzman**(holtzman@dstu.univ-montp2.fr)¹,**Mark Zimmerman**(mark@olivine.geology.umn.edu)²,**Nathan Groebner, Susan Ginsberg,****David Kohlstedt** (dlkohl@tc.umn.edu) &**Jason Phipps Morgan**³¹ Laboratoire de Tectonophysique, Univ. de Montpellier, France² Dept. of Geology & Geophysics, Univ. of Minnesota, USA³ GEOMAR, Kiel, Germany

We observe melt localization in two types of partially molten synthetic rock samples deformed in a simple shear geometry: anorthite + basaltic melt and olivine + chromite + mid-ocean ridge basalt (MORB). In these experiments, the melt concentrates into bands at least several times wider than the grain scale. These "melt bands" consist of melt located in oriented, connected, pocket-like pore spaces with melt fractions significantly higher than the background. In contrast, in two other systems, olivine + MORB and olivine + albite melt, the melt is found in uniformly distributed, connected pockets without the larger scale organization in bands. In these simple shear experiments, the melt pockets have approximately the same orientation as the bands (in those experiments with bands), ~20 degrees to the shear plane. The presence or absence of melt bands can be predicted by comparing the compaction lengths of each system to the known length scales of pressure perturbations in the experimental apparatus. These perturbations are caused by peaks and grooves in the tungsten pistons used to grip the sample during shear. The compaction length is defined as $L_c = (k/\mu)^{1/2}$, where k is the permeability, μ is the solid viscosity, and μ is the melt viscosity; physically, it is the length over which melt migration and solid deformation are coupled. If the compaction length is smaller than the scale of the pressure perturbations, melt instabilities nucleate at these perturbations and propagate towards the sample center. If the compaction length is larger than the scale of the perturbations, melt is distributed uniformly across the sample. Scaling and application to natural systems involves an understanding of the driving forces for melt segregation and of the compaction length dependence. We combine analyses of finite strain, melt distribution, and olivine crystallographic fabric in the olivine+chromite samples to characterize the heterogeneity of deformation mechanisms and rheology in the deforming system. Comparing these data with the results of numerical simulations enables us to quantify the driving forces of melt localization and the weakening effect of melt bands on the rock viscosity. The segregation of melt in deforming rock into aligned bands increases permeability in a highly anisotropic manner; this segregation has significant implications for melt transport and melt/rock interaction in many geologic settings. Furthermore, simple scaling suggests that bands forming in partially molten mantle should be spaced at length scales smaller than the wavelength of an S-wave. Thus, if these melt distribution processes scale to natural conditions, they may produce predictable and testable shear wave splitting characteristics in deforming, melt-producing regions of the mantle and lower crust.

FMF6 : MOPm34 : F4**Dilatant Behaviour in Sheared Magma****Suspensions: Melt Movement and Pore Fluid Pressures****Nick Petford** (n.pet@king.ac.uk) &**Curt Koenders** (koenders@kingston.ac.uk)

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We present a quantitative treatment for the macroscopic behaviour of a sheared crystal mush using a modified form of Biot's theory. Shearing of densely packed granular media during magma ascent or emplacement results in a phenomenon known as dilatancy. Calculations relevant to magma in the range 55 to 70% solids for high viscosity (granitic) magmas show that the resulting excess pore pressure distribution is a function of position and the time (eg. Koenders & Petford, 2000). A sensitivity study of the parameters describing the rheology of the solid matrix (including permeability features) will be presented that allows estimates of pressure and flow rates, thus opening a way of understanding features in deforming crystal mushes caused by upflowing magma. At high strain rates (c. $10^{-10}s^{-1}$), flow rates due to shear far exceed melt movement associated with

buoyancy effects. As a result of the upflow of the pore fluid certain layering effects may take place, as well as particle size segregation. Crystal size segregation is predicted with effects similar to geotechnical filtration problems. The grain size at which the magma has been crystallised is shown to be relevant to the development of excess pore pressure at continued shearing. The reigning pressure regime is compared to the stresses required for fracturing of the skeletal elements. At higher loading rates typical of the emplacement regime ($> 10^{-14}s^{-1}$), shear-induced dilation in granitic magmas with high solidosities ($\phi > 0.5$), can lead to fracture. The available excess skeletal pressure at a given strain rate is a function of grain size and tortuosity, with higher skeletal pressures favoured by smaller mean particle size.

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