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# HT SHEAR ZONES
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# Abstract volume

# HT SHEAR ZONES IN THE LITOSPHERE
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# ABSTRACTS

## HIGH - TEMPERATURE SHEAR FLOW IN THE CRUST AND UPPER MANTLE: IN SEARCH FOR RELATIONSHIPS AND GEODYNAMIC SETTING

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Decades of research in high-grade crustal rocks has provided ample evidence that the deeper continental crust may be affected by intense deformation at temperatures as high as those required for partial melting. Likewise, there is growing field-based evidence of high-temperature flow in upper mantle peridotites in the presence of a melt. Studies, however, of high-temperature deformation in crustal rocks are seldomly connected to similar studies in upper mantle rocks and vice versa. Instead, our understanding of such high-temperature processes at the scale of the entire lithospheric column is commonly inspired by modelling studies, rather than by field observation in crustal and upper mantle sections affected together by one and the same lithosphere-scale process responsible for high-temperature shearing. One reason obviously is that the Earth surface provides limited exposure of upper mantle rocks, and where such exposures occur, primary relationships with the pertinent crustal rocks are commonly overprinted by intense later ductile and brittle shearing associated with mantle emplacement. In addition, the available exposure of mantle fragments of subcontinental origin is even more limited, as many mantle sections are clearly ophiolitic and thus reflect ocean ridge and ocean floor processes instead of those associated with extensive melting in continental crust. Studies of high-temperature metamorphism in crustal rocks often conclude that the heat needed to explain the observed metamorphism and crustal melting cannot have been generated by the crust itself, and that some process in the mantle is needed involving the rise of the thermally defined asthenosphere. The Variscan belt of western Europe seems a very good candidate to explore such processes, and future field-based research in the Variscan may focus on potential relationships between the tectono-thermal histories in the crustal and mantle parts of such deforming, thermally anomalous lithosphere.

## MICROSTRUCTURES IN HOLE 1274, ODP LEG 209, MID-ATLANTIC RIDGE - TRACKING THE FATE OF MELTS PERCOLATING IN PERIDOTITE AS THE LITHOSPHERE IS INTERCEPTED

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Any asthenospheric peridotite rising under an ocean ridge must encounter at one point the thermal boundary layer, i.e. the base of the lithosphere. For slow spreading conditions, the conversion of asthenospheric to lithospheric peridotite may occur in a steep flow orientation, thus avoiding the accumulation of large shear strain during corner flow conditions in fast spreading. Slow spreading conditions thus favor the preservation of pristine microstructures related to the decompression (melting) regime. We report the microstructures of harzburgites and dunites from ODP Leg 209, Site 1274, 15°N in the Mid Atlantic Ridge. A set of features in these peridotites is so unaffected by plastic flow that they must have formed very late by magmatic processes. We believe that they record the interaction between a peridotite and a percolating melt as the thermal boundary layer was encountered (cf. Seyler et al., 2007). The following chronology is derived: 1st association - resorption of opx associated with olivine precipitation, enhanced by a migrating melt; 2nd association - conversion of opx to cpx by a percolating melt; 3rd association - precipitation of cpx and spinel as intricate intergrowth (symplectite), associated with olivine dissolution, from an interstitial melt. The chronological order is derived mainly from critical samples near dunite-harzburgite contacts. For the reactions, the ratio of melt generated to melt consumed is progressively decreasing, as would be expected for a peridotite encountering the base of the lithosphere. Analogeous microstructures to Site 1274 are found in the Lanzo Massif and the Little Port Complex Ophiolite. For all three settings we can infer slow spreading conditions and, surprisingly, an ancient depletion event. We thus suggest a model where the combination of two features is required to generate and preserve the reported microstructures: (1) slow spreading in order to avoid accumulation of strain during corner flow; (2) a harzburgitic residue at the end of melting, allowing for high melt permeabilities. Since slow spreading typically generates lherzolitic residues (because a thick lithospheric lid terminates the melting) with poorer permeabilities, we require that a source with a previous depletion history entered the decompression regime.Seyler et al, 2007, CMP 153, 303-319

## THE COMPOSITE STRUCTURAL FRAMEWORK IN VARISCAN HIGH-GRADE METAMORPHICS: AN EXAMPLE FROM THE PORTO OTTIOLU-PUNTA DE LI TULCHI AREA (NE SARDINIA, ITALY)

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The Porto Ottiolu-Punta de li Tulchi area represents the southern part of the sillimanite + K-feldspar zone and is located in the axial zone of the Variscan chain of NE Sardinia. In this area, an Ordovician migmatized orthogneiss outcrops in contact with its sedimentary cover, now consisting of sillimanite paragneiss, layered migmatite and rare calc-silicate nodules. Towards Punta de li Tulchi, biotite content in the migmatized orthogneiss decreases and rocks appear leucocratic and nebulitic. At Punta de li Tulchi, a 100m-long, 20-30m-thick metabasite lens with eclogite facies relics oriented N 80°-60° is hosted in nebulitic migmatite.

The layered migmatite, paragneiss and migmatized ortogneiss show a composite structural framework.

The first deformation event ($D_1$) is poorly constrained but it is at times clearly recognizable as rare intrafoliar folds in the paragneisses.

The second event ($D_x$ or $D_2$ according to Franceschelli *et al.*, 1989) generates the most pervasive foliation $S_2$, striking N 60°-70° and dipping 30°-70° towards SE. This schistosity is the axial plane foliation of tight folds with sub-vertical axes. More rarely, the $D_2$ phase is related to eyed folds with axes striking N 80°-100°. The Dx phase also folded centimeter-thick granitic leucosomes.

On the XY plane of the $S_2$ schistosity, three types of polymineralogical lineations were recognized. From the oldest to the youngest, they are: (i) K-feldspar + quartz rod lineation oriented N 70°-80° SW 30° and N 140°-150° SE 40°; (ii) Fibrolite lineation oriented N 150°-160° SE 20°-40°; (iii) Muscovite lineation striking N 50°-70° and dipping 2°-20° NE-SW. Kynematic indicators such as $\sigma$, $\delta$ porphyroblasts, S-C planes and asymmetric boudins suggest a generally top-to-the-SE shear component.

The $D_2$ folding phase is followed by two main shear events. The first one generated sinistral shear zones of about 2-3 cm in thickness, striking NEE-SWW. The most impressive structures related to the second shear event are tension gashes in the migmatized orthogneiss (sinistral shear component) and S-C planes (both dextral and sinistral shear components) with synkinematic intrusions of granitic leucosomes. These structures strike NW-SE and, according to Corsi and Elter (2006), could be defined as Y shear zones related to the main Posada Valley Shear Zone. Several leucosomes, mostly in the orthogneiss, are intruded along shear bands oriented N 70° and characterized by S-C structures with a left shear component.

The $D_3$ folding phase mainly produced open to tight decimetric folds lacking any pervasive axial plane schistosity, with axes striking E-W and dipping about 5°-20° E-W. These folds can sometimes be observed near the contact between migmatite and the metabasite lens at Punta de li Tulchi. $D_3$ deformation was followed by late shear events and minor foldings.

The metabasite with eclogite facies relics at Punta de li Tulchi shows a banding oriented EW – N 50° at a high angle with respect to regional migmatite foliation, consisting of an alternation of garnet-pyroxene-rich and amphibole-plagioclase-rich layers.

Garnet-pyroxene-rich layers show preferred layering defined by thin dark and white layers consisting of alternating garnet rich- and clinopyroxene-plagioclase symplectite-rich layers parallel to the main $S_x$ schistosity. Garnet shows inclusion of omphacitic pyroxene.

Individual lobes of symplectitic lamellae are roughly aligned locally along a preferred orientation forming a high angle with $S_x$. This feature might indicate mimetic growth of lobes along an older $S_1$ (?) schistosity. Grain-size variations along and between garnet-pyroxene-rich layers, as well as garnet elongation in the same layers, suggest the occurrence of syn-$D_2$ deformation along shear zones. Moreover, the amphibolitization of the original granulitic rock is clearly recognizable in some outcrops showing an amphibolitic front with faded contours, clearly cutting the $S_2$ of replaced granulitic layers.

In amphibole plagioclase-rich layers, a third N 80°-SE 30°-oriented retrograde $S_{x+1}$ foliation is defined by thin elongated white pods made up mainly of plagioclase-amphibole kelyphites. The $S_3$ is locally cut by centimeter-sized shear zones which developed after the amphibolite stage.

Both the migmatite and metabasite are affected by minor duttile and two major brittle deformations. The first brittle deformation consists of a very rare event forming millimetric, discontinuous E-W-oriented shear zones with a sinistral shear component.

The second one is the most important brittle event. It strikes NE-SW subvertical, and is recognizable in the whole migmatite complex of NE Sardinia, where it is related to syn-kinematic intrusions of mafic to acid dikes.

In summary, in the Porto Ottiolu-Punta de li Tulchi area, the Variscan basement of Sardinia is affected by at least three main deformation phases. The first phase is not clearly recognizable, either in the metasedimentary sequence or in the metabasite with eclogite facies relics. The $D_2$ phase is the most pervasive deformation in the migmatites and metabasite and can be linked to the granulite or the granulite-amphibolite transition. The $D_2$ phase is probably a composite phase associated with folding and shear deformation that developed under amphibolite facies P-T conditions. A late shear event postdating the $D_3$ deformation developed under green schist facies P-T conditions. The occurrence of kyanite, sometimes associated with K-feldspar, reveals that migmatites most probably attained the P-T conditions of the granulite facies.

Therefore, since the granulitic stage, eclogites and migmatites have shared the same structural and metamorphic history. Whether or not migmatites also underwent the eclogitic stage may be clarified by further studies, such as those involving new geochronological and systematic data on inclusions in zircon.

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# GEOMETRY OF DEFORMATION, STRAIN FEATURES AND DISTRIBUTION OF MAGMATIC-BODIES IN THE HIGHER HIMALAYA CRISTALLINE BETWEEN KARTA AND TINGRI (TIBET-HIMALAYA)

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As described by different authors (e.g. Rosenberg et al., 2006 and references therein) the presence of melt can be closely related to localization of deformation in a variety of crustal-scale fault zones. This supports the idea of a positive feedback between melting and faulting (Brown & Solar 1998) and grants melt a critical role in shaping major features of the inner part of orogens.

Field relationships between melting and faulting within the Higher Himalaya Cristalline unit (HHC) in the Tibet-Himalaya orogen are the object of a controversial debate (Rosenberg et al., 2006). In this contribution we present a crustal scale cross-section through the HHC between the Main Central Thrust zone (MCT) and the South Tibetian Detachment (STD) emphasizing the geometry of deformation, granite distribution and shape as well as their internal strain features.

The cross section is based on a new structural map by Pertusati & Lombardo of a region of c.300 kmq between the Ra Chou (Tingri) and the Choung Chou (Karta) valleys including Cho Oyu, Everest, Lotshe and Makalu peaks. In the region, Miocene leucogranites can be found in different geometrical positions and with different internal strain state.

Three different structural domains are recognizable at the scale of the whole HHC. A central domain, with a total thickness of c. 5 Km, is characterized by three giant sill complexes with individual thickness up to 1,5 Km. The sills are intruded parallel to the main foliation and show local effects of ballooning at their terminations (e.g. Nuptse pluton). Solid state deformation is localized at their boundary whereas the bulk of bodies shows magmatic features. The central domain is bounded upward and downward by two kilometer-scale domains in which dykes and sills up to hundreds of meters in thickness can be observed. High temperature solid state deformation with opposite kinematics dominates in the two boundary domains. Top-to-north \”extensional\” shearing is dominant in the upper domain. Sills and dykes can be observed in the footwall shear zone of STDS up to few decimeters from the brittle detachment. Top-to south \”contractional\” kinematics locally characterizes the lower domain, although more commonly sills and dykes can be observed as folded with the main foliation in hectometric scale top-to south collapse folds. Granite distribution and deformation features in the investigated area will be compared with the recently proposed model of the melt-dominated channel of a crustal scale \”extrusional fault\” (Rosenberg et al., 2006).

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# PLUTON EMPLACEMENT IN THE LAB - WHAT WE CAN LEARN FROM ANALOGUE CENTRIFUGE EXPERIMENTS ABOUT THE BEHAVIOUR OF GRANITOID BODIES

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Three main features are frequently observed in granitoid plutons: (1) they are often intruded along shear zones; (2) many of them consist of several magma batches to form so-called CEPs – concentrically expanded plutons; (3) geophysical investigations reveal that they generally possess a tabular shape: either laccolithic, lopolithic or phacolithic.

We used the results of three sets of experiments to understand the formation mechanisms behind these three features. Moreover, we wanted to find out if diapirism or dyking are more suitable for the formation of shear-zone related plutons, CEPs and tabular plutons.

1 - Plutons in shear zones:

Models (100 mm long and 80 mm wide) consisting of a ca. 25 mm thick overburden resting on a 6 mm thick buoyant PDMS layer ($\mu = 4* \quad 10^4$ Pa s, $\rho = 0.964$ g/cm$^3$) were sheared and centrifuged to study the relationship between strike-slip shear zones within the continental crust and buoyant granitoid intrusions. Three experiments were carried out: In model 1, the overburden consisted of a viscous material ($\mu = 10^5$ to $10^6$ Pa s, $\rho = 1.725$ g/cm$^3$). No perturbation as a trigger for diapirism was introduced at the top boundary of the source layer (PDMS) in this experiment to see, if shearing alone is capable to initiate the diapiric rise of the PDMS. No diapirs formed in this model even after shearing up to an angular shear $\gamma$ of -1.07 and 27 min centrifuging at ca. 700 g. In models 2 and 3, where the overburden was made of a semi-brittle plastilina ($\mu$: $10^7$ to $10^8$ Pa s, $\rho$: 1.705 g/cm$^3$), prescribed cuts at two different orientations (model 2: parallel to $\sigma1$; model 3: perpendicular to $\sigma1$) were initiated in the overburden in order to see whether such cuts can act as pathways for intrusions. In model 2, the prescribed cuts were used by the buoyant material as pathways because they had opened due to combined shearing ($\gamma = -0.33$) and centrifuging for 8 min at ca. 700 g. Consequently, the PDMS extruded on the surface of the model. Continued shearing (up to an angular shear of -0.38) and centrifuging for further 5 min at ca. 700 g widened the cuts and allowed further upward movement of the buoyant material to form a coalesced elliptical sheet on top of the model. In model 3, where the pre-existing cuts were perpendicluar to $\sigma1$, the cuts were cealed during shearing and prevented the intrusion of the buoyant material. Further shearing up to an angular shear of -0.38 and centrifuging at ca. 700 g rotated and activated the prescribed cuts as strike-slip faults bounding pull-apart basins. Such pull-apart basins were not deep enough to tap the buoyant material. Nevertheless, the results of the experiments suggest that magma ascends in shear zones not as diapirs, but rises along pre-existing pathways as dykes.

2 - CEPs

The 100 mm wide model consisted of three layers from bottom to the top; a 5 mm thick buoyant lower layer of (RG1; $\mu = 8.5* 10^4$ Pa s, $\rho = 1.224$ g/cm$^3$) simulating a partially molten magma ($\mu = 8.5* 10^{18}$ Pa s, $\rho = 2.45$ g/cm$^3$), a 50 mm thick non-Newtonian overburden (DC+P; $\mu = 10^6$ Pa s, $\rho = 1.344$ g/cm$^3$) simulating a natural silicic overburden ($\mu = 10^{22}$ Pa s, $\rho = 2.7$ g/cm$^3$); and a 10 mm thick layer of PDMS ($\mu = 4* 10^4$ Pa s, $\rho = 0.964$ g/cm$^3$) simulating a less dense overburden. The model was centrifuged for 9 min and 30 sec at 700 g before a profile was cut for photographing. Two mushroom-shaped diapirs of the buoyant layer intruded the overburden and spread below the top, less-dense PDMS layer. During their rise, the diapirs deformed the overburden units and dragged them upward. A second buoyant layer of similar density and viscosity as the first buoyant layer, (differently stained, RG2; $\mu = 8.5x10^4$ Pa s, $\rho = 1.224$ g/cm$^3$) was attached to the bottom of the model. The model was then centrifuged for further 6 min and 10 sec at 700 g. A profile of the model shows that the second-stage intrusions occurred along the stems of the preexisting diapirs, which were easier to intrude than producing new intrusion paths. The second intrusion was not diapiric, instead the second buoyant material rose as dykes using the stem of the preexisting diapir as a mechanically weak pathway. Once reaching the level of neutral buoyancy, the intrusive material spread laterally resulting in extensive expansion of the overhang of the pre-existing diapirs. Model results show that nested diapirs are not necessarily the result of multiple phases of diapirism. Instead, they can be the result of subsequent "ductile" dyking of buoyant material through the stems of preexisting diapirs. Consequently, nested intrusions (such as CEPs) can form only when the stems of the earlier intrusions remain weak.

3 - Phacoliths

This model (67 mm high and 100 mm wide) was build of a sequence of 14 differently stained plastilina layers (between 2.5 and 7 mm thick; $\mu = 4.2* 10^4$ Pa s, $\rho = 1.71$ g/cm$^3$). At the base and in the middle of the model, two 5 mm thick buoyant PDMS layers ($\mu = 4* 10^4$ Pa s, $\rho = 0.964$ g/cm$^3$) were introduced with 7 mm thick cuboidal protrusions atop of each other to cause the formation of two diapiric intrusions. After centrifuging for 30 min at 700 g, the model was sectioned. The PDMS of both the buoyant layers had risen only a few millimeters to form two lenticular sills (phacoliths) of 30 mm long and 10 mm high directly above both the cuboidal protrusions. During their move, the PDMS phacoliths had pushed their hanging wall plastilina upward and pressed down their footwall plastilina simultaneously. Pushing down of the footwall material choked the inflow of further PDMS into the feeder channel of the developing PDMS sills and inhibited their further lateral growth or the continuation of their rise through the plastilina overburden. The observed forced downward movement of the plastilina footwall of the forming PDMS phacoliths resembles the so-called "ductile downward flow" of host rock material around a rising pluton. Ductile downward flow of crustal rocks is supposed to be a very important vertical material transfer process which provides space for granitoid diapirs ascending through the Earth's crust. The downward pushing of host material made space for the developing PDMS phacoliths, but also inhibited their growth. This may indicate, that ductile downward flow is a viable space making process for the emplacement of a pluton, but not for its diapiric ascent.

In conclusion, all our experiments suggest, that a soft buoyant material (may it be PDMS or RG in experiments or granitoid magma in nature) rises more easily through a stiffer overburden (may it be a mixture of plastilina with silicone putty or pure plastilina in experiments or silicic crustal rocks in nature) as dykes along mechanically weak zones than diapirically by vertical material transfer processes.

## RHEOLOGY AND DEFORMATION OF PARTIALLY MELTED CRUSTAL ROCKS

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A review and reinterpretation of previous experimental data on the deformation of melt-bearing crustal rocks (Rosenberg and Handy, 2005) revealed that the relationship of aggregate strength to melt fraction is non-linear, even if plotted on a linear ordinate and abscissa. At melt fractions < 0.07, the dependence of aggregate strength on is significantly greater than at > 0.07. This melt fraction (= 0.07) marks the transition from a significant increase in the proportion of melt-bearing grain boundaries up to this point to a minor increase thereafter. Therefore, we suggest that the increase of melt-interconnectivity causes the dramatic strength drop between the solidus and a melt fraction of 0.07. A second strength drop occurs at higher melt fractions and corresponds to the breakdown of the solid (crystal) framework, corresponding to the well-known "rheologically critical melt percentage" (RCMP; Arzi, 1978). Although the strength drop at the RCMP is about 4 orders of magnitude, the absolute value of this drop is small compared to the absolute strength of the unmelted aggregate, rendering the RCMP invisible in a linear aggregate strength vs. melt fraction diagram.

Predicting the rheological properties and thresholds of melt-bearing crust on the basis of the results and interpretations above is very difficult, because the rheological data base was obtained from experiments performed at undrained conditions in the brittle field. These conditions are unlikely to represent the flow of partially melted crust. The measured strength of most of the experimentally deformed, partially-melted samples corresponds to their maximum differential stress, before the onset of brittle failure, not to their viscous strength during "ductile" (viscous) flow. To overcome these problems, we extrapolated a theoretically-derived flow law for partially melted granite deforming by diffusion-accommodated grain-boundary sliding (Paterson, 2001) and an experimentally-experimentally-derived flow law for quartz deforming in the dislocation creep regime in the presence of 1-2 % of melt (Gleason and Tullis, 1995). In addition, we compared these data with deformation experiments on olivine plus basalt melt, also conducted in the ductile (viscous) field (Hirth and Kohlstedt, 2003). All these data show a dramatic decrease in viscosity for melt fractions < 0.06. Therefore, they are consistent with the aforementioned results of experimentally deformed granite in the brittle field. Extrapolation of these results to natural conditions suggests that localisation of deformation should effectively coincide with the onset of melting, or with very small melt fractions (0.06-0.07), which may not always be detected in the field.

Analogue, "see-through" experiments on the grain-scale deformation of melt-bearing aggregates also point to a dramatic effect of small melt fractions on the bulk deformation of the aggregate. Melting of the aggregate during deformation induces a transition from a distributed to a highly localised type of deformation. This transition, which finally leads to the development of interconnected melt-bearing shear bands, takes place after a small increment of ~ 0.15.

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## EMPLACEMENT MECHANISMS OF THE LATE-OROGENIC GRANITES IN SW FINLAND - A HISTORY OF REPEATED INTRUSIONS AND STRUCTURAL CONTROL

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The development of the crust of the Fennoscandian shield progressed from the earliest Archaean areas in the Kola peninsula towards SW and the Proterozoic Svecofennian in central and southern Finland and Sweden.

In the later development of the paleoproterozoic crust of southern Finland there is a transpressional phase with strong shearing along crustal-scale zones, high heat production, formation of migmatites and intrusions of granites around 1840 Ma. Around 1800 Ma the crust in this part of the shield was stabilized and the shearing continued in separate phases of activity along steep zones during the following c. 30 Ma. Small bimodal c. 1790 Ma old late orogenic intrusions were localized along some of the major shears during their last stage of ductile or mylonitic activity. The latest reactivation along some of the shear zones is recorded by brittle pseudotachylites c. 1.6 Ga ago.

## THE ROLE OF HIGH-T SHEAR ZONES IN EXHUMATION OF AN OROGEN: INSIGHTS FROM THE VARISCAN GRANULITIC-AMPHIBOLITIC METAMORPHIC BASEMENT IN SOUTHEAST CORSICA (FRANCE)

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A system of high temperature, crustal-scale shear zones developing under a transpressive dextral tectonic regime is thought to have deeply controlled the exhumation of the Variscan high-grade basement cropping out between Solenzara and Porto Vecchio, southeast Corsica (France).

A structural, petrological and geochronological (U/Th/Pb of zircon and monazite) study revealed that this metamorphic basement represents an exhumed, supra-subduction tectonic mélange and can be considered the root with peri-Gondwanan affinity of the Variscan chain in Sardinia-Corsica. This tectonic mélange is made up of rocks having experienced different PT conditions (eclogite-?, high-pressure granulite- and amphibolite-facies) in different times, reflecting the progressive active non-coaxial deformation of the orogenic belt during the post-collisional exhumation stage. The Solenzara granulites testify for the burial of continental crust down to high pressure (1.4-1.9 GPa) and high- to ultrahigh temperature conditions (900-1000°C) during the Variscan convergence about 360 Ma ago. The amphibolite-facies migmatites cropping out in the Porto Vecchio region represent middle crustal levels rocks that reached their peak T conditions (~800°C at ~1.0 GPa) at about 340 Ma. The diachronism of the two events suggests that the migmatites formed when the granulites were already exhumed at middle crustal levels, most likely through channel flow tectonics under continuous transpression. Starting from about 320 Ma the migmatites from Porto Vecchio and the granulites of Solenzara shared the same structural and metamorphic evolution and were tectonically juxtaposed through the development of a major dextral mylonitic zone under amphibolite facies conditions. The intrusion of large volumes of granodioritic melts at low-pressure conditions (~0.3 GPa) and under low strain regime is constrained at 308-312 Ma by monazite U/Th/Pb isotope dating of andalusite- and cordierite-bearing coronitic migmatites, and marks the final steps of the Variscan evolution in this sector of the chain.

## GABBROIC BODIES IN THE TRINITY OPHIOLITE

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Models for slow spreading systems have been developed from drilling and seismic results in recent oceanic crust (International Oceanic Drilling Programm; Atlantic-, Arctic-, Indian-Oceans) as well as field studies in ophiolites (e.g., Josephine, Alps, Ligurian,Trinity). A current endmember model for slow spreading systems suggests the crystallisation of discrete magma pulses in a lithospheric mantle environment (Cannat et al, 2006).

The Trinity Ophiolite displays discrete gabbroic bodies in a mantle environment. It might be a good on-land analogue to test the applicability of the available models. We report here first results from a geologic study of three gabbroic bodies in the Trinity Massif: a northern body (China Mountain), a central body (Bear Creek) and a southern body (Bonanza King).

The central body is the smallest one but contains the most regular lithological transitions. From bottom to top, it consists of: 1) mantle peridotite with narrow pyroxenite layers. 2) a shallow dipping transition zone with alternating bands of wehrlite, harzburgite and pyroxenite. The pyroxenites exhibit a thickness of more than 100 m and show a weak magmatic foliation. Unlike a transition zone in fast spreading environments only rare plastic strain is visible. 3) weakly foliated gabbro. The transition from pyroxenite to gabbro is characterised by a gradual increase of interstitial plagioclase. 4) vary-textured amphibole-bearing gabbro with local magmatic strain.The whole sequence including the mantle is intruded by pegmatitic leucocratic gabbro dykes. A roughly estimated thickness of this sequence is 800 m.

The northern body consists, from bottom to top, of the following: 1) wehrlitic and pyroxenitic rocks representing in our view a disrupted transition zone. 2) a vary-textured amphibole-bearing, mainly isotropic gabbro. 3) amphibolized gabbro which shows plastic strain. Disruption of the transition zone appears thus related to the formation of the amphibolized gabbro. Observed plastic strain is restricted to this later intrusive body, suggesting to us that it is related to extensional ridge tectonics.

The southern body consists, from bottom to top, of the following: 1) small exposures of wehrlitic and pyroxenitic rocks overlying mantle peridotite, juxtaposed against foliated gabbro and dolerites. 2) gabbro and gabbronorite, foliated subparallel to the local dykes, i.e. with a steep foliation. A gradual transition from pyroxenite to gabbro as in the Bear Creek body is thus not observed. 3) vary-textured amphibole-bearing gabbro with a very local foliation. 4) doleritic dikes and sills.

We observe two types of lateral contacts: 1) xenolithic margins, with mantle peridotite xenoliths in a magmatic breccia displaying heterogeneous magmatic strain. This type exhibits brittle behavior during emplacement of melt in a cold lithosphere. Cannat and Lecuyer (1991) describe this type as occurring in basal, lateral and roof positions. We also observe relic stems and blocks of mantle peridotite lying in vary-textured gabbro. 2) a sharp transition between mantle peridotite and gabbro. This sharp contact is defined by dyke-like pyroxenitic intrusions, cut by pegmatitic leucocratic gabbros. No magmatic strain is obvious. We interprete this as a reactivated contact because of the sharp, sheet-like marginal zone.

The topograhic highest positions of the northern and southern body might reflect roof positions. There we observe an inhomogeneous succession of rare peridotite, pyroxenite, as well as doleritic dykes and mostly vary-textured gabbro. This sequence is invaded by late plagiogranitic dykelets.

Because of the predominance of pyroxenite as opposed to troctolitic rocks, we confirm the arc-origin of the Trinity Ophiolite. The disrupted character of the transition zones in China Mountain and Bonanza King suggests the presence of multiple intrusive events.They probably caused displacement of existing rock units. Specifically it is our impression that the abundance of pyroxenites and primitive gabbros is too low relative to the exposed volume of evolved vary-textured gabbro for a regular mantle derived magma.

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## MYLONITIC GNEISS IN THE VARISCAN BASEMENT AT PUNTA ORVILI, NE SARDINIA, ITALY

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The Punta Orvili area is located at the southern edge of the Migmatite

Complex in the Axial Zone of the Variscan belt, a few kilometers north of the Posada Valley (NE Sardinia).

Punta Orvili is an Alpine horst structure lying between a vertical northern NE-SW-oriented fault and a southern one oriented E-W.

Punta Orvili rocks consist mainly of gneiss, mylonitic gneiss, calc-silicate nodules and rare lenses of metabasite with eclogite facies relics. The main foliation is the $S_2$ schistosity striking N 80° and dipping 30°-50° towards SE, related to the $D_2$ regional deformation event. Locally the $S_2$ schistosity is transposed by centimetric, sinistral strike-slip green-schist shear zones ($S_3$) striking N 30° and dipping 60° towards SE. Three mineralogical lineations have been recognized in the $S_2$ schistosity. From the oldest to the youngest, they are: a Kfs+ Qtz lineation striking N30° - 50° and dipping 20°-30° towards SW with a syn-tectonic top-to-SW shear component; a Qtz lineation oriented N 40°, dipping 30° towards SW with the same shear component as the previous one; a Bt ± Chl lineation striking N 20° and dipping 15°-30° towards SW.

The mylonitic gneiss is characterized by millimetric to centimetric quartz-feldspathic aggregates enveloped by the $S_2$ foliated phyllosilicate-rich matrix. Three main types of crystal aggregates can be distinguished: quartz, plagioclase and K-feldspar. Quartz-rich aggregates consist of deformed quartz crystals (up to 10-15) irregular in shape and varying in size, mainly elongated parallel to the regional schistosity. Deeply-sutured boundaries can sometimes be observed. Plagioclase-rich aggregates are made up of polygonal plagioclase (up to 20-25 grains) crystals with nearly 120° grain boundaries, interstitial quartz and K-feldspar. Plagioclase ranges in composition from oligoclase ($An_{20}$) in the core to albite $An_{1-2}$ in the rim. Some of these aggregates consist of polygonal albite crystals.

K-feldspar-rich aggregates consist of layers of recrystallized polygonal grains of K-feldspar with nearly 120° grain boundaries alternating with K-feldspar ribbons. Some of the ribbons contain elongated K-feldspar crystals. The polygonal grains of K-feldspar are surrounded by an irregular thin albite rim. Albite is almost pure ($An_{1-2}$), while K-feldspar contains $Na_2O$ up to 0.7-1.0 wt%. Elongated, irregularly-shaped quartz porphyroclasts sometimes occur within K-feldspar-rich centimetric clusters. Preliminary XRD data on two centimetric K-feldspar-rich aggregates reveal the presence of orthoclase.

A few aggregates consist of 15-20 polygonal apatite grains surrounded and enveloped by the phyllosicate matrix.

The matrix is made up of abundant muscovite, chlorite and fibrolitic sillimanite parallel to rock foliation, flowing around the quartz-feldspathic aggregates described above. Muscovite has Si content close to 6.2 a.p.f.u. and $X_{Mg}$ of 0.3-0.4. Large flakes of muscovite often grow on fibrolitic sillimanite. Chlorite, mostly associated with K-feldspar and rutile, mainly represents the re-equilibration product of a Ti-rich biotite.

Accessory minerals are zircon, monazite and Fe-oxide. Zircon grains, mostly within 50-100 microns in size, occur as anhedral, zoned crystals made up of an euhedral core surrounded by a continuous rim of variable thickness.

Relics of an $S_1$ metamorphic foliation are sometimes preserved in centimetric feldspar-rich aggregates. Feldspar-rich aggregates are characterized by an absence of pressure shadows, suggesting post-tectonic with respect to $S_1$ and syn-tectonic with respect to $S_2$: i.e intertectonic growth between $D_1$ and $D_2$. Moreover, feldspar crystallization continued after the $D_2$ deformation as a recovery process (Felds > $D_2$).

As a working hypothesis, these microstructures could be interpreted as high-temperature recrystallization coeval with non-coaxial $D_2$ deformation, perhaps in the presence of melt.

## RECORD OF LITHOSPHERIC THINNING IN THE SUBCONTINENTAL MANTLE (EXTERNAL LIGURIDE OPHIOLITES, NORTHERN APENNINE, ITALY): FROM RIFTING TO CONTINENTAL BREAKUP

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The External Liguride peridotite bodies from the Northern Apennine represent a rare tectonic sampling of deep levels of subcontinental lithosphere exhumed at an ocean-continent transition and therefore provide a good opportunity of throwing light into the evolution of subcontinental lithospheric mantle affected by extensional processes. In the External Liguride units, ophiolites consist of slices of exhumed subcontinental mantle, basalts and rare gabbroic rocks, together with continental crust bodies locally displaying primary relationships with the ophiolites (Marroni et al., 1998). This association has been interpreted as a fossil ocean-continent transition along a non-volcanic continental margin (Marroni et al., 1998). The mantle rocks are Ti-pargasite-bearing spinel-plagioclase lherzolites with a fertile geochemical signature that represent unroofed subcontinental litosphere of the former Adria-Europe system (Rampone et al., 1995). They are associated in places with garnet-bearing pyroxenite layers recording an early stage of equilibration in the subcontinental lithosphere under high pressure and temperature conditions (~2.8 GPa and ~1100 °C, Montanini et al., 2006).

In the peridotites enclosing the garnet-pyroxenite layers, the oldest recognisable texture a spinel-facies low-strain tectonite, preserved in small domains. The spinel-facies assemblage is widely overprinted by plagioclase-facies recrystallization associated with development of a mylonitic fabric along hectometre-size shear zones. The mylonite microstructure is characterised by aligned porphyroclasts of pyroxene + brown spinel + brown amphibole and by an ultrafine-grained (~20-50 ?m) polyphase aggregate composed of olivine + pyroxenes + plagioclase (+/- spinel, +/- accessory brown amphibole) occurring as mm-sized bands, lenses and porphyroclast tails. Crystals in this polyphase matrix commonly display grain boundary alignment parallel to the mylonitic foliation. Orthopyroxene porphyroclasts are stretched along the mylonitic foliation with high aspect ratio (up to ~10). Both pyroxenes commonly show evidence for intracrystalline deformation. Plagioclase occurs as (i) thin rims between spinel and pyroxene porphyroclasts, (ii) tiny neoblastic grains in the mylonitic matrix and, rarely, (iii) exsolution in clinopyroxene porphyroclasts. Textural, chemical and mineralogical evidence indicate that plagioclase formation and concomitant deformation occurred under subsolidus, melt-absent conditions (T ~ 950 °C) during exhumation of this mantle section. The fine-grained plagioclase-bearing mylonites were subsequently overprinted by a widespread polyphase brittle deformation under decreasing temperature conditions, coupled with hydration. The brittle evolution included an early amphibolite-facies stage, followed by low-temperature hydrothermal alteration and serpentinisation associated with polyphase cataclasis. These ubiquitous brittle structures are consistent with a shallow detachment fault event that re-activated rheological weaknesses of the lithospheric mantle developed under high temperature conditions (i.e. the plagioclase-facies shear zones).

The timing of the early decompression of the External Liguride mantle section, from the garnet stability field, is unconstrained. Conversely, Lu-Hf and Sm-Nd cooling ages obtained on garnet pyroxenites indicate that the low-pressure (< 0.9 GPa) portion of the exhumation, including the plagioclase-facies mylonites, was related to the Upper Triassic-Lower Jurassic rifting that led to continental break-up. We propose that the External Liguride plagioclase mylonites formed by an extensional shearing event related to lithospheric “necking stage” caused by the ascent of underlying asthenosphere, as predicted by numerical, analogue and conceptual models of formation of non-volcanic-rifted margins (Brun & Beslier, 1996; Bowling & Harry, 2001; Whitmarsh et al., 2001; Michon & Merle, 2003), and marked the onset of the Mesozoic rifting evolution.

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## QUARTZ C-AXIS PATTERNS DURING THE GRANITOIDS COOLING: EXAMPLES FROM THE LATE HERCYNIAN MID-CRUSTAL SHEAR ZONE OF SILA MASSIF (CALABRIA, SOUTHERN ITALY)

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The geometry of quartz c-axis data distribution in X (foliation and stretching lineation), Z (normal to the foliation and lineation given by X) and Y (perpendicular to X and Z) stereonets allows to extrapolate, strongly associated with microstructural observations, important indications on metamorphic conditions, finite strain and structural evolution during natural deformation of quartz-rich rocks. This research study emphasizes the importance of the quartz c-axis texture, associated with microstructural observations, to infer temperature conditions and remarks on the microstructural development of quartz during non-coaxial deformation of Late-Carboniferous, mid-crustal granitoids of the Sila Massif.

Microstructural observations and c-axis measurements have been carried out on foliated granodiorite and tonalite, which are the most widespread syn-tectonic plutonic rocks. The foliation is continuous or spaced. Continuous foliation is magmatic and defined by the alignment of both biotite flakes and outstanding igneous, euhedral to subhedral K-feldspar grains, sourronded by a fine-grained matrix made up of millimetric quartz and plagioclase grains and biotite flakes. Spaced foliation is represented by layering highlighted by composition and grain-size variations. In particular, cm-thick leucocratic layers of quartz and feldspar grains alternate with millimetric to centimetric grain-size biotite-rich melanocratic layers. The magmatic lineation, in granitoids with continuous foliation, is defined by the alignment of igneous K-feldspars, while a stretching lineation, given by elongated aggregates of quartz and feldspars, is present in layered plutonics. As regards microstructures, elongated grains of quartz locally form mm-thick ribbons in the leucocratic layers. In the layers and matrix, grains of quartz exhibit a wide range of microstructures such as chessboard patterns, prismatic and sutured grain boundaries, deformation bands, deformation lamellae, undulose extinction. The c-axis of elongated grains in ribbons and scattered grains with sutured boundaries both in the biotite-rich layers and matrix have been measured using the universal stage. The c-axis textures in stereonets are mainly characterized by point maxima with a monoclinc simmetry. In addition, some c-axis textures show an orthorhombic simmetry and a strong dispersion of data. Three different point maxima characterize those c-axis textures with a monoclinic simmetry: (i) point maxima at 20-40° from X axis, toward the east-dipping stretching lineation; (ii) point maxima at 50-70° from X axis, toward the east-dipping stretching lineation (iii); point maxima around Y axis. The first two point maxima are related to the simultameous prism [c] and basal slip, respectively. A similar domination of slip systems is inferred for the c-axis patterns with an orthorhombic simmetry showing two point maxima at 30-40° from X axis, with an opening angle around Z axis up to 120°. Simultaneous prism [c] and basal slips operated during deformation at HTs (above 700° C) in the high-quartz stability field, as suggested by the presence of chessboard patterns in quartz. The point maxima around Y axis is related to the domination of prism slip system in elongated grains forming mm-thick ribbons, which operated in intemediate temprature conditions.

Despite the presence of microstructures in quartz, suggesting deformation under intermediate- to low-grade conditions, it is possible to infer that c-axis orientations acquired under higher temperature conditions was partially preserved under later decreasing temperature during deformation. Under HT conditions (above c.a. 700° C) chessboard patterns in quartz grains developed in the crystallized magma during deformaton. A lattice preferred orientation was reached by the simultaneous operation of prism [c] and basal slips, as recorded by point maxima between X and Z axis. HT conditions during deformation are also suggested by the opening angle between point maxima around Z axis. Under subsequent intermediate temperature conditions mm-thick ribbons locally formed with a new c-axis orientation in elongated grains around the Y axis. Despite grain boundary migration recrystallization, the previous lattice preferred orientation acquired during HT deformation is preserved in the measured quartz grains with sutured boundaries embedded in biotite-rich layers and matrix. Prismatic and sutured subgrain boundaries in quartz developed during deformation under intermediate temperature conditions. Finally, deformation bands, deformation lamellae and undulose extintion widely produced in quartz grains during deformation under low temperature conditions without changing the previously preferred orientation of c-axis in the measured grains.

## DIFFERENT MELT FRACTIONS IN A SINGLE MIGMATITE BELT: THE ROLE OF ROCK-COMPOSITIONS, FLUID-INFILTRATION PATHWAYS AND TECTONICS

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In migmatite areas deformation depend on two important factors: (1) the local melt fractions and (2) the distribution of melt. The first part will influence the rheology of the crystal mush and the second factor control strain localization in crustal scale. In areas of pure hydrate breakdown melting the melt volumes and melt distribution may be relative uniform, whereas in areas of fluid assisted melting, both varies strongly.

Melting triggered by influx of a free aqueous fluid in the continental crust has often been inferred, but the source of water in such a context remains a matter of debate. As an illustrating example, we discuss the petrology, structures and geodynamic setting of water assisted melting in the Central Alps (Switzerland, Northern Italy). These migmatites comprise various structural types (e.g. metatexites, diatexites, melt in shear zones), which reflect variable melt fractions. The melting event itself as well as the variable melt fractions is often related to the amount of aqueous fluids. At a given P and T, melt-fractions in rocks of minimum melt composition correlate with the amount of infiltrated aqueous fluids. In more granodioritic systems the water distributes between melt and newly crystallizing hydrous phases such as amphibole, such that the melt fraction correlates with the contents of $H_2O$, Al, and Ca in the system. Phase-equilibrium modelling indicates that the stabilization of amphibole leads to slightly lower melt fractions than in a granitic system at the same P, T and bulk water content. In addition muscovite breakdown melting contribute to the migmatite belt. In this example the volume of muscovite and the bulk chemistry control the amount of melt.

The structural relevance of these different types of melting and melt volumes affect the local mechanical behavior of the partially molten rocks. Thereby, we have to consider volume changes occur during water assisted melting, apparent overprint relations of leucosomes by water recycling and different type of deformation localisation depending on the type of melting and melt fractions

## ULTRAMAFIC PSEUDO-TACHYLITES IN THE MONCUNI OPHIOLITIC PERIDOTITE (LANZO MASSIF, WESTERN ALPS): RECORDS OF EARTHQUAKES DURING FORMATION OF THE JURASSIC LIGURIAN TETHYS

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The small (a few km$^2$) ultramafic body at Mt. Moncuni (southern side of the Susa Valley), is a satellite of the South Lanzo ophiolitic peridotite body and consists of plagioclase peridotites, metre-scale masses of spinel(sp) dunites and harzburgites, and widespread gabbroic dykes and porphyritic mafic dykes. plagioclase peridotites and gabbroic dykes are deformed along metre- to decametre-scale extensional shear zones which show cm- to dm-wide, dm- to m-long, veins of extremely fine-grained pseudo-tachylites, both concordant (fault-vein type) and discordant (injection-vein type) to the tectonite-mylonite foliation of shear zones, and have very sharp contacts with the host rock. Coarse-grained porphyritic mafic dykes cut across both deformed plagioclase peridotites and shear zones.

Host plagioclase peridotites, similarly to the South Lanzo plagioclase peridotites (Piccardo et al., 2007), record melt-peridotite interaction and melt refertilization during the pre-oceanic evolution of this lithospheric mantle section. The very fine grained tectonite-mylonite and cataclastic bands of the shear zones have neoblastic mineral assemblage (ol + plg + px) indicating early equilibration under plagioclase-facies conditions (< 1.0 GPa). In places within the shear bands, Mg-hornblende amphibole was formed stable with plagioclase and pyroxenes and, subsequently, tremolitic amphibole was formed in equilibrium with plagioclase, but replacing both clinopyroxene and olivine. Amphibole-bearing assemblages suggest subsequent equilibration under amphibole-bearing plagioclase-peridotite facies conditions and, subsequently, under amphibolite-facies conditions.

The plagioclase-peridotite-facies of the host plagioclase peridotites record T of about 1150°C, most probably related to the melt impregnation event; the amphibolite-facies assemblage of the hydrated shear zones, record T of about 900°C, suggesting that this mantle section was exhumed to shallower and colder lithospheric levels during extension-driven exhumation, prior to pseudo-tachylite formation.

Pseudo-tachylite veins are composed of an ultra-fine grained to glassy matrix with minor amounts of clastic olivine grains or aggregates and lithic mylonitic clasts. The matrix of the larger, dm-wide veins is crystallized to spinifex-type textures, formed by radial aggregates of elongated orthopyroxene crystals, showing clinopyroxene rims, surrounded by microgranular aggregate of rounded olivine crystals. Pseudo-tachylite bulk rock composition is peridotitic (i.e. $SiO_2$ = 42.9-44.3 wt%, $Al_2O_3$ = 2.4-3.8 wt%, CaO = 2.3-3.1 wt% and MgO = 39.4-41.9 wt%), and show bulk rock C1-normalized REE patterns flat in the M-HREE region (< 2xC1) and variably fractionated in the LREE (CeN/SmN 0.22-0.50). Pseudo-tachylite minerals preserve, in places, peculiar major element compositions: i.e. olivine (CaO up to 0.39 wt%, $Cr_2O_3$ up to 0.4 wt%), clinopyroxene ($Al_2O_3$ up to 14.5 wt%) and orthopyroxene (CaO up to 2.03 wt%), which indicate very high temperature of formation. In fact, geothermometric estimates indicate crystallization temperatures higher than 1250°C. The host peridotite, close to the contact with the veins, has orthopyroxene showing exceptionally high CaO contents (up to 3.3 wt%), indicating that very high thermal conditions (T up to 1430°C) were locally reached in the shear zones.

Structural and compositional characteristics indicate that pseuo-tachylites originated by localized, nearly complete melting of the host peridotite. Formation of ultramafic melts in peridotite shear zones implies the presence of strongly localized, very high shear heating due to very high shear stresses on the fault plane represented by the shear zones. The formation of spinifex textures indicates very rapid crystallization of the ultramafic melt. These conditions are fully consistent with an earthquake. Thus, faulting close to the ductile-brittle transition in the hydrous peridotite system provides a mechanism for earthquakes in the shallow upper mantle.

Bulk rock and mineral compositions of intrusive gabbroic dykes and subvolcanic porphyritic mafic dykes which preceded, the former, and followed, the latter, the formation of shear zones and ultramafic pseudotachylites indicate the MORB affinity of their parental magmas. MORB gabbroic dike intrusion has been dated at 160 Ma in the Lanzo massif (Kaczmarek et al., 2005). Accordingly, shear zones and pseudo-tachylites were formed between different episodes of MORB oceanic magmatism in the Jurassic Ligurian Tethys.

In conclusion, ultramafic pseudo-tachylites in the Mt.Moncuni ophiolitic peridotite are records of Jurassic earthquakes related to extensional faulting in the shallow mantle during exhumation from sub-continental lithospheric levels to the sea-floor of the Jurassic Ligurian Tethys.

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## TECTONIC AND MAGMATIC PROCESSES IN A FOSSIL ULTRA-SLOW SPREADING OCEAN: THE STUDY CASE OF THE JURASSIC LIGURIAN TETHYS

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The Jurassic Ligurian Tethys formed by lithosphere extension and failure in the Europe-Adria realm. Stratigraphic-structural evidence from the Alpine-Apennine ophiolites indicate that the basin was floored by mantle peridotites and was characterized by a discontinuous basaltic cover (along-axis alternance of a-volcanic and volcanic segments).

In present-day oceanic basins the direct exposure at the sea-floor of crust-free mantle lithosphere is more common than previously recognized. It has been suggested that nearly half of the global mid-ocean ridge system is made of mantle peridotites (Dick et al., 2003). Recent investigations of the South-West Indian and Arctic Ridges have evidenced an ultra-slow spreading ridge class that is characterized by intermittent volcanism (alternance of a-volcanic and volcanic segments) and continuous emplacement of mantle to the seafloor over large regions, whereas the spreading rate is approximately lower than 20 mm yr -1 (Dick et al., 2003).

Distinctive characteristics of the ultra-slow spreading ridges are: (1) the strong compositional variability of the exposed abyssal peridotites which has been related to melt migration and melt-peridotite interaction; (2) the relative abundance of mildly enriched or even alkaline basalts, which have been related to melting of garnet-eclogite/pyroxenite or veined mantle sources.

Recent investigations on ophiolitic peridotites from the Alpine-Apennine ophiolites have evidenced: (1) the strong compositional heterogeneity of mantle peridotites (both pyroxene depleted/olivine enriched harburgites/dunites and melt-impregnated and refertilized plagioclase peridotites) related to widespread interaction of pristine sub-continental lithospheric peridotites with percolating MORB-type melts (Piccardo et al., 2004; 2007a); (2) the presence of melts showing alkaline affinity which migrated within replacive spinel harzburgite channels cutting impregnated plagioclase peridotites (Piccardo et al., 2006; 2007b).

Accordingly, stratigraphic-structural features (i.e. mantle at the sea-floor and alternance of a-volcanic and volcanic segments) and petrologic features (presence of alkaline melts and strongly heterogeneous, melt-modified mantle peridotites) are in favour of the interpretation of the Ligurian Tethys as a Jurassic analogue of modern ultra-slow spreading ridges (Piccardo, 2006; 2007).

Structural-petrologic features of the Alpine-Apennine ophiolitic peridotites document the interplay between lithosphere extension and deformation, asthenosphere partial melting and melt percolation in the mantle lithosphere (Piccardo and Vissers, 2007; Piccardo, 2006; 2007). During pre-oceanic rifting stages of the basin: (1) lithosphere extension caused formation of km-scale shear zones in the mantle lithosphere which were relevant to lithosphere thinning and to exhumation of the sub-continental mantle; (2) lithosphere extension and thinning caused adiabatic upwelling and decompressional melting of the underlying asthenosphere; (3) diffuse porous flow of asthenospheric melts through the extending mantle lithosphere caused compositional and rheological modification of the mantle lithosphere leading to its thermo-chemical erosion.

Deformation and melt-related processes in the mantle lithosphere mutually enhanced during lithosphere exhumation, played a fundamental role in weakening the extending mantle lithosphere and were controlling factor in the transition from distributed continental deformation to localised oceanic spreading (Piccardo and Vissers, 2007; Corti et al., 2007; Ranalli et al., 2007).

Across-axis variation of the petrologic characteristics of mantle peridotites evidences the different evolution stages of the basin: (1) peridotites from Ocean-Continent Transition (OCT) Zones are represented by exhumed sub-continental lithospheric mantle, representing the rifting stage; (2) Peridotites from More Internal Oceanic (MIO) Setting are represented by strongly heterogeneous, melt-modified peridotites, representing the transitional drifting stage; (3) Some peridotite bodies (Monte Maggiore, Corsica) from More Internal Oceanic (MIO) Settings could represent Jurassic residual mantle, cogenetic with the Jurassic MORB melts, representing the oceanic spreading stage.

The LIGURIA MODE, a conceptual model for inception and evolution of an ultra-slow spreading oceanic basin, whose formation was dominated by the passive extension of the continental lithosphere, implies:

A) The rifting (continental) stage, dominated by extension and thinning of continental lithosphere and tectonic exhumation of sub-continental lithospheric mantle by km-scale extensional shear zones.

B) The drifting (transition) stage, characterized by progressive thinning of the continental lithosphere an by concomitant melt-related processes. Lithosphere extension and thinning induce adiabatic upwelling and decompressional partial melting of the asthenosphere. MORB-type fractional melts percolate through the overlying sub-continental lithospheric mantle along the axial zone of the future oceanic basin, and modify large areas of the extending sub-continental mantle. Oceanic refractory peridotites, residual of asthenosphere partial melting and cogenetic with the MORB melts are formed and continuously accreted to the thermal lithosphere after MORB melt extraction.

C) The spreading (oceanic) stage, characterized by complete failure of the continental crust, and direct exposure at the sea-floor of mantle peridotites: (1) sub-continental peridotites (at OCT settings), (2) melt-modified sub-continental peridotites and (3) refractory residual peridotites after oceanic partial melting (at MIO settings).

Accordingly, lithosphere extension and thinning are accomodated by lithosphere-scale extensional shear zones and induce asthenosphere adiabatic upwelling and decompressional melting. Mantle lithosphere is weakened by heating from upwelling asthenosphere and diffuse percolation of asthenospheric melts. The thermo-mechanical erosion of the mantle lithosphere facilitates transition from distributed lithosphere deformation to localized oceanic spreading.

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## EXTENSIONAL DEFORMATION, MANTLE MELTING AND MELT PERCOLATION IN THE ERRO-TOBBIO PERIDOTITE (VOLTRI MASSIF, LIGURIAN ALPS)

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The Erro-Tobbio (E-T) ophiolitic peridotite (Voltri Massif, Ligurian Alps, Italy) represents a mantle section which has been equilibrated at spinel-peridotite facies and lithospheric thermal conditions (T in the range 1000-1100°C) in the sub-continental lithosphere of the Europe-Adria system prior to the Early Jurassic. In response to lithospheric extension leading to opening of the Ligurian Tethys basin, the E-T peridotites has been exhumed along a subsolidus P-T trajectory and emplaced at the sea-floor of the Ligurian Tethys ocean. Lithospheric mantle exhumation was accomodated by km-scale extensional shear zones, forming peridotite tectonites and mylonites (Drury et al., 1990; Vissers et al., 1991; Hoogerduijn Strating et al., 1993; Piccardo and Vissers, 2007).

The E-T massif comprises km-scale volumes of peridotites with structural and compositional characteristics pointing to melt-peridotite interaction. These peridotites were formed by interaction of pristine lithospheric peridotites with MORB-type melts ascending by porous flow, which led to the development of reactive spinel harzburgites, impregnated plagioclase peridotites and replacive spinel dunites (i.e. melt-modified peridotites) (Piccardo et al., 2004; Piccardo and Vissers, 2007). The melt-related processes in the mantle lithosphere are a consequence of MORB-generating decompressional partial melting of the asthenosphere which was induced by near-adiabatic upwelling related to lithosphere extension and thinning. Melt fractions from the upwelling asthenosphere migrated upwards through the extending mantle lithosphere by diffuse porous flow, interacted with the percolated mantle peridotites and caused their significant structural and compositional modification.

Field relationships between sheared lithospheric peridotites, including coarse tectonites as well as fine-grained mylonites, developed during lithosphere extension, and melt-modified peridotites suggest that the melt-related processes occurred during exhumation of the E-T mantle. Our field, structural and petrologic data allow to evidence that lithosphere extension, asthenosphere partial melting and lithosphere melt percolation were closely inter-dependent and led to the thermo-chemical and thermo-mechanical erosion of the extending mantle lithosphere. Present data allow us to conclude that the entire pre-oceanic evolution of deformation, metamorphism and magmatism recorded by the E-T mantle started during the Early-Middle Jurassic and was related to lithospheric extension leading to the Late Jurassic opening of the Ligurian Tethys ocean.

It has been, thus, substained (Piccardo, 2007; Piccardo and Vissers, 2007) that: (1) lithosphere extension caused extensional deformation and tectonic-metamorphic evolution of the subcontinental mantle lithosphere, forming km-scale tectonite-mylonite shear zones which were relevant to lithosphere thinning and to exhumation of the lithospheric mantle; (2) lithosphere extension and thinning caused inception of decompressional melting of the underlying upwelling asthenosphere; the asthenospheric melts migrated via diffuse porous flow through the extensional lithospheric rifting system; (3) deformation and melt-related processes in the mantle lithosphere were inter-dependent and mutually enhancing during lithosphere exhumation.

It has been, accordingly, recognized that the interplay between deformation, melt percolation and compositional-rheological modification of the mantle lithosphere had a fundamental role in weakening the extending mantle lithosphere and was a controlling factor in the transition from distributed continental deformation to localised oceanic spreading (Piccardo, 2007; Corti et al., 2007; Ranalli et al., 2007; Piccardo and Vissers, 2007).

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## SHEAR ZONES IN THE MANTLE: THE ROLE OF METAMORPHIC AND MELT-ROCK REACTIONS
### (Invited Contribution)

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There is abundant field and microstructural evidence in orogenic and ophiolitic mantle massifs for localization of deformation into high-temperature (T>800°C) peridotite shear zones. Models for the strength of the lithosphere are generally based on the assumption of homogeneous flow, and in these models the mantle lithosphere is often considered to be strong with respect to the crustal part. However, if mantle shear zones are widespread, and if these shear zones are weak, then models based on homogeneous flow seriously overestimate the strength of the mantle lithosphere. To constrain how widespread mantle shear zones are, we need to understand the conditions under which they form, as well as the processes involved in their initiation and development. To constrain the strength of these shear zones, we need to understand the microphysical deformation mechanisms that are active in these shear zones, and the softening mechanisms that make them weaker than the enclosing mantle rocks.

There are two main broad categories of mantle shear zones: relatively coarse-grained tectonite shear zones and fine-grained to ultrafine-grained mylonite shear zones, which can anhydrous or hydrous. In tectonite shear zones, softening processes associated with localization are probably melt-related weakening in the medium to coarse tectonites and a change in limiting slip system in the fine grained tectonites. In peridotite mylonites, the most likely cause for softening and localization is a change in dominant deformation mechanism from dislocation to grain size sensitive creep. As laboratory deformation experiments show that the weakening produced by this change in deformation mechanism can be very dramatic, it is important to look into the details of how this change is brought about.

One feature that all mylonite shear zones which preserve evidence for the importance of grain size sensitive creep processes - such as diffusion creep and grain boundary sliding - have in common is their fine to ultrafine grain size (down to 1 µm). It is therefore obvious that the grain size reduction is one of the key processes in the production of mylonitic mantle shear zones. There are broadly three types of processes that can cause drastic grain size reduction: cataclasis, dynamic recrystallization, and recrystallization associated with phase transformations, metamorphic reactions, or fluid- or melt-rock reactions, chiefly referred to as ‘reaction recrystallization’ here. In this contribution, the importance of these types of processes will be discussed using some highly illustrative samples of different mantle mylonite zones. Based on microstructural observations, it is included that recrystallization associated with reactions is a very important process for the initiation of shear localization, and for the development and long-term preservation potential (due to phase mixing) of natural mantle mylonite shear zones. In addition, consideration of the relative importances of internal strain energy that can be released by dynamic recrystallization, and free energy due to chemical disequilibrium that can be released by reaction recrystallization, shows that the latter can be at least as important as the former in natural rocks. Finally, there are now also well-documented case studies that illustrate how deformation, in turn, promotes reaction recrystallization, leading to a positive feedback between deformation and recrystallization.

We can expect that significant chemical disequilibrium, the driving force for reaction recrystallization, exists almost everywhere in the mantle, in particular in active tectonic regions where rocks move through P,T-space rapidly. At the same time, it is known that reactions under dry conditions and without deformation can be sluggish. In fact, almost every mantle rock found today, whatever its age, preserves chemical disequilibrium in its minerals, in particular in pyroxenes. The onset of deformation can unlock the energies stored in the minerals due to chemical disequilibrium, which can then drive reaction recrystallization and set in motion the positive feedback between deformation and reactions. We can thus conclude that it is almost inevitable that mylonitic shear zones form and play a crucial role in active tectonic regions, and that they control the strength of the mantle lithosphere at the time when it matters most, i.e., during active tectonic periods.

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## THE OTTANA-MT.E' SENES SHEAR ZONE (CENTRAL SARDINIA, ITALY): CONSTRAINTS ON A MAJOR OROGEN-NORMAL SHEAR ZONE OF LATE VARISCAN AGE

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The Upper Carboniferous intrusive igneous activity related to the emplacement of the Sardinia-Corsica Batholith in the region of Nuoro (central Sardinia, Italy) occurred contemporaneously with a non coaxial deformation.

A composite magmatic sequence (Bt-Amp-bearing calc-alkaline granodiorites, peraluminous two-mica and Crd-bearing granodiorites and two-mica leucogranites) crops out within a 10 km wide, almost 60 km long zone with a SW-NE trend. This direction is orthogonal to the main regional orogenic NW-SE strike of both the metamorphic and magmatic foliations measured in the other sectors of the Variscan chain of central-northern Sardinia.

Crosscutting relationships between different granitoids, coupled with deformational fabrics in the granodiorites and some foliated peraluminous granites indicating heterogeneous sub-solidus high-T ductile shearing on magmatic fabric, provide evidence for a syn-kinematic magma emplacement in the upper crust within a right-lateral shear system.

The emplacement of the St. Basilio peraluminous intrusion in this area (the largest peraluminous pluton in the Sardinia-Corsica Batholith) is also controlled by this regional-scale transcurrent shear zone. Field relationships and preliminary geochronological data indicate that the orogen-normal deformation along this crustal-scale structure developed from about 310 Ma to around 300 Ma. The Ottana-Mt. E' Senes Shear Zone was later reactivated and strongly overprinted and dismembered by the well known brittle sinistral transcurrent fault (the "Nuoro Fault") in Alpine times.

## MELT MIGRATION AND HIGH TEMPERATURE SHEAR ZONE IN THE UPPER MANTLE (LANZO MASSIF, ITALY)

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Different mantle domains characterize present-day and ancient ocean-continent transition zones and many of them show signs of melt/rock reaction, but their relationships to deformation processes in the thermal boundary layer are poorly understood. The transition from melt-poor to -rich regions is likely to be an important rheological boundary. To constrain the rheological weakening of mantle lithosphere, we investigate the relationships between deformation, melt-rock reaction and mafic dike emplacement in the Lanzo peridotite massif (NW-Italy).

Mapping of the Lanzo massif, in the northern and central parts, has revealed a peridotite mantle shear zone, which is at least 200 meters wide with a sub-vertical foliation generally dipping to the NE. Fieldwork, microscopic observation and grain size analyses highlight 6 deformation textures: coarse-grained secondary granular (CGSG), fine-grained secondary granular (FGSG), proto-mylonite, mylonite, hydrous-mylonite and ultra-mylonite. CGSG shows weakly deformed porphyroclastic zones composed of orthopyroxene (opx), clinopyroxene (cpx) and olivine (ol), and domains of igneous recrystallization. Mylonite, hydrous-mylonite and ultra-mylonite show a fine-grained polycrystalline matrix of ~50 μm, 50 to 20 μm and 20 to 10 μm grain size respectively. The matrix is composed of olivine, plagioclase (plg), clinopyroxene, orthopyroxene, spinel and Ti-hornblende enclosing deformed porphyroclasts. Hydrous-mylonite contains important fine-grained areas composed of hornblende. The spatial distribution of deformation is asymmetric with respect to the mylonite, increase from S to N and tend to be localized in the mylonite zone. Discordant gabbroic dikes are asymmetrically distributed and concentrated in the southern part of the shear zone, which is interpreted as the footwall of the shear zone.

The pyroxene porphyroclast cores indicate high Al and Cr content and a decrease toward the rim and neoblasts. Porphyroclastic core thermometry indicates high temperatures originated at the spinel facies (1100-1030°C) and a lower equilibration for neoblasts in the plagioclase facies (850-855°C). Cr# (molar Cr/Cr+Al) and TiO2 concentrations in spinel show an extreme variability and cover the entire range from spinel to plagioclase peridotites, indicating disequilibrium. The variability does not seem to be microstructurally controlled. The largest variation is observed in the CGSG rocks, while in deformed rocks the composition is more homogeneous in terms of TiO2 and Cr# suggesting a faster equilibration with small grains. However spinel from the northern body display homogeneous composition in the plagioclase facies. This indicates that once the plagioclase peridotites completely crystallized, exhumation to shallower depth must have been rapid, in order to preserve disequilibrium chemical compositions. Moreover, the hanging-wall record a relatively lower exhumation then then footwall. Some cpx porphyroclasts show signs of previous reaction textures with a melt (cpx + liq -> opx + plg ± ol), a texture, which is common in the southern Lanzo massif. In all rocks, vermicular orthopyroxene is located in contact with olivine. Si-saturated liquids corrode olivine grains and crystallized opx along the reaction Liq. 1 + olivine -> orthopyroxene (± Liq. 2). These textures are rare in the mylonite zone, indicating that the mylonite formation postdates melt/rock reactions.

The whole rock analyses display a large compositional variation at the Lanzo massif scale (from fertile plagioclase peridotite to refractory harzburgite), and a tendency of enrichment in the footwall the mantle shear zone. The $Al_2O_3$, $Na_2O$ and incompatible elements show an enrichment in the more deformed rocks (proto-mylonite, mylonite and hydrous-mylonite) compared to the northern body (CGSGn). Considering $Al_2O_3$, $Na_2O$ and Ce, Sm, Yb, the composition is more homogeneous with increasing deformation.

Our results indicate that melt migration and high temperature deformation are juxtaposed both in time and space. Melt migration occurred on a km-scale over the entire massif, but local differences exist. The presence of melt in the rock will change the rheological behavior and increase the weakening. The preservation of chemical disequilibrium of minerals suggests a rapid exhumation and a rapid temperature decrease from near-solidus conditions to Ti-hbl conditions. Melt migration, peridotite composition and the concentration of dikes in the footwall suggest that the shear zone acted as a melt barrier and a melt conduit.

# EMPLACEMENT OF MAGMATIC BODIES AND ACTIVATION OF SHEAR ZONES IN THE COUNTRY ROCKS: AN EXAMPLE FROM EASTERN ELBA ISLAND (TUSCAN ARCHIPELAGO, ITALY)

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The study refine the structural evolution of the central-eastern Elba tectonic pile and its relationships with the emplacement of the Upper Miocene-Lower Pliocene magmatic intrusions. The fault rocks of two important shear zones (the Terranera cataclasite east of Porto Azzurro and the Zuccale Fault cataclasite in the north-west part of the Mt. Calamita promontory: Barberi et al., 1969; Keller and Pialli, 1990; Pertusati et al., 1993; Keller and Coward, 1996; Bortolotti et al., 2001; Collettini and Barchi, 2004) were studied in Eastern Elba Island. In particular we performed 1:5.000 geological mappings, meso- and microstructural analyses, petrographical and mineralogical studies on the fault rocks and on the surrounding tectonic units in the two considered areas.

The Terranera cataclasite, tectonically intercalated between two Tuscan polymetamorphic successions (the Porto Azzurro Unit and the overlying Monticiano-Roccastrada Unit), consists of a cataclasite with phyllitic, quartzitic, carbonatic and aplitic clasts in at times foliated carbonate-phyllosilicatic matrix and locally (specially in its upper part) including tectonic slices of phyllitic-quartzitic and marble-calcschist successions (probably coming from the Acquadolce Unit of Bortolotti et al., 2001).

The Zuccale cataclasite, which separates the Triassic formations of the Porto Azzurro Unit (Verrucano and Tocchi Formation) from the overlying Ligurids (Cretaceous Flysch Unit), consists of five horizons (from the base to top): a) cataclasite with phyllitic and quartzitic elements (coming from the underlying Verrucano anagenites and quartzites) in a non-foliated chlorite-quartz matrix; b) mylonite consisting in alternating phyllitic and calcschist levels with yellowish to orange crystalline limestones, dolomitic limestones and quartzitic lenticular intercalations; c) foliated carbonatic cataclasite containing phyllitic, quartzitic and, minor, serpentinite (antigorite) clasts, up to metric in size, and characterized by a complex network of extensional fractures filled with fibrous calcite; d) foliated gouge with often recrystallized and largely silicified carbonatic and pelitic elements, coming from the overlying Cretaceous Flysch, in a marly-clayey matrix; e) basal fault breccia of the Cretaceous Flysch Unit.

The kinematic indicators collected within the shear zones (S-C fabric, extensional duplex, book-shelf, drag folds, boudinage, augen structures, winged porphyroclasts, slickensides) point to a general top to east/north-east sense of shear, but locally younger indicators with a top to south-west sense of shear are also recognizable. Moreover, pre-cataclasis (pyrite at Punta Zuccale) and syn-/post-cataclasis (hematite + pyrite at Terranera; quartz+hematite and hematite + goethite at Punta Zuccale) mineralizations were distinguished.

The activity of the studied shear zones can be summarized as follows: a) a pre- ($D_2$ tectono-metamorphic event pp. of Garfagnoli et al., 2005) to ?syn-intrusions mylonitic event characterized by a top-to-east sense of shear, that affected the Mesozoic formations of the Porto Azzurro Unit (e.g. Tocchi Formation at Punta Zuccale) and of the Acquadolce Unit (e.g. Marble and Calcschists at Terranera); b) thermometamorphic and hydrothermal (e.g. epidote, pyrite) imprint, caused by the magmatic intrusions (Zuccale and Barabarca); c) formation of the Zuccale cataclasite, with a top-to-east/north-east sense of shear, linked to detachments on the eastern slope of a magmatic-structural high placed in the central-western Elba (?Mt. Capanne pluton); d) reactivation of the Zuccale cataclasite with a top-to-south/west sense of shear, due to the uplift of the La Serra-Porto Azzurro (-Mt.Calamita) pluton; e) high-angle normal faulting with associated hematite -rich mineralizations.