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STRUCTURE AND COMPOSITION OF THE LOWER CONTINENTAL CRUST

GEOLOGICAL, PETROLOGICAL, GEOCHEMICAL AND GEOPHYSICAL PERSPECTIVES

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ABSTRACTS VOLUME

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This volume contains the abstracts of participants in the school (7-10th October 2019 – Pavia, Italy), organized by the PhD Program in Earth and Environmental Sciences (University of Pavia). The school is held in the historical Palazzo Vistarino. The major purpose of the School is to share and discuss the modern knowledge of the lower continental crust, from geological, structural, petrological, geochemical and geophysical viewpoints. The School is targeted to PhD students, post-docs, advanced master students and young researchers.

The school consists of three days of lectures and one-day field trip in the Ivrea-Verbano Zone (Italian Alps). The lecturers are Roberto Braga (University of Bologna), Bruna B. Carvalho (University of Padova), Bernardo Cesare (University of Padova), György Hetényi (University of Lausanne), Matthew D. Jackson (Imperial College, London), Antonio Langone (Institute of Geosciences and Earth Resources, CNR Pavia), Sandra Piazolo (University of Leeds), Silvano Sinigoi (University of Trieste), and Thomas Zack (University of Gothenburg).

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ORIGIN OF THE PERIDOTITE-PYROXENITE ASSOCIATION FROM ROCCA DI ARGIMONIA, IVREA MAFIC COMPLEX (IVREA-VERBANO ZONE)

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We present a petrological-geochemical investigation of the Rocca d'Argimonia peridotite-pyroxenite sequence, which is exposed in the lowermost continental crust of the Ivrea-Verbano Zone (South Alpine domain). This sequence is up to 400 m thick and is enclosed within Upper Carboniferous-Lower Permian gabbronorites from the southern-western sector of the Ivrea Mafic Complex. The main purpose of this study is to unravel the evolution experienced by primitive magmas intruding the lower continental crust.

The Rocca d'Argimonia peridotites are amphibole-bearing dunites to harzburgites. Associated pyroxenites are also amphibole-bearing and range from olivine websterites to plagioclase-bearing websterites, with orthopyroxene modally prevailing over clinopyroxene. Hornblende gabbronorite dykes (up to 25 cm thick) crosscut the peridotites and show amphibole-bearing orthopyroxenite reaction zones (mm-scale thick) along the contact with host rocks. Peridotites, pyroxenites and gabbronorite dykes typically display nearly polygonal structure, which most likely reflects slow cooling and recrystallization in the lower continental crust. However, structures and micro-structures of primary magmatic origin are typically preserved, as for instance shown by the local occurrence of poikilitic orthopyroxenes in the peridotites.

The whole-rock Mg# [$Mg/(Mg+Fe^{2+}_{tot})$] decreases from the peridotites to the pyroxenites and the gabbronorite dykes (90 to 75), and these Mg# variations are paralleled by olivine, pyroxene and spinel compositions. The decrease of olivine forsterite proportion (90 to 85 mol%) is associated with $\delta^{18}O$ increasing from +5.8 to +6.6 ‰. Taken as a whole, the peridotites, the pyroxenites and the hornblende-gabbronorite dykes show substantial variations in incompatible trace element signature and Nd-Hf isotopic compositions. The gabbronorites enclosing the ultramafic sequence have low Mg# of 56-37 and are geochemically distinct from the hornblende-gabbronorite dykes intruding the peridotites. In particular, the gabbronorites enclosing the ultramafic sequence show LREE-enriched chondrite-normalized patterns and low initial $_{\varepsilon Nd-Hf}$ values.

We propose that the peridotite-pyroxenite Rocca di Argimonia sequence formed by injection of primitive mantle melts into gabbronorites of the Ivrea Mafic Complex. These melts most likely experienced: (i) fractional crystallization driven by olivine + accessory spinel ± clinopyroxene, and (ii) assimilation of crustal material released by pre-existing gabbronorites, which promoted the development of orthopyroxene. The geochemical fingerprint of the peridotites is inferred to vary in response to a late-stage process of reactive melt migration, but it concurs to the idea that the mantle melt sources underwent metasomatism in conjunction with the Varisican subduction.

EVOLUTION OF MANTLE MELTS INTRUDING THE LOWER CONTINENTAL CRUST: CONSTRAINTS FROM THE MONTE CAPIO-ALPE CEVIA ULTRAMAFIC SEQUENCES (IVREA-VERBANO ZONE, NORTHERN ITALY)

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Keywords: *Mafic-ultramafic sequence; dunite; melt-rock reaction; crustal contamination; trace element amphibole compositions.*

This study presents a new petrological-geochemical dataset for the Monte Capio and Alpe Cevia mafic-ultramafic sequences, which are exposed in the deepest levels of the Ivrea-Verbano Zone. The mafic-ultramafic sequences are composed of a peridotite core, with dunite in the center, mantled by minor, orthopyroxene-dominated pyroxenites and subordinate hornblende gabbronorites. Amphibole is ubiquitous in the peridotites and the pyroxenites (≤15 vol% and 10-40 vol%, respectively), and the peridotite-pyroxenite associations are frequently crosscut by amphibole-rich (45-90 vol%) veins/dykes showing diffuse to sharp planar boundaries towards host rocks. The whole-rock Mg# [100 × Mg/(Mg+Fe2+tot)] decreases from the peridotites to the pyroxenites and the crosscutting amphibole-rich dykes (84-81, 80-77 and 73-66, respectively), consistently with the Mg# variations shown by included orthopyroxene, clinopyroxene and amphibole. Olivine has relatively low forsterite and NiO amounts (84-78 mol% and ≤0.14 wt%), and spinel is characterized by low Cr# # [100 × Cr/(Cr+Al)] of 7 to 24. The anorthite content of plagioclase varies from 91-88 mol% in plagioclase-bearing pyroxenites to 91-75 mol% in amphibole-rich dykes. The chondrite-normalized REE patterns of amphibole from peridotites and pyroxenites show nearly flat MREE-HREE, no evident Eu anomaly, and LREE that are slightly depleted to slightly enriched with respect to MREE. Amphibole from the amphibole-rich veins/dykes regularly exhibits slight LREE depletion. Whole-rock and amphibole separates show substantial variations in initial Nd-Sr isotopic compositions (e.g., whole-rock εNd calculated at 290 Ma ranges from -0.3 to -4.7), irrespective of the rock-type and of incompatible element amphibole compositions.

The chemically evolved signature of the Monte Capio-Alpe Cevia dunites documents earlier crystallization of chemically primitive dunites at lower levels, or olivine fractionation within the dunites during melt ascent. We attribute the formation of the pyroxene-bearing peridotites to a magmatic evolutionary process ruled by reaction of a semi-consolidated crystal mush with migrating melts relatively rich in SiO2 and H2O, which developed orthopyroxene and amphibole at the expenses of olivine ± clinopyroxene. These melts may be reconciled with those feeding the amphibole-rich veins and dykes crosscutting the peridotite-pyroxenite sequences. Unraveling the origin of the pyroxenites is hampered by the complicated open-system magmatic evolution, which most likely also included assimilation of material released by basement metasediments, and involvement of primary melt batches with different compositions.

THE GENESIS OF PLUMASITES FROM DEPLETED MANTLE SOURCE DURING TRIASSIC: NEW INSIGHTS FROM ZIRCON (VAL SABBIOLA, IVREA-VERBANO ZONE)

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Plumasite is a pegmatitic rock consisting of sodic plagioclase (typically oligoclase), corundum (>16%vol.), zircon, biotite, hercynite ± K-feldspar. The occurrence of plumasite was documented in Val Sabbiola (Bertolani, 1957) and in Val Cannobina (Langone et al., 2017) as small dykes discordantly intruding both magmatic and metamorphic rocks of the Adria lower crust (Ivrea-Verbano Zone). We recognized two plumasite dykes in Val Sabbiola: one crosscuts mafic intrusives (Mafic Complex) and shows mylonitic deformation; the other one intrudes granulites (Stronalite), preserving pegmatitic texture. Petrogenetic models reported in literature suggest a hybrid nature for the plumasite parent melt, resulting by the interaction of silica-undersaturated melts and felsic rock. We present new constraints on the petrologic origin of plumasite by petrographic and geochemical characterization of zircons. BSE-CL images revealed the same internal zircon structures in both dykes: a broad banding zoning, typical of zircons segregated by melts, is commonly overprinted by irregular structureless domains. Trace elements, U-Pb and Lu-Hf surveys on zircon performed by LA-(MC)-ICP-MS suggest a Triassic intrusion age for both dykes, pointing to a pronounced Depleted Mantle geochemical signature for the parent melts. This magmatic activity post-date the youngest intrusion of mafic–ultramafic pipes of mantle origin intruded within the lower crustal levels of the IVZ (Locmelis et al., 2016); it is coeval or slightly older than alkaline dykes reported in the northern sector of the IVZ (e.g. Schaltegger et al., 2015) and pre-date the intrusion of carbonatites during Jurassic time (Galli et al., 2018).

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PERMIAN BASIC MAGMATISM FROM CORSICA TO THE SOUTHEASTERN ALPS, A NEW LIP?

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Keywords: *Corsica, Southern Alps, post-Variscan, Permian, U-Pb dating*

Permian Post-Variscan magmatism is known to be widespread in the Alps, in particular within the Southalpine units, where voluminous intermediate to acidic volcanics and basic– ultrabasic intrusive rocks crop out. Here we report new geochronological and geochemical data of basic intrusive rocks from Southern Tyrol (Italy) and western Corsica (France), which may be related to this widespread event. In South Tyrol, a relatively small intrusive body represents the easternmost known occurrence of Permian gabbros. Zircon collected in one of these samples yielded an age of ca. 282 Ma (single zircon TIMS analysis). The geochemical compositions of whole-rocks (including Sr-Nd-Pb isotopes) and minerals (major and trace element data) suggest that these rocks are formed by mantle-derived magmas contaminated by crustal rocks either within the mantle source or during shallow level AFC processes.

Permian basic rocks from Corsica are represented by hundreds of dykes sampled South and East of Ajaccio. Dykes are meter to decameter-thick and yield variable directions (N-S to E-W). They show calc-alkaline to tholeiitic affinities and their mineralogy is dominated by plagioclase, clinopyroxene, and rare altered olivine. Sr-Nd-Pb isotopic compositions span a relatively wide range from compositions close to MORB to compositions yielding a marked crustal fingerprint. We report the first ages for these dyke swarms, which yielded zircon U-Pb ages of ca. 282 Ma (laser-ablation ICP-MS data).

Globally, these data support the existence of a large igneous province expanding from the eastern South-Alpine (South Tyrol) to the southern parts of the European continent (Corsica) and affected the Variscan belt at the end of the orogenic cycle, which is commonly associated to orogenic collapse due to gravitational re-equilibration (e.g., Rey et al., 2001), extensive tectonics (e.g., Whitney et al., 2012), lithospheric thinning, increase of the geothermal gradient and production of magmatism (Bonin et al., 1998). The densely spaced dykes in Corsica, their essentially random distribution and variation from calc-alkaline to tholeiitic affinities may represent heterogeneous mantle sources conveyed to the melting region.

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LAMPROPHYRES AS PRECURSORS OF THE ALPINE TETHYS OPENING: A LATE TRIASSIC ALKALINE-CARBONATITIC MAGMATIC EPISODE IN THE DOLOMITIC AREA (SOUTHERN ALPS)

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We present a detailed petrological, geochemical and geochronological characterization of the alkaline lamprophyric dykes cropping out in the Dolomitic Area (Southern Alps). The relationship between them and their host Middle Triassic plutons is crucial for investigating the role played by lamprophyres in the geodynamic evolution of the Southern Alps domain. Whole-rock major and trace element analyses suggest that lamprophyres magmatic system was dominated by fractional crystallization processes, even if some complex textures of amphibole phenocrysts could have formed in response to small-scale mixing. Moreover, the occurrence of primary carbonate ocelli in the lamprophyres matrix led to speculate about the coexistence of a carbonatitic and an alkaline melt. According to 40Ar/39Ar data, lamprophyres emplaced ~20 Ma later than the calc-alkaline to shoshonitic magmas of the Dolomitic Area, thus cannot be anymore considered as a late-stage pulse related to that Middle Triassic magmatic episode. A comparison with the main coeval magmatic occurrences of the Alps and Carpathians regions led us to hypothesize that these lamprophyres belong to the alkaline-carbonatitic magmatic event that intruded the mantle beneath the Southern Alps between 225 and 190 Ma (Stähle *et al.*, 2001; Schaltegger *et al.*, 2015). Trace element and Sr-Nd isotopes suggest that they were generated by a garnet-amphibole-bearing mantle source interacting with an asthenospheric component. These new finding enabled us to hypothesize that the lamprophyres of the Dolomitic Area could represent the geochemical/geochronological connection between the orogenic-like Ladinian magmatism and the rifting phase related to the Alpine Tethys opening.

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TIMING AND DEFORMATION FEATURES OF SHEAR ZONES AT DIFFERENT CRUSTAL LEVELS (VAL D'OSSOLA, IVREA-VERBANO ZONE, WESTERN ALPS)

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The studied area is situated in the Ivrea-Verbano Zone, which consists of a Variscan continental lower crustal section showing Permian to Carboniferous magmatism and high temperature metamorphism overprinted by ductile deformation occurred at high temperature conditions during Jurassic time. In particular, the area of Premosello-Vogogna-Val d'Ossola preserves shear zones developed mainly within mafic rocks during the post collisional, extensional setting (Pittarello et al., 2012). Along the Ossola Valley, three shear zones of progressively higher T conditions, i.e. the Pogallo, the Anzola and the Premosello shear zone, are preserved but the timing of their activity is still unconstrained.

The PhD project consists in a comprehensive study integrating petrological, geochemical, geochronological and micro-structural analyses to characterise the activity (P-T-t-d) of the studied shear zones. The aim is to understand the link between metamorphism and deformation and the effect of deformation on different geochronometers. In order to achieve the aim, a rigorous micro-structural (SEM-EBSD) study of the deformation features of the geochronometers found in the collected samples (zircon, monazite, rutile, titanite, biotite) is expected. The combined use of different systematics (e.g., U-Pb and Rb-Sr) and several geochronometers may allow to get information on the timing of ductile deformational at different crustal levels during exhumation.

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RHEOLOGICAL WEAKENING IN THE LOWER CONTINENTAL CRUST: AN EXAMPLE FROM THE PROVOLA SHEAR ZONE IN THE FINERO MAFIC COMPLEX

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Keywords: *strain localization, strain partitioning, shear zone, continental lower crust, dehydration melting, dislocation creep, grain size sensitive creep, Finero, Ivrea-Verbano Zone.*

The rheology and strength of the lower continental crust play a key role in lithosphere dynamics, influencing the formation and evolution of orogenic belts and rift systems. Yet, the mechanical properties of this layer and the conditions needed for it to weaken and localize strain are still poorly constrained. To address this question, we here present microstructural results from a natural shear zone that developed at lower crustal conditions. The studied shear zone is located in the Finero mafic complex of the Ivrea Verbano Zone (Italy); a compositionally-layered mafic intrusion made up of *amphibole-rich* and *amphibole-poor* metagabbros.

Geothermobarometric estimates and thermodynamic modelling of equilibrium phase assemblages indicate that the complex experienced high temperature conditions accompanied by shearing after the emplacement of the intrusion (700 - 900°C). HT conditions triggered amphibole dehydration melting reactions in the *amphibole-rich* layers. Dehydration melting of amphibole generated fine-grained symplectites of pyroxene and plagioclase as dehydration reaction products, which coalesced into an interconnected network of fine-grained polyphase material (< 20 µm average grain size) that evolved into localised ultramylonitic shear zones. Conversely, *amphibole-poor* layers did not experience dehydration melting reactions, and were transformed into protomylonites and banded mylonites with relatively low degrees of phase mixing.

EBSD (electron backscatter diffraction) analyses of the *amphibole-rich* layers indicate that the fine-grained polyphase material deformed by grain size sensitive creep (diffusion creep + grain boundary sliding), accompanied by anisotropic grain growth of amphibole and plagioclase. In contrast, EBSD analysis on *amphibole-poor* layers indicates that plagioclase deformed primarily by dislocation creep on multiple slip systems, including (but not limited to) the (010)[001] on elongated grains. Dislocation creep of plagioclase was accompanied by subgrain rotation recrystallization. Clinopyroxene porphyroclasts deformed by a combination of crystal plasticity and microfracturing, associated with neocrystallization.

This study underlines how weakening and strain localization in the mafic lower crust can be governed by dehydration melting reactions that drastically reduce grain size and trigger grain size sensitive creep. Furthermore, this study finds that pre-existing lithological (mineralogical) heterogeneities are crucial in determining where these reactions – and weakening – are likely to occur.

THE METAMORPHIC RETROGRESSION OF THE HIGH TEMPERATURE GRANULITIC OAXACAN COMPLEX, MEXICO: A DETAILED PETROGRAPHIC, CHEMICAL AND GEOTHERMOMETRIC STUDY

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Keywords: *granulites, metamorphic retrogression, retrograde textures, exhumation*

The Oaxacan Complex is the largest inlier of Precambrian rocks in Mexico, comprising an area of about 7,000 km^2 in southern Mexico. The complex is constituted by mafic, pelitic, quartzofeldespathic and calcisilicate rocks of igneous and sedimentary origin that were metamorphosed under granulitic facies 990±10 Ma ago and reached peak temperatures between 700-909°C at pressures of 7.2-8.2 Kbar.

Here we present the first petrological study specifically dedicated to understanding the Oaxacan Complex metamorphic retrogression. The study of the lithologies that comprise the three units of the Oaxacan Complex (El Marquez, El Catrín, and Huitzo) involved field sampling, preparation and analysis of 51 thin sections under a petrographic microscope, SEM and EMPA analysis of 11 selected samples, and application of conventional geothermometry.

These data characterized the petrological and chemical evolution of the retrograde textures of the samples. The associated mineral and textural diversity illustrates several stages of a rather hydrous alteration by the growing of individual amphiboles (Amph), defining coronae around ortho and clinopyroxenes (Opx and Cpx), and of more complex textures such as multiple and symplectitic coronae around both pyroxenes and high-Ti amphiboles and Ilmenite (Ilm), including the formation of partial to complete pseudomorphs constituted by Amph, biotite and finally chlorite (Chl).

Chemical composition of Opx, Cpx, Amph, Chl, Ilm and feldspar present in the retrograde textures were used to estimate the equilibrium temperatures that some of these phases could have reached during the exhumation and cooling process. In particular, the retrogression of Opx and Cpx in mafic granulites of the three structural units of the Oaxacan Complex was the better illustrated, departing from assemblages associated to the peak conditions (T>900°C) into the retrograde assemblages formed under lower greenschist facies conditions (T= ~320°C).

This approach represents the first stage of a methodology that eventually could lead to the accurate constriction of the retrograde portion of the P-T-X (X = fluid composition) metamorphic trajectory or trajectories followed by Oaxacan Complex granulites during their exhumation, and potentially contribute to define the tectonic events that controlled the timing and route followed by the Oaxacan Complex to the surface.

RECONSTITUTING WHOLE ROCK COMPOSITIONS OF LOWER CRUSTAL GNEISSES FROM THE KAPUSKASING STRUCTURAL ZONE USING AN INTEGRATED SEM-EDS, EPMA AND LA-ICPMS APPROACH

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The composition and genesis of the lower continental crust (LCC) are still poorly understood in comparison to the upper continental crust. Several estimates of LCC composition have been produced by combining geophysical and geochemical data of lower crustal granulite terrains and xenoliths (Rudnick and Gao, 2003). However, the elemental concentrations obtained in these models of LCC can vary greatly, with some trace element concentrations differing by an order of magnitude. Consensus is also lacking for the radioactive heat-producing elements (K, Th and U).

Estimating the composition of LCC samples with traditional analytical techniques can be complicated by small sample sizes (e.g., xenoliths) and the fact that many LCC rocks suffer from decompression, alteration and contamination. Typical methods used to acquire whole rock compositions (XRF for major elements, solution ICPMS for trace elements) cannot distinguish these secondary compositions from the primary composition of the rock when it resided in the LCC.

Here we tested a method for overcoming these difficulties by combining modal mineralogy with in situ chemistry. The goal of the study was to test the accuracy of the modal mineralogy/mineral chemistry approach, compared to conventional methods, on a suite of fresh samples lacking secondary effects. Our studied objects are fresh rocks from exposures of the granulite gneisses of the Kapuskasing Structural Zone, southeastern Superior Province, Canada. The whole rock major and trace element compositions were first determined conventionally (XRF fused discs and pressed pellets, solution ICP-MS), to be compared to the reconstituted chemistry. Modal mineralogies of the samples were quantified through SEM-EDS phase mapping. The bulk rock compositions were then reconstituted by combining the mineral modes with the major element compositions of each mineral phase, obtained by EMPA spot analyses. Trace element concentrations were determined by multiphase LA-ICPMS elemental mapping, with a focus on the distribution of the most incompatible elements, which can be concentrated in secondary products. The comparison shows that the modal mineralogy/mineral chemistry approach works well for major and minor elements and produces accurate data for incompatible elements, provided the minor and accessory phases are adequately captured during phase mapping. We propose that the new approach will help to resolve current discrepancies for global LCC average compositions.

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SPATIAL AND TEMPORAL EVOLUTION OF ARC-LIKE POST-SUBDUCTION MAGMAS: METALIFERI MOUNTAINS, ROMANIA

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Keywords: *post-subduction magmatism, tellurium, geochronology, Neogene, Metaliferi Mountains*

Even though tellurium is becoming a critical metal for a modern, advanced society, the underlying processes that lead to its enrichment in Au-rich deposits are still debated. A relationship has been observed between Te enrichment and post-subduction, and one of the key mechanisms is thought to be the melting of sulphide bearing arc cumulates or metasomatized subcontinental lithospheric mantle (Richards, 2009). Due to their strongly chalcophile/siderophile nature, elements like Te and Au will be enriched in sulphides residual in the mantle, or fractionated into cumulates.

In the Metaliferi Mountains, Romania, tellurium-rich porphyry and epithermal Cu-Au deposits are hosted in Neogene magmatic rocks emplaced along graben structures in an extensional regime generated by the rotation of the underlying crustal blocks (Rosu et al., 2001). The majority of rocks are andesitic, calc-alkaline and exhibit arc-like trace element profiles with enrichments in LREE, LILE or Pb and relatively depleted HFSE and HREE. Rocks with high Sr/Y values, named adakitic-like, are present throughout the region. The Apuseni Mountains have a rich history of arc magmatism, with previous events during the Jurassic and Late - Cretaceous. The current understanding is that the Neogene magmatism was generated through the melting of subcontinental lithospheric mantle metasomitized during subduction in Mesozoic times (Harris et al., 2013); however, melting of lower crustal cumulates formed in previous magmatic events as a source for magmas cannot be ruled out.

New U-Pb zircon data obtained using LA-ICP-MS, represent emplacement ages and xenocrystic populations which have been used to decipher the spatial and temporal evolution of the Neogene magmas and their sources. Samples show emplacement ages between 12.9 and 7.2 Ma for the main phase of Neogene magmatism, younging towards the North-Eastern volcanic centres. The younger magmas tend to be more mafic and show higher enrichments in incompatible elements indicating a change in source or different degrees of crustal contaminations. The xenocrystic population is diverse and differs between individual volcanic centers suggesting different geological histories for the crustal blocks in which the magmas intrude.

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U-TH-PB DATING OF RUTILE IN ECLOGITE FACIES RELICS WITHIN THE MIDDLE-UPPER CONTINENTAL CRUST OF "MASSICCIO DEI LAGHI", NORTHWEST ITALY

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The basement of the South Alpine domain from northwest Italy exposes a nearly complete section of Permian continental crust, locally known as Massiccio dei Laghi. Relics of pre-Permian, eclogite facies assemblages are in places present within amphibolites of this continental crust section (e.g., Boriani and Giobbi, 2004; Franz and Romer, 2007). In particular, rutile-bearing eclogites were found within the middle-upper continental crust of the Strona Ceneri Zone (Gambarogno locality), and along the tectonic boundary separating the lower continental crust of the Ivrea-Verbano Zone from the Strona Ceneri Zone (Alpe Morello locality). To shed light on the temperature-time evolution experienced by the Massiccio dei Laghi, we carried out new U-Th-Pb analyses of rutile from these eclogites by laser ablation ICP-MS.

Both Gambarogno and Alpe Morello eclogites gave U-Th-Pb rutile dates that cannot be related to the age of the eclogite facies metamorphism. Rutile from the Monte Gambarogno eclogites yielded dates clustering in the Lower Permian, which are younger than the $^{40}Ar/^{39}Ar$ amphibole dates of 342 ± 2 Ma to 321 ± 3 Ma reported for the same rock body (Boriani and Villa, 1997). Rutile from the Alpe Morello eclogites gave Upper Triassic U-Th-Pb dates. Notably, an amphibolite body exposed at few hundred meters from Alpe Morello gave a ^{40}Ar-^{39}Ar amphibole date of 271 ± 1 Ma (Siegesmund et al., 2008). Taken as a whole, the U-Th-Pb rutile dates are progressively younger from the Strona Ceneri Zone to the base of the Ivrea Verbano Zone, where Jurassic dates were obtained (Smye et al., 2019, and references therein). The obtained pattern of U-Th-Pb rutile dates presumably reflects heating events experienced by the continental crust.

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ZIRCON DEPTH-PROFILING PETROCHRONOLOGY RECORDS THE THERMO-TECTONIC EVOLUTION OF AN ACTIVE CONTINENTAL RIFT (RIO GRANDE RIFT, NEW MEXICO, USA)

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Keywords: *lower crust, zircon, depth profiling*

Zircon U-Pb and trace-element data provide invaluable records of metamorphic processes. Though zircon has been ubiquitously characterized in high-*T* rocks, the application of metamorphic zircon petrochronology to active tectonic settings is limited – yet such data are essential for characterizing the rates, durations, sequence, and style of geodynamic processes. Here, we present preliminary U-Pb and trace-element laser-ablation split-stream (LASS) depth-profiling data from zircons hosted in metapelitic and metaigneous xenoliths from the Rio Grande Rift (RGR). The RGR represents a N-S oriented region of localized lithospheric extension on the eastern flank of the Colorado Plateau, with rift initiation by the Oligocene (~32 Ma) followed by a 20–10 Ma quiescence and rejuvenated extension and basaltic magmatism starting at ~10–5 Ma. Crustal thickness varies along the axis of the rift, but both crust and subcontinental lithospheric mantle have likely been thinned, and long-wavelength gravity anomalies suggest the influence of asthenospheric upwelling along the rift.

Each of the analyzed xenoliths is sourced from the lower crust of the orogen (~1 GPa; Padovani and Carter, 1977; Cipar *et al*., in prep), providing a deep window into rift evolution. The zircon depth-profiling data record an array of U-Pb dates extending from 1400 Ma to effectively zero age, with numerous dates spanning the timing of rift initiation and evolution. The 1400 Ma dates indicate that both metasedimentary and metaigneous xenoliths are authochthonous, i.e., they do not represent sediments underplated during Farallon subduction. Though individual depth profiles are complex, the compiled zircon data show several critical age-correlated changes, including i) non-monotonic, fluctuating changes in trace elements (e.g., Th/U, REE) that preclude analytical mixing as the primary explanation for the observed age spread; ii) garnet-present, flat HREE at ~40–20 Ma that transition to garnet-absent, positively sloping HREE <20 Ma; and iii) Ti-in-zircon data that record lower-crustal cooling from ~20–8 Ma followed by reheating <8 Ma. The extended, continuous RGR zircon record thus provides a robust framework for characterizing how continental lower crust responds to rifting.

THE ROLE OF MELT/ROCK RATIO IN OLIVINE-RICH TROCTOLITE FORMATION VIA BASALT-DUNITE REACTION: ISOTHERMAL AND STEP-COOLED EXPERIMENTS AT 0.5 GPa.

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Keywords: *melt-olivine reaction, oceanic lithosphere, high-pressure experiments.*

Microstructural and chemical evidence supports the origin of olivine-rich troctolites through multistage interactions between a precursor mantle dunite and an infiltrating basalt (Drouin et al., 2010). Borghini et al. (2018) recently performed reactive dissolution and crystallization experiments juxtaposing MORB-type glasses on a melt-bearing dunite at 1300°C and then cooling to 1150°C at constant pressure (0.5 and 0.7 GPa). Their results showed that olivine-rich troctolites might form through dunite infiltration followed by reactive crystallization of interstitial melts resulting in textural relations and mineral chemistry comparable with natural rocks. Significantly they suggested that the initial melt/rock ratio strongly influences the extent of interaction and, thus, the final mineral abundances and chemistry. However, the reaction couple strategy used in their experiments did not allow a quantification of the role of melt/rock ratio.

At this purpose, we are performing piston cylinder experiments at 0.5 GPa using a mixture of San Carlos olivine (Fo_{90}) and a reacting MORB-type melt at variable proportions olivine:melt (9:1, 3:1 and 1:1). For each mixture, we perform at 0.5 GPa both isothermal run at 1300°C for 24 hours and crystallization experiment step cooled at a rate of 1°C/min from 1300°C down to 1100°C. Specific aims are to define and quantify how the melt/rock ratio controls the amount of olivine dissolution, the lithology produced by reaction, and the final mineral chemistry.

Preliminary results of the isothermal experiment run at 0.5 GPa and 1300°C with 25 wt% of initial basalt powder in the starting mix (olivine:melt 3:1) show run products made of olivine and glass. Olivine occurs both as large subhedral crystals with straight and lobate curvilinear rims against the interstitial glass or as smaller rounded grains. Mineral chemistry indicates that after the high-temperature interaction reacted olivine has slightly lower X_{Mg} and higher CaO contents. Remarkably, NiO content is significantly lower than that of the starting San Carlos olivine and it is still lower than NiO content in olivine from reaction experiments with lower melt/olivine ratios. Compared to the initial melt, final glass composition is characterized by higher X_{Mg}, SiO_2 and NiO contents and lower FeO, Cr_2O_3 and Al_2O_3 abundances.

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PETROCHRONOLOGY OF TEMPERATURE-DOMINATED METAMORPHIC PROCESSES: PETROLOGY AND DATING OF ACCESSORY MINERALS FROM THE IVREA VERBANO ZONE, ITALY

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Keywords: *Ivrea-Zone, monazite, zircon, U-Th-Pb-dating, phase equilibria modelling*

The emerging field of petrochronology relates absolute ages with petrological information derived from the same minerals. Modern U-Th-Pb in-situ-dating techniques of accessory minerals (AM) like monazite or zircon allow to gain age information from multiple episodes of crystal growth, dissolution and reprecipitation if these features are preserved within single crystals. Provided that the petrology of these AM, their evolution through metamorphism is well understood, the U-Th-Pb in-situ dating methods can be used to unravel rates of processes in Earth's crust.

Petrological observations and ages are presented for monazites and zircons from migmatic metapelite samples from the Val Strona di Omegna transsect in the Ivrea Zone, Italy.

The Ivrea Zone is part of the pre-Alpine basement located in the Southern Alps of NW Italy. Most regional studies interpret the Ivrea Zone as an almost complete section from mid- to lower continental crust showing Permian HT-metamorphism (e.g. Zingg, 1980; Handy et al., 1999). The Val Strona di Omegna shows a 14km long transect with amphibolite facies in the SE and granulite facies in the NW (Barboza and Bergantz, 2000; Redler et al., 2012).

In all samples monazites exhibit complex zonation patterns. Several monazite-domains from amphibolite to granulite facies samples were dated in-situ by EPMA-CHIME.

A granulite facies metapelite sample (IV 20/05) shows vermicular-shaped metamorphic zircons in proximity to rutile and ilmenite. SIMS in-situ U-Pb dating reveals Permian ages (286.2 ± 2.0 Ma) thus tentatively dating the post-granulite facies peak, Zr-exsolution of rutile or rutile breakdown to ilmenite.

P-T-pseudosections are presented for metapelitic and metabasic rocks from Val Strona di Omegna. P-T-forward modelling was performed in the MnNCKFMASHT-System for metapelites and in the NCKFMASHT-system for metabasites using the Software THERIAK-DOMINO (de Capitani and Brown, 1987; de Capitani and Petrakakis, 2010) with the Holland and Powell (2011) database ver. 6.2 with updates from White et. al. (2014) and Green et al. (2016) for metabasites.

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PETROGENESIS OF AMPHIBOLE-RICH ULTRAMAFIC ROCK IN THE HIDA METAMORPHIC COMPLEX, JAPAN: ITS ROLE IN ARC CRUST DIFFERENTIATION

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Keywords: *cortlandite, arc magma differentiation, Jurassic, Japan arc.*

The difference in mineral assemblages in lower crusts affects thier solidus temperature and crustal melt composition. Hydrous minerals play a key role in crustal melting and differentiation. Amphibole is considered to be a significant fractionating phase causing variations in major and trace element composition of arc magmas (e.g., Davidson et al., 2007). However, amphibole phenocryst is generally scarce in arc lavas and this fractionation process is cryptic. In contrast, amphibole-rich cumulates are evidence of abundant amphibole and their petrogenesis could provide insights into the differentiation of arc magma.

In this study, we conducted the petrological and geochemical examination of amphibole-rich ultramafic rock in the Hida metamorphic complex, Japan to obtain a better understanding of the role of amphibole-rich cumulates. The studied sample is characterized by large poikilitic amphibole and orthopyroxene enclosing olivine grains. Ultramafic rocks showing such texture are referred to as cortlandites. The olivine grains show resorbed or anhedral textures and are partly serpentinized. Apatite, Cr-spinel, and Fe-Ri-oxide occur as accessory phases.

The olivine shows relatively homogeneous compositions with an average forsterite content of 84. Poikilitic amphiboles (pargasite) and orthopyroxene yielded higher Mg# of ~85–89 and ~84–86, respectively. Textural relation and trace element compositions showed that olivine and spinel crystallized prior to amphibole and orthopyroxene. The estimation of melt in equilibrium with amphibole using partition coefficients (Tiepolo et al., 2007) revealed the affinity to arc basalts in terms of the depletion of high field strength elements such as Nb, Ta, and Ti. Another important finding is that the liquidus assemblage of the reconstructed melt consists of amphibole and orthopyroxene without clinopyroxene. The crystallization of orthopyroxene instead of clinopyroxene could be attributed to the peridotite-hydrous basaltic melt interaction at a lower crustal level (0.8 GPa) (Wang et al., 2016) or the peridotite-felsic melt interaction causing mantle metasomatism (Gervasoni et al., 2017). The crystallization of amphibole is consistent with the results of the experiments mentioned above. Therefore, the reaction of pre-existing peridotite and hydrous arc magma under lower crustal conditions could explain the formation of the studied amphibole-rich ultramafic rock. If that is the case, the peridotite-hydrous melt interaction at lower crust can be a significant process for arc magma undergoing cryptic amphibole fractionation.

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CHALLENGES OF CORE-LOG-SEISMIC DATA INTEGRATION FOR THE HIGH-RESOLUTION SEISMIC STRATIGRAPHY IN A METAMORPHIC ENVIRONMENT

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As part of the International Continental Scientific Drilling Program's (ICDP) drilling project "*Collisional Orogeny in the Scandinavian Caledonides (COSC)*", we investigate the integration and linkage of geophysical properties from laboratory investigations, borehole measurements, and reflection seismic data in the western Scandinavian Caledonides. We aim to construct a high-resolution seismic stratigraphy along the 2.5 km deep and fully cored COSC-1 borehole, which was drilled in 2014 into the lower part of the Seve Nappe Complex to better understand the deep orogenic processes in mountain belts.

By calculating synthetic seismograms from core and borehole logs and matching them to 2D and 3D seismic data, we aim to identify lithological boundaries that represent seismic reflectors and to correlate them not only to composition but also structure and metamorphic overprint. In terms of compositional variations, these reflections mainly correspond to interfaces between mafic and felsic rock units and mineral structure. We then compared the P-wave velocity data measured with a multi-sensor core logger with those obtained under in-situ conditions by a downhole sonic log. The differences in P-wave velocities between the two data sets are likely ascribed to the formation of micro-cracks during drilling and depressurization of the cores. This was confirmed by velocity and seismic anisotropy measurements on selected core samples in the laboratory under in-situ pressure conditions. Moreover, from these samples we also derived a primitive anisotropy-depth profile along the borehole showing highest anisotropies for the phyllitic mica schists. It also emphasizes that seismic velocity and anisotropy are of complementary importance to better distinguish the present lithological units.

We can address two main challenges when attempting core-log-seismic data integration in a metamorphic environment. Firstly, seismic velocities of core samples are particularly strong affected by excavation damage during drilling and the directional dependence of their properties, thus, are a poor proxy for in-situ seismic properties, which hinders correlation of core and borehole logs. Secondly, the high seismic velocities (>5 km/s) at shallow depths and very complex geology lead to poorer seismic imaging if, e.g., compared with sedimentary basins in the offshore domain. Consequently, this requires additional seismic processing efforts for a successful data integration.

STUDY OF A POLYMICT CONGLOMERATE FROM REILLY RIDGE (NORTHERN VICTORIA LAND, ANTARCTICA): INDIRECT EVIDENCE FOR THE EVOLUTION OF THE ROSS OROGEN

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During the GANOVEX XI campaign in the 2015-16 Antarctic season, a conglomerate sequence was sampled at Reilly Ridge in the north- eastern Lanterman Range in northern Victoria Land (NVL). This conglomerate represents one of different conglomeratic units within the Bowers Supergroup (e.g. Carryer Conglomerate, Reilly Conglomerate, etc.), which are poorly studied and still not fully understood. The Bowers Supergroup is part of the Bowers Terrane, which represents the central of three lithotectonic units formed during the Late Ediacaran to Early Palaeozoic Ross Orogeny in the Transantarctic Mountains (e.g., Kleinschmidt and Tessensohn, 1987). The internal Wilson Terrane in the west and the external Robertson Bay Terrane in the east adjoin it tectonically. The study of the Bowers Terrane is fundamental for understanding the evolution of the paleo-Pacific active continental margin of former East Gondwana at that time, which experienced a long period of subduction from the latest Ediacaran into early Paleozoic (e.g., Goodge et al., 2012). However, there are still uncertainties about the geodynamics related to this subduction system, e.g. the migration of the slab to a continuously more outboard position with time. Thus, the geodynamics related to the Ross orogeny may be the starting point for any interpretation of the more recent history of NVL. Here, we provide new constraints on the conglomerates from Reilly Ridge with regard to provenance of pebbles and detrital minerals and its possible source regions within the general frame of the Ross Orogen. We supply field observations and lab-based structural-petrographic and geochemical analyses of clasts and matrix (optical microscopy, point-counting, non-destructive μ-EDXRF/M4 Tornado). The analysed rocks represent a polymict conglomerate composed of clasts comprising different igneous and metamorphic lithologies (e.g.; granitoid, volcanite, orthogneiss, low grade-metamorphic sandstone and limestone) fitting the neighbouring units of the Wilson and the Bowers terranes. More specifically, the erosional products derived from two potential sources, namely from a continental arc and an island arc located at a relatively close position to the depositional basin. The conglomerate and the associated finer-grained rocks most likely indicate a shallow marine environment with high-energy transport and relief, located within an area affected by active tectonics in an active continental margin setting. Based on our own and data from the literature, we assigned the studied rocks to the so-called Southend Conglomerate of the likely late Cambrian Spur Formation (Mariner Group - Bowers Supergroup; see Bradshaw et al., 1985a; Cooper et al., 1990).

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CHEMICAL PROPERTIES OF A WATER-INFLUXED MOLTEN METAGRANITE WITH CONTRASTING PARTIAL MELT DEGREES

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The Areado Granite-Migmatite unit presents different partial melt degrees and marks the northwestern embasement of the Southern Brasilia Orogen. These rocks comprise three lithotypes. A porphyritic meta-syenogranite with garnet and k-feldspar coronas between plagioclase and biotite and few melt patches. The second unit is a patch metatexite with leucosome composed of k-feldspar, plagioclase, quartz and idioblastic hornblende, while residuum has k-feldspar porphyroclasts, garnet, titanite, allanite, quartz and zircon. The third lithology is a diatexite with leucosome composed of plagioclase, quartz and k-feldspar and residuum made of biotite, quartz, plagioclase, epidote and titanite (Julião et al., 2019). Petrography and field relations revealed that the meta-syenogranite is the protolith of the other migmatitic units and the melting process involved water-influx (Julião et al., 2019). The aim of the current work is to understand the behaviour of the chemical components during the water-influx melting of the meta-syenogranite using whole-rock geochemical data obtained by XRF and ICP-MS of leucosome and residuum of the migmatites and from their metagranitic source.

Major oxides concentrations from the metatexite vary little when compared to the protolith, with the exception of an increase in Fe_2O_3 that is controlled by garnet and hornblende abundances. However, this unit presents an enrichment in minor and trace elements, including the REE. We interpret that these variations are controlled mainly by allanite crystallization and some contribution of zircon. Major oxide composition from both residuum and leucosome of the diatexite evidence strong discrepancies from its source, in special an enrichment in Fe_2O_3, MgO and TiO_2 by the residuum, constrained by biotite formation, and high disparities in CaO between leucosome and residuum, which represents the composition variation of plagioclase. Leucosome from the diatexite also exhibits high Sr content and slightly Eu positive anomaly, which indicates the importance of feldspar fractionation into its petrogenesis. Data suggests that major elements mobility occurs when a higher partial melt degree is achieved. We interpret that the main mechanism of differentiation of the diatexite is fractional crystallization, corroborated by textural evidence. Later, we intend to model the melting and crystallization from these rocks, based in Allègre & Minster (1978), Hanson (1978) and Sawyer (1987).

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HOW THE WIDE-ANGLE SEISMIC RESEARCH CAN INVESTIGATE THE LOWER CRUST

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Keywords: *seismic wide-angle experiment, crustal structure*

Seismic wide-angle studies use the seismic waves refracting and reflecting at the boundaries of the layers with different velocities to explore the Earth's lithosphere. Since the velocities of the seismic waves depend not only on depth (temperature and pressure) but also on the properties of the medium (e.g. elastic parameters, anisotropy, porosity, saturation), comparing the obtained data with laboratory petrological studies, the mineral composition of the rock can be approximated. Combining the wide-angle results and data from the other methods and fields (e.g. reflection seismics, passive seismic studies, geology) allows to build the model of the Earth's lithospheric structure.

The poster describes how wide-angle seismic data constrain the properties of the lower crust (thickness, seismic wave velocity, heterogeneity) and discuss potential limitations of the method. The presented examples of seismic data and models come mainly from wide-angle experiments carried out by the Department of Lithospheric Research, Institute of Geophysics Polish Academy of Sciences.

The possible sources of wide-angle information on the lower crust properties are:

> first arrivals of the P-wave refracted in the lower crust,

> the Moho reflections at overcritical distances,

> ringing character of the P-wave signal reflected from or penetrating the lower crust, which gives hints about fine structure (e.g., lamination) of this layer,

> if observed – S-wave arrivals allow for determination of the Vp/Vs ratio distribution.

Depending on the actual crustal structure and resulting observed wide-angle wavefield, information about lower crust can be ambiguous or substantially limited. Non-uniqueness of some parts of the wide angle-model is an inherent feature of this method. The presented examples discuss possible limitations and ambiguities.

EXPERIMENTAL STUDY OF THE EFFECT OF STRESS ON α->β QUARTZ TRANSFORMATION AT LOWER CONTINENTAL CRUST PRESSURE AND TEMPERATURE CONDITIONS

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Several polymorphic phase transformations are known to occur in the Earth's lithosphere and the aim of this study is to investigate the role of stress, and in particular of deviatoric stress, on the equilibrium of phase transitions. Indeed, although a number of studies have been performed in order to understand whether the mean or principal stresses may trigger polymorphic phase change, the case is still not completely clear. Amongst the most common polymorphic transitions, the α->β quartz transition is of particular importance in the lower continental crust, in particular for its effect on the seismic properties of continental crust lithologies. The α->β quartz transition is a thus good experimental case both because of the significant changes in physical properties associated to it, as well as because of its displacive quasi-instantaneous nature.

To study the effect of stress on this reaction, we performed a series of experiments within the GRAAL apparatus, a new high pressure Griggs-type apparatus equipped with ultrasonic monitoring installed at the Laboratoire de Géologie of ENS Paris. During these experiments, solid rock cylinders (4.5mm diameter, 10mm long) of translucent Arkansas Novaculite (grain size 3-10 µm) were subjected to pressure and temperature conditions at which the metamorphic reaction should occur, i.e. pressures and temperature in the range of 0.5-1.5GPa and 700-900°C respectively. In some experiments, a deviatoric stress σ_m in the range of 0.5-1.5GPa was also imposed on the rock specimen. In consequence, the mean stress σ_m was either equal (hydrostatic conditions) or higher (deviatoric conditions) than the confining pressure P in all experiments. The temperature was ramped across the transition under fixed $\Delta\sigma$-σ_m-P conditions. An ultrasonic transducer (Olympus V156, Shear wave, 5MHz) located below the sample assembly was used in pulse-echo to enable an active acoustic monitoring of the transition during each experiment. With this method, the transition is directly observed by a time-shift of the acoustic signal, which travelled back and forth through the specimen. Further signal processing is needed to extract the travel times in the sample. Travel times are then used to calculate the variation of both P and S elastic wave velocities in the sample at in-situ conditions.

Preliminary results of our experiments show that the phase transformation is controlled by mean stress and that the variation of elastic velocities we observed are in agreement with thermodynamic models of elastic properties at P-T conditions of α->β quartz.

HETEROGENEOUS PRIMARY MELTS THROUGH THE LANZO SOUTH OPHIOLITE: EVIDENCE FROM RE-OS ISOTOPES OF REPLACIVE MANTLE BODIES.

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Keywords: *Mantle, Ophiolite, Re-Os & PGE*

The Lanzo South ophiolite is a lithospheric mantle section exhumed during the widening of a Jurassic basin akin to the modern slow to ultraslow spreading ridges. The peridotites consists mainly of Pl-bearing depleted harzburgites with evidence for refertilisation by MORB-type melts (Piccardo et al., 2007). Here, we found two generations of replacive bodies, in turn, produced by melt with an extreme geochemical variability (Sanfilippo et al., 2019). The first type, concordant to the foliation of the host-rock, is composed by Px-free dunites and it is related to the migration of melts with a MORB-like geochemical affinity. The second type consists of Px-poor harzburgites that are clearly discordant and geochemically depleted.

The host Pl-peridotites have nearly flat PGE patterns and initial $^{187}Os/^{188}Os$ ratios (at 165 Ma) of ~0.124, in agreement with an event of refertilization by MORB-type melts. Compared to the host rocks, the MORB-type dunites result preferentially enriched in Pd and Re, though having similar initial $^{187}Os/^{188}Os$ ratios (~0.123-0.126), thereby confirming the formation by MORB-type melts at very high melt flux. Differently, the replacive harzburgites are depleted in Pd and Re and have initial $^{187}Os/^{188}Os$ ratios extending towards highly unradiogenic compositions (down to 0.117). The variation in Al_2O_3 initial Os/Os in these rocks agree with the radiogenic Hf compositions of the clinopyroxenes from the same rocks and recall those of the depleted harzburgites from 15.20 FZ in the Atlantic (Harvey et al., 2006; Marchesi e al., 2013) and Gakkel Ridge peridotites (Liu et al., 2008).

With this contribution, we show that the whole-rock Re-Os isotopes and PGE compositions of the two types of replacive rocks found in the Lanzo South ophiolite agree with a formation by melts with different geochemical affinities. These data corroborate the idea that the replacive harzburgites from Lanzo South formed through an incomplete reaction with an ultra-depleted melt originated by an anciently depleted (>1 Gy) portion of the asthenosphere (Sanfilippo et al, 2019).

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DIRECTLY DATING LOWER-CRUSTAL DEFORMATION: MICROSTRUCTURAL GEOCHRONOLOGY OF TITANITE

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Constraining the rates of lower-crustal deformation is essential to understanding a number of tectonic processes, including strain partitioning, plate boundary initiation, and the feedbacks between near-surface and deep-crustal processes. Despite its importance, directly dating deformation in the lower crust remains an unsolved challenge in structural geology and geochronology. Titanite is common in a variety of bulk compositions, has a high Pb closure temperature (≥ 750 °C; e.g. Holder et al., 2019), incorporates trace elements as a function of the evolving pressure and temperature in the host rock (e.g. Garber et al., 2017), and preserves deformation microstructures (Bonamici et al., 2014), making it the ideal candidate for a deformation chronometer. We present a titanite U–Pb geochronology approach that can be applied to directly date deformation in the lower crust. Combined microstructural analyses, U–Pb geochronology, and trace-element geochemistry from titanite in the Coast shear zone, British Columbia, provide evidence for Pb loss as a result of subgrain formation during crystal-plastic deformation. EBSD maps of ~500 µm-long titanite show up to 70° of intragrain misorientation, with subgrains exclusively present at grain tips. U–Pb LASS dates range from ~60–50 Ma and correlate with intragrain microstructure. The oldest dates (~60 Ma) are associated with undeformed cores; subgrains at titanite tips have the youngest dates (54–50 Ma). The U–Pb dates have a weak or zero correlation with distance to the edge of the titanite grain, suggesting that volume diffusion was not significant. Similarly, there is no straightforward correlation between titanite trace-element composition and U–Pb date, implying that the variations in U–Pb date do not reflect titanite growth. The correlation between date and microstructure and the absence of or weak correlation between date and any other variable imply that the 54–50 Ma dates record the timing of crystal-plastic deformation during slip on the Coast shear zone. This interpretation is consistent with independent constraints on the timing of Coast shear zone deformation, including the 70–55 Ma crystallization age of the Great Tonalite Sill, which intruded before and during slip along the Coast shear zone (Ingram and Hutton, 1994; Rusmore et al., 2001).

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DETAILED GEOCHEMICAL STUDY ON LOWER CRUSTAL GARNET GRANULITE XENOLITHS

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Keywords: *silicate melt inclusion, granulite, partial melting.*

Mafic garnet granulite xenoliths were studied from the Plio-Pleistocene alkali basalts of the Bakony–Balaton-Highland Volcanic Field (Hungary). Two particular samples which contain primary silicate melt inclusions (SMI) in the rock-forming minerals in plagioclase-rich veins were chosen for detailed petrological and geochemical analyses.

The samples have non-equilibrium texture in contrast with the majority of known mafic garnet granulite xenoliths form the area. SMIs were observed in plagioclase (Pl), clinopyroxene (Cpx) and ilmenite (Ilm) in both xenoliths. The major element composition suggests the presence of a SiO_2-rich melt at relatively high temperatures (830-920 °C). The small Mg-number and high SiO_2-contents of the SMIs (up to 0.38) excludes the effect of the host alkaline basalt on the formation of these SMIs. On the other hand, the major and trace element composition of SMIs resembles the composition of early Miocene calc-alkaline magmas from the Carpathian Pannonian Region (Harangi et al., 2001).

SMI trapped in Pl and Cpx are enriched in Cs, Rb and Pb, in addition they are characterized by negative Nb and Ta anomalies. Such melt is usually characteristic of island arc volcanism (Pearce, 1983; Saunders et al., 1991). The enrichment of the SMIs in fluid-mobile elements and their high K_2O and Na_2O content may also indicate that the H_2O-rich melt is originated from melting a water-bearing mineral phase (e.g., biotite and / or amphibole). The most likely reason for the observed negative Ta-Nb anomaly is that there was residual rutile, ilmenite or titanite that sequesters these elements during partial melting of the source rock. These minerals commonly occur as accessories in many mafic granulites and Grt-pyroxenites in the same localities.

The chemical composition of SMIs and their host minerals can be modeled by a two stage process: 1) local melting of a lower crustal mafic amphibolite and metasedimentary granulite mélange in the presence of C-O-H±S±N fluids; 2) reequilibration of the melts formed during the first step with a garnet-rich granulite wall rock.

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ASSESSING THE PT EVOLUTION OF HIGH-PRESSURE MIGMATITIC PARAGNEISSES VIA THERMODYNAMIC MODELLING (UPPER ALLOCHTHONOUS UNIT, ÓRDENES COMPLEX, NW IBERIAN MASSIF)

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In the European continent, the Variscan belt extends from the Iberian Massif to the Bohemian Massif, and is characterized by an internal zone in the core of several allochthonous complexes (Arenas et al., 2016). In the NW of the Iberian Massif, the Órdenes Complex contains an Upper Allochthonous Unit that represents the remnants of a Cambrian magmatic arc located in the periphery of the West African Craton (Gondwana, Albert et al., 2015a,b). This terrane underwent HP-HT metamorphism during the initial stage of the Devonian collision between Gondwana and Laurrusia that led to the formation of Pangea. It includes ultramafic rocks, eclogites, granulites and migmatitic paragneisses. The mineral assemblage of the migmatitic paragneisses is composed by garnet+kyanite+biotite+plagioclase+K-feldspar+quartz+rutile+Ti-hematite+melt.
Thermodynamic modelling of the measured bulk composition in the NCKFMASHTO system reveals metamorphic peak conditions at ~15 kbar and ~825ºC. To assess the prograde evolution of the rocks a bulk-rock melt-reintegration approach is performed. To do so, an internally consistent liquid was calculated at 11 kbar and 801ºC and 26 mol.% of this liquid was added to the measured bulk composition to simulate the protolith composition before melting. This melt-reintegrated composition reveals a colder high-pressure event for the paragneisses. Hence, a PT trajectory is proposed which implies includes deep subduction of the rocks to mantle depths along a colder path. Subsequent isobaric heating occurred at such depth as a consequence of a long residence time. Drastic almost isothermal decompression uplifted the paragneisses to the lower crust, where they reached the thermal peak. The final exhumation to shallower levels is characterized by a substantial cooling.

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NUMERICAL MODELLING AND EXPERIMENTAL MEASUREMENTS OF SEISMIC ANISOTROPY OF THE BALMUCCIA PERIDOTITE, ITALY AND THE HOROMAN PERIDOTITE, JAPAN

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Keywords: *Seismic anisotropy, Balmuccia Peridotite, Horoman Peridotite, MTEX, E-wave, Ivrea-Verbano zone, Hokkaido.*

The Balmuccia and Horoman Peridotites are pristine examples of exhumed peridotite massifs which outcrop in the western Italian Alps and south-central Hokkaido, Japan respectively. The massifs collectively provide samples of a wide spectrum of typical peridotite lithologies (e.g. dunite, harzburgite, lherzolite, wehrlite), textures (protogranular, porphyroclastic, mylonitic, etc), and were equilibrated or partially equilibrated in P-T fields ranging from plagioclase to spinel zones. My research employs a novel combination of modern methods to understand the anisotropic seismic properties of these peridotites. I will couple static and numerical simulations based on measured microstructures of natural samples, with experimental measurements of elastic wave propagation under confining pressure and in the presence of fluids. The numerical simulations are based on ‘fabric tensors’ ie. 3D characterisations of the rocks’ microstructures including both mineralogical and crystallographic orientation data, acquired by combined Electron Backscatter Diffraction (EBSD) and Energy Dispersive x-ray Spectroscopy (EDS). The numerical modelling methods employ MTEX for static and E-wave for dynamic simulations to calculate the behaviour of seismic waves as they pass through these real mantle rocks, and the experiments provide critical comparative data.

The bulk seismic properties of these peridotite bodies must combine those properties of representative samples of all constituent lithologies in a realistic way that considers the 3D geometric arrangement of the representative lithologies. We are determining this by combined traditional and modern structural mapping, including drones.

Better understanding of seismic anisotropy within these peridotites will enhance our ability to determine lithospheric mantle rheology and deformation kinematics, and allow stress distributions beneath active faults to be mapped with greater accuracy, by remote geophysical methods. It will also clarify the specific petrologic features responsible for the production of anisotropic seismic behaviour of a rock mass (i.e. crystallographic preferred orientations (CPOs), shape preferred orientations (SPOs), microcracks, dilated grain boundaries, mineral phase, etc.) This project will also aid future borehole targeting by allowing firmer constraints on the elastic wave propagation properties of the Balmuccia and Horoman peridotites to be incorporated into local crustal geophysical models.

FLUID-ASSISTED STRAIN LOCALIZATION IN QUARTZ AT THE BRITTLE-DUCTILE TRANSITION

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Keywords: *EBSD, quartz, fluid-rock interaction.*

A mylonitic quartzite characterized by sheared quartz layers with intracrystalline shear bands was investigated by Electron BackScatter Diffraction (EBSD) and optical microscopy to obtain insights on recrystallization mechanisms and strain localization in quartz at plastic to semibrittle conditions close to the brittle-ductile transition. The mylonitic quartzite was deformed during Late Miocene thrusting coeval with contact metamorphism in the Calamita Schists from Elba Island, Italy (Musumeci & Vaselli, 2012; Papeschi et al., 2017, 2018, 2019). Mylonitic deformation accompanied retrograde metamorphism of the Calamita Schists from amphibolite to lower greenschist facies conditions. Dynamic recrystallization, dominated by dislocation creep by prism <a> slip, produced recrystallized quartz layers mantling relic large quartz porphyroclasts. Under decreasing temperature and fluid-rich conditions, quartz porphyroclasts acted as relatively rigid bodies and fractured along synthetic and conjugate C' shear bands. Shear bands developed along kinematically favored orientations, just locally assisted by weak crystallographic planes in quartz. Fracturing along shear bands was enhanced by fluid infiltration that assisted fracture propagation and healing by recrystallization and authigenesis of new quartz and phyllosilicate grains. Nucleation of quartz from fluids likely caused the development of a c-axis CPO in quartz oriented parallel to shear bands. The progressive propagation of intracrystalline shear bands in quartz was assisted by the development of bands of 'weak' phyllosilicates. This study highlights the importance of the interplay between brittle and crystal-plastic processes and fluid ingress in the semibrittle regime to understand deformation partitioning and strain localization. The study is published on Papeschi & Musumeci (2019).

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TOWARDS UNDERSTANDING METAL MIGRATION THROUGH SUBCONTINENTAL CRUST-MANTLE TRANSITION ZONES: FIRST INSIGHTS FROM THE IVREA-VERBANO ZONE

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The nature of chalcophile metal migration across the subcontinental crust-mantle transition zone is not well constrained due to scarcity of suitable exposures. As sulfides are very sensitive to melt-mantle reactions, however, crust-mantle transition zones are crucial to understand the behavior of chalcophile metals for modelling melt differentiation or global mass balances. Here, we use a set of rocks from the contact zone between the Balmuccia peridotite massif and the adjacent Mafic Complex (Ivrea-Verbano Zone, northwest Italy) to better understand potential sulfide distribution across a subcontinental crust-mantle transition zone.

The inherent sulfides are up to 2-mm large forming irregular or globular grains and represent former sulfide liquid exsolved to pentlandite ($[Ni,Fe]_9S_8$), chalcopyrite ($CuFeS_2$), and pyrrhotite ($Fe_{1-x}S$). Pyroxenite and dunite veins contain 3-5 times more sulfides than the host Balmuccia lherzolites. Whereas the lherzolite sulfides are dominated by pentlandite (~65 vol%) with only ~5 vol% pyrrhotite, the pyroxenite and dunite veins are markedly enriched in pyrrhotite, which is as abundant as pentlandite (35 vol% each). First electron microprobe analyses of the contact zone sample containing dunite veins and host lherzolites show that pentlandite reveal a close to stoichiometric metal (Me)/S of 1.09-1.10. In addition, pentlandite displays low Co content (0.3 wt%) and Ni/(Ni+Fe) ranging from 0.39 to 0.43. Chalcopyrite is Cu-poor with Cu/(Cu+Fe) of 0.46. Pyrrhotite is Ni-poor (~0.1 wt%) and characterized by low variation of Fe (61.5-62.0 wt%) and a formula $Fe_{0.97}S$ close to the troilitic composition of FeS.

Our initial results suggest high efficiency of pyroxenitic pipes in transporting Fe-S-rich melts from the primitive mantle. However, sulfide-rich melt-rock reaction zones represented by dunite channels demonstrate that uppermost mantle is refertilized with these melts during their ascent through the uppermost mantle. Hence, large portion of sulfur and metals is retained in the mantle never reaching the crust as has been observed in the oceanic lithosphere (Ciazela et al., 2017, 2018). During the next 3 years of a project funded by National Science Centre Poland (July 2019 - July 2022), the investigation of the Balmuccia peridotite massif and associated Mafic Complex will allow us to constrain the trace element and isotope composition of the Fe-S-rich melts, and to characterize how depleted mantle is refertilized with these melts.

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OXYGEN ISOTOPE VARIATIONS IN THE ECLOGITE TYPE LOCALITY: EVIDENCE FOR EXTENSIVE HYDROTHERMAL ACTIVITY IN AN EXTENSIONAL SETTING

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Keywords: *eclogite, oxygen isotopes, fluid-rock interaction*

The polymetamorphic basement of the Austroalpine Koralpe–Saualpe nappe system mostly consists of aluminous metapelites hosting subordinate eclogites and metagabbros. Due to tectonic dismemberment, deformation and exhumation of crustal slices, accompanied by subsequent metamorphic events, the paleogeotectonic setting remains poorly constrained. We report a new comprehensive oxygen isotope dataset from individual minerals of the eclogite type locality, showing a wide variability (2.66–15.71 ‰) consistent with low and high-temperature hydrothermal alteration of the protolith, by reaction with seawater.

Classic eclogites (g (garnet)–o (omphacite)–q (quartz)– ep (epidote)–ru (rutile)±hb (hornblende)) have g δ18O values (8.36–12.49 ‰) superior to the mantle g values (5.5±0.4 ‰), typical for low-temperature altered oceanic crust. Conversely, kyanite (ky)-bearing eclogites (g–o–ky–q–hb–ep–ru) have g δ18O values (4.02–4.42 ‰) strictly inferior to the mantle range, which are commonly attributed to high-temperature seawater-rock fractionation. Coarse-grained, discordant veins (q–ky and q–phengite) have δ18O values of ~9.69 ‰ and thermodynamic modelling tightly constrains their formation to ~22 kbars, 700°C. Compositionally, classic eclogites are coherent with a basaltic protolith, restricted to the shallow section of an oceanic crust, whereas ky-eclogites require a plagioclase-rich protolith, from deeper crustal levels.

These findings are in agreement with previously identified high-Ti and low-Ti eclogites. They suggest a compositionally stratified oceanic crust, corresponding to a MORB-type basalt and a pyroxene-plagioclase cumulate respectively, as possible protoliths. Given the wide range in δ18O values, roughly corresponding to a complete section of an oceanic crust, we infer the protolith was formed during crustal fragmentation related to extensive rifting. Moreover, the low δ18O values of the ky-eclogites suggest that the extension most likely involved penetrative faulting, acting as main channels for seawater infiltration to deep crustal levels.

CONSTRAINING PEAK METAMORPHIC TEMPERATURES OF THE NORTHERN OAXACAN COMPLEX USING ZR-IN-RT, TITANIQ AND TWO-FELDSPARS THERMOMETER: ULTRA-HIGH TEMPERATURE METAMORPHISM IN THE OAXAQUIA MICROCONTINENT

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Keywords: *Ultra-High Temperature Metamorphism, Oaxaquia, TitaniQ, Zr-in-Rt, Two-Feldspar thermometry, Rodinia, Greenville, Mexico.*

The Mesoproterozoic microcontinent Oaxaquia represents the basement forming most of continental Mexico. Its position on the amalgamation of Rodinia makes it a key terrane to understand the geodynamics of the collision of Baltica and Amazonia, since it was trapped along the suture and underwent granulite metamorphism (Zapotecan Orogeny; 978-1004 Ma). The Oaxacan Complex (OC) is located in the southern region of Oaxaquia and represents the largest of the four outcrops comprising the microcontinent. The metamorphic evolution of the OC is one of its least studied aspects, limiting the interpretations of its geological history. Geothermobarometric conditions determined for the OC yielded only moderate temperatures and pressures of 700-750 ºC and 0.7-0.75 GPa (Mora et al., 1986). However, textural and mineralogical evidence reported for the rocks, such as (rutile lamellar inclusions in quartz, rare spinel + garnet + sapphirine + biotite + cordierite ± quartz assemblages, ubiquitous mesoperthites, wollastonite-fassaite calcsilicates, highly meionitic scapolites lamellar exsolution in metamorphic pyroxenes and Mg-symplectitic metacarbonates; suggests nearly ultra-high-temperature (UHT) conditions (Solari et al., 2014; Ortega-Gutiérrez et al., 2018). In this work, we use new and published data to constrain the temperature conditions of the metamorphic peak of the OC. We calculated minimum temperatures of crystallization using TitaniQ (899 ± 50 °C) and Zr-in-Rt (874± 30 °C), trace element geothermometers, and a re-calculation of the two-feldspar thermometer (>900 °C). We show that the OC experienced ultra-high temperature metamorphism during the Zapotecan Orogeny, making it a new UHT terrane related to the amalgamation of the supercontinent Rodinia. It is well known that the four outcrops that comprise Oaxaquia have a similar tectono-metamorphic history; the discovery of UHTM in the OC suggests that the Huiznopala Gneiss, the Novillo Gneiss and the Guichicovi Complex experienced a similar metamorphism. Furthermore, the recognition of UTHM in Oaxaquia should be accounted for in revising the tectonic connections of Oaxaquia with the peripheral orogens of Amazonia.

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INTERACTION BETWEEN MIGMATITE-RELATED MELTS AND AMPHIBOLE-GABBROS: EVIDENCE FROM MINERAL GEOCHEMISTRY AND ZIRCON DATING (VARISCAN LOWER CRUST, PALMI AREA, SW CALABRIA)

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The Palmi area (SW Calabria) exposes a portion of the Variscan lower to intermediate crust mainly consisting of tonalite and migmatitic paragneiss. The latter shows a peak metamorphic assemblage of biotite, K-feldspar, garnet and sillimanite. The migmatites include layers of calc-silicate-bearing marble and orthogneiss. Gabbros occur as foliated, decimeter-thick layers within the migmatites and as a decametric main body adjacent to the paragneiss. No contacts are exposed between the migmatites and the gabbro body, which is mainly unfoliated and fine-grained, even though coarse-grained portions rarely occur. The gabbros overall contain plagioclase (An89-80) frequently developing triple junctions, amphibole, biotite, and accessory zircon + ilmenite ± allanite. Minor quartz is present in the gabbro layers within the paragneiss. Amphibole consists of cummingtonite grading into hornblende on the rims and retains some relic cleavage from a pyroxene predecessor.

Here we combine mineral major and trace element data with U-Pb zircon dating of the gabbros in order to understand the interaction among HT metamorphism, migmatization and emplacement of mafic magma at lower crustal levels.

In the main gabbro body, cummingtonite and hornblende from the fine-grained portions have lower Mg# and LREE than those from the coarse-grained domains. The hornblende also shows increasing Al in the passage from the coarse- to the fine-grained portions. The LREE-depleted patterns reflect crystallization of a LREE-rich phase (i.e., allanite) simultaneously with amphibole. Plagioclase and amphibole from the gabbro layers within the paragneiss show a highly evolved REE and incompatible elements geochemical signature. Parallel patterns and increase of REE and incompatible trace elements contents indicate that the transition from cummingtonite to hornblende did not involve reaction with other minerals or exotic agent, but most likely reflect variations of temperature conditions. We propose that interaction with migmatite-related melts produced a geochemical gradient within the gabbro. Hence, the coarse-grained portions in the gabbro body most likely preserve the pristine composition. U-Pb dating of sector-zoned, magmatic zircon cores from the gabbro body yielded a Carboniferous age of intrusion. Rare thin, homogeneous zircon rims gave Lower Permian ages, which could be related to recrystallization under amphibolite-facies conditions during the regional-scale HT metamorphism.

UPPER MANTLE STRUCTURE AND ANISOTROPY BENEATH SUDETES BASED ON DATA FROM PASSIVE SEISMIC EXPERIMENT AniMaLS

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Keywords: *seismic passive experiment, seismic anisotropy, shear wave splitting, lithosphere*

The Sudetes mountains constitute the NE part of the Bohemian Massif and belong to internal zone of Variscan Orogen. The sudetic lithosphere represents a complex mosaic of units with distinct histories of tectonic evolution and with ages ranging from the upper Proterozoic to the Quaternary. Previous active seismic experiments (e.g., SUDETES 2003) provided information about crustal structure in this region. However, the upper mantle properties in this part the Bohemian Massif were not studied up to now. In order to fill this gap, in 2017 a passive seismic experiment was organized, involving 23 broadband seismic stations located in Sudetes, between Elbe Fault in SW and Odra Fault in NE. The stations cover a ~200 x 100 km large area, with ~30 km spacing.. The stations are deployed for a period of ~2 years and will acquire recordings of local, regional and teleseismic events.

Seismic anisotropy (variation of seismic velocity as a function of direction of propagation and polarization), is common in the Earth's interior, and can be an important indicator of tectonic deformations, shear and other processes shaping the mantle. Anisotropy influences the seismic wavefield recorded on the surface in several ways (direction-dependent P-wave velocities, S-wave splitting, polarization-dependent velocities of surface waves). Thus, seismic measurements allow for determination of the anisotropy parameters and give constraints on tectonic evolution and structure of the upper mantle.

The objective of the experiment is to study anisotropy and the structure of the upper mantle in this region, and to trace seismic discontinuities (Moho, lithosphere-asthenosphere boundary, mantle transition zone). Shear-wave splitting analysis method is one of the most commonly used techniques for determination of the seismic anisotropy parameters (time delays and azimuths of the fast velocity axis). In this study, we focus on analysis of splitting of SKS and SSKS phases for teleseismic events in the epicentral distance range between 85-130°. The first and preliminary results, based on analysis of a part of the data set, document time delays between slow and fast S-wave components in the range of ~0.5-1.2 sec. Determined directions of fast velocity axis are relatively consistent over the studied area and correlate well with orientation of major fault zones and other tectonic lineaments the region. The poster presents the experiment, data examples and first results of SKS-splitting method.

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COMPOSITION OF THE LOWER CONTINENTAL CRUST THROUGH JOINT GEOCHEMICAL-GEOPHYSICAL INVERSIONS

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Medium- to high-grade metamorphic lithologies serve as analogues for deep crustal composition, yet amphibolite and granulite facies terrains and xenoliths range from mafic (< 52 wt.% SiO_2) to felsic (> 68 wt.% SiO_2). We invoke seismic profiles to resolve deep crustal composition in environments that would otherwise yield nonunique solutions in geochemical space. Using a joint geochemical-geophysical inversion, paired with constraints on heat flow, we predict lower crust compositions in specific physiographic provinces.

Global crustal models predict anomalously low Vs, Vp, and density in the Basin and Range of the southwestern United States. Using high resolution ambient noise datasets, paired with literature values on the geothermal gradient, we investigate the Vs of the lower crust in this high heat flow region. We estimate Vp, Vs, and density for the Basin and Range interpreted at 1 km intervals. We compare the results of this seismic model to thermodynamically generated Vs values from geochemical data of locally erupted granulite xenoliths. Our thermodynamic model is consistent with the seismic model but cannot explain the full shape of the seismic profile without invoking a depth dependency on composition, even within the lower crust.

PRELIMINARY DATA FROM MADO MEGAMULLION: LOWER OCEANIC CRUST EXPOSURE IN THE SHKIKOKU BACK ARC BASIN.

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Keywords: *oceanic lower crust, OCC, gabbros*

The Mado Megamullion (MM) in the Shikoku Basin represents an important tectonic window to understand the accretionary processes of the backarc oceanic lithosphere. Due to the easy accessibility (only ~1300 km from Tokyo) this oceanic core complex (OCC) is unique compared to the others well-studied OCCs worldwide. The rocks sampled during the 2007 and 2018 expeditions are mainly peridotites and gabbros, locally associated with minor basalts. The gabbros are deformed and undeformed varieties, the latter including varitextured and microgabbros. Most of these gabbros are fairly evolved consising of olivine-free to oxiderich gabbros locally intruded by felsic material, whereas primitive lithologies are missing. Microtextural and chemical data are here used to show that the association of varitextured to fine-grained gabbros with felsic material resembles those of the gabbros formed at the dike-gabbro transition. Hence, we preliminarly propose that the MM exposes a portions of a crustal sequence intruded into the shallow mantle. Finally, our data indicate that covariations in plagioclase anorthite (An) versus clinopyroxene Mg/(Mg+Fe) of the Mado MM gabbros form a trend notably steeper than those of abyssal oceanic gabbros. This trend mirrors that of the lower crust from the Godzilla Megamullion, a largest OCC in the Parece Vela backarc basin (Ohara et al., 2001), suggesting that the so far considered peculiar composition of the Godzilla gabbros (Sanfilippo et al., 2013) can be instead typical of the crust formed in backarc basins.

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FLUID-FLUXED MELTING OF ECLOGITE DURING EXHUMATION: AN EXAMPLE FROM THE ECLOGITE-TYPE LOCALITY (EASTERN ALPS, AUSTRIA)

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Keywords: *fluid-fluxed melting, eclogite, aH_2O*

Eclogites and their metapelitic hostrock from the eclogite type-locality (Eastern Alps, Austria) experienced conditions of contrasting H2O-activity (aH2 O) during common Eoalpine high-pressure–low-temperature metamorphism. Both rock types were fully fluid saturated (aH_2O = 1.0) at or close to the pressure maximum of 21 ± 2 kbar at 700 ± 20°C, calculated via Zr-in-rutile- and isopleth-thermobarometry of an epidote–phengite eclogite. Near-isothermal decompression following P_{max} occurred under closed-system conditions in eclogites, implying low aH_2O of ~0.2–0.3 with the preservation of garnet–omphacite assemblages. In parallel, the metapelitic host reached a minimum aH_2O of ~0.7 during early exhumation (16–18 kbar and ~700–720°C) and became fluid saturated due to dehydration at mid-crustal conditions. Hydrous fluid released from metapelites infiltrated eclogites along discordant cracks caused by unloading. Fluid infiltration was supported by strong gradients in aH_2O between fluid-saturated pelitic host (aH_2O = 1.0) and embedded fluid-absent eclogite (aH_2O ~0.2–0.3). Local fluid injection may have occurred, causing hydrofracturing in eclogite. Portions of eclogite distal from fluid sources/pathways was affected by limited retrogression whereas locally high aH_2O (~0.9–1.0) caused minor fluid-fluxed melting and pervasive re-equilibration, forming discordant megacrystic segregations of hornblende–plagioclase–epidote–titanite–quartz and less than ~3 vol. % melt. Preservation and syn-melting growth of epidote is attributed to addition of H2O and the release of Fe^{3+} from the breakdown of omphacite. Zr-in-titanite thermometry on titanite crystals from the melt segregations yields a temperature of 697 ± 10°C at 8.5 ± 1.5 kbar for this event, consistent with conditions of dehydration recorded by the pelitic host. Our results suggest that even small-scale melting in eclogite requires fluid infiltration from a suitable near-field source, such as dehydrating metapelites at the eclogite type-locality.

PHASE RELATIONS IN HYDROUS REE-BEARING CARBONATITE AT 1 GPA, 700-1250°C.

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Keywords: *Carbonatites , REE , experimental study.*

Carbonatites are important sources of Rare Earth Elements (REEs). These rocks are the result of liquid immiscibility or fractional crystallization at low pressure; they are often extremely enriched in alkali and may contain up to 15.000 ppm of La (Cullers and Graf, 1984). REEs mainly reside in Ca-bearing phases (carbonates, apatites, Ca-Nb oxides, Ca-silicates) and in accessory phases such as monazite, bastnaesite (La, Nd, Ce) CO_3F and hydroxyl-bastnaesite (La, Nd, Ce) $CO_3(OH, F)$.

This study focuses on processes, precursor to the late differentiation, that lead to the formation of hydrous carbonatite melts at high pressure (>1 GPa). In particular we will investigate the stability of REE-bearing carbonates and silicates at near solidus conditions and the distribution of REEs among accessory phases and melt. Moreover, in alkali free systems, the complete miscibility between silicate and carbonate liquids is expected. However, it is widely known that, while silica glasses are experimentally recoverable, calcite is not quenchable. The compositional threshold at which carbonate-silicate liquids might form a glass is still unexplored.

We performed single stage and end-loaded piston cylinder experiments in the model system CaO-SiO_2-La_2O_3-H_2O-CO_2 in the range 700-1000°C, at 1 GPa. Starting materials were prepared as a powder mixture of $La_2(CO_3)_3$, amorphous SiO_2 and $CaCO_3$. Three different bulk compositions at fixed $La_2(CO_3)_3$ = 10 wt.% with SiO_2:$CaCO_3$ = 0.7, 1 and 1.4 have been considered. Gold capsules of 3 mm of diameter were loaded with starting mixtures, added with approximately 5-10 wt.% of H_2O, and sealed while freezing the capsule in order to avoid the loss of volatile components.

Run products, carefully prepared to avoid any contact with water and polished with diamond paste, are characterized by BSE images, X-ray diffractometry, Raman spectroscopy and chemically analyzed by electron microprobe. At subsolidus conditions all bulk compositions contain calcite and quartz coexisting with a Ca-Lanthanum silicate with up to 66 wt% of La_2O_3, 9.8 wt.% CaO and 23 .5 wt% SiO_2. Preliminary X-ray diffraction data suggest that this phase has an apatite-type structure of general formula $Ca_2La_8(SiO_4)_6O_2$. An additional Ca, La-bearing phase of few µm has been observed in BSE images. Although further investigation is required, microprobe analysis indicate a likely carbonate composition.

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MULTIPHASE INCLUSIONS IN GARNETS OF INTERMEDIATE AND ULTRAMAFIC GRANULITES IN THE CABO ORTEGAL COMPLEX (NW-SPAIN)

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Keywords: *multiphase inclusion, granulites, subduction fluid, Cabo Ortegal Complex*

Rocks from Cabo Ortegal Complex (COC) in NW Spain have been already studied from petrologic, geochemical and structural aspects; however, the direct knowledge about fluids/melts, existing during its P-T path, is poorly constrained. The HP metamorphic assemblage of the COC is characterized by arc-root lithospheric mantle peridotites associated with MORB-derived eclogites, volcanic arc granulites, ortho- and paragneisses and metagabbros (Ibarguchi et al., 1990, Tilhac et al., 2016). These units are thought to represent a convergent plate margin setting, and are products of accretion in a subduction/collision orogenic channel (Ábalos et al., 2003 and Puelles et al., 2005). Granulites in the COC exhibit a heterogeneous unit with various modal proportions of garnet, clinopyroxene and plagioclase with minor amounts of zoisite ± quartz ± rutile ± ilmenite (Puelles et al., 2005).

Our study aims to investigate primary multiphase inclusions in garnet porphyroblasts of intermediate and ultramafic granulites from the COC in order to better understand the nature of deep fluids present during metamorphism in a subduction zone. Garnet hosts primary multiphase inclusions which occur in 3D clusters in the core. At room temperature the inclusions consist of polycrystalline aggregates of micron-submicron sized solid and fluid phases. They are generally 5-30 µm in size and characterized by negative crystal or sub-spherical shape.

According to Raman spectroscopy and SEM-EDS, the following solids have been identified in theses inclusions: Fe-Mg-Ca-carbonates (ankerite, siderite, dolomite) and pyrophyllite as dominant phases, whereas rutile and an unidentified sulfide can be also present in lesser amounts. Fluid phases appear between the aggregates of solids and around the wall of these inclusions. CO_2 is predominant, since residual fluid compositions in multiphase inclusions in intermediate and ultramafic granulites are CO_2: 74-83 mol%, N_2: 17-26 mol% and CO_2: 88-96 mol%, N_2: 4-12 mol%, respectively. The volume ratio of solid and fluid phases shows wide ranges with the "endmembers" of only solid or only fluid–containing inclusions in the same fluid inclusion assemblage.

The studied multiphase inclusions, with well-preserved fluid phases, trapped during the growth of garnet porphyroblasts might serve as exceptional records of deep carbon-rich fluids trapped at subduction zone conditions.

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TETHYS RELATED CONTINENTAL COLLISION IMAGED BY GEOPHYSICAL MODELLING

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Keywords: *Tethys, Continental Collision, Geophysical Modelling.*

We present a new 2D crustal-scale model of the NW Iranian plateau based on gravity-magnetic modeling along the 500 km long CIGSIP seismic profile across major tectonic provinces of Iran from the Arabian plate into the South Caspian Basin (SCB). The seismic P-wave receiver function model along the profile is used to constrain major crustal boundaries in the density model. Our 2D crustal model shows significant variation in the sedimentary thickness, Moho depth and the depth and extent of intra-crustal interfaces. The Main Recent Fault between the Arabian crust and the overriding Central Iran crust dips at ~13° towards the NE to a depth of ~40 km. The geometry of the MRF suggests ~150 km of underthrusting of the Arabian plate beneath Central Iran. We identify a new crustal-scale suture beneath the Tarom valley between the South Caspian Basin curst and Central Iran and the Alborz. This suture is associated with sharp variation in Moho depth, topography and magnetic anomalies and is underlain by a 20 km thick high-density lower crustal root at 35-55 km depth.

Based on seismological and petrological studies, the lower crust is globally composed of high-density mafic rocks with density range of 2900 < ρ < 3000 kg/m^3 (Christensen and Mooney, 1995; Rudnick and Fountain, 1995). Generally, the trade-off between Moho depth and lower crustal density leads to non-uniqueness of these parameters. However, we reduced the ambiguity of density of lower crust by the a' priori constrained Moho depth from the receiver function model. The relatively large Bouguer anomaly above the thick crust in the Zagros belt requires the presence of an anomalously high-density lower crust (3050 kg/m^3). Likewise, high crustal or low mantle densities (3100 kg/m^3), depending on the choice of Moho depth, are required below the Alborz mountains. The very strong positive converter at depths around ~40 km beneath Zagros and Alborz implies a very high velocity in the lower crust. The high density layer may reflect partial eclogitization of the lower crust as has been suggested for Himalaya (Hetényi et al., 2007; Schulte-Pelkum et al., 2005) and other active and former orogenies (e.g., Abramovitz and Thybo, 2000).The results indicate that the high density lower crust may be present everywhere where the Arabian plate descends to depths deeper than 40 km.

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METAMORPHISM AND PARTIAL MELTING OF DEEP-SEATED CONTINENTAL CRUST IN A COLLISIONAL OROGEN

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The Sveconorwegian orogenic belt in the Baltic Shield is a collisional orogen which formed during the 1 Ga assembly of the supercontinent Rodinia. The Eastern Segment is a formerly deep-seated continental crust, which underwent metamorphism and ductile deformation 990-970 Ma ago. The Eastern Segment allows the study of the metamorphic behavior of deep-seated crust along a 120 km metamorphic field gradient from epidote amphibolite- to high-pressure granulite-facies.

In particular, observations from the Eastern Segment indicate that the metamorphism was short-lived and fluid-induced rather than a protracted process with continuous prograde metamorphism (Möller & Andersson, 2018). In the Eastern Segment, there is also evidence that water-rich fluid infiltration was accompanied by deformation. These relations are found in the eastern margin, which is characterized by discrete deformation zones, as well as in the high-grade internal section, where the rocks are near-penetratively deformed, and along the tectonic boundary zone to the west (the Mylonite Zone).

Our first study focusses on characterization of the felsic (granitic) lithologies. Rocks in the eastern margin have been affected by both brittle and ductile deformation, in the epidote-amphibolite facies and locally greenschist facies. The Sveconorwegian increase in metamorphic temperature from east to west is accompanied by an increase in strain state, and syn-tectonic migmatization is common in the internal section. Dry rocks record high-pressure granulite-facies conditions, and an eclogite-bearing nappe is present in the westernmost area.

One model for the Alps explains fluid production by dehydration of a cooler continental crust during extensional orogenic collapse with the simultaneous exhumation of a hot granulite-bearing terrane, and propagation of the fluids along active shear zones (Müntener, *et al.,* 2000). Although the Alps exposes rocks that have been exhumed from deep crustal levels, geophysical transects (Schmid, *et al*., 2004) illustrate that the erosional cut of the Alps is overall not as deep as that of the Sveconorwegian orogen. The model of the Alps (op. cit.) indicates lower crustal imbrication and thick-skinned thrusting near to 30 km in depth, which may have guided fluid migration (and migmatization).

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MULTI-MECHANISM DEFORMATION OF GARNETITE AT LOW TEMPERATURES: INTERPLAY OF DEFORMATION, METAMORPHISM AND METASOMATISM

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Keywords: *garnet, deformation, pressure solution, rheology, fluids*

Intergranular pressure solution is suggested as the dominant deformation mechanism in leucocratic rocks at ultra-high pressures (Stöckhert, 2002), even operating at low stresses, and is driven by the vast amounts of silica-undersaturated fluids generated in dehydrating serpentinites in the subducting slab. However, any microstructural evidence hereof is erased by the breakdown of coesite to quartz and other retrograde processes. As result, studies on the deformation of natural samples should focus on rock types where more resistant minerals are dominant and will represent whole-rock deformation. Well-preserved garnetite layers from the UHPM unit of Lago di Cignana, Western Alps, provide a natural laboratory for the deformation of garnet at temperatures too low for plastic deformation. As these garnetites are within a quartz/coesite dominated system, it allows us to compare the relative strength at UHPM conditions.

Here we show complex deformation in the garnetite focused at grain boundaries, including the first ever report of pressure solution at UHP conditions, and how varying stresses and fluids control this system. Microstructural analysis indicates that grain boundary migration took over from a combination of intergranular pressure solution and grain boundary sliding as the composition of the fluid changed, no longer only dissolving garnet but rather modifying it. New garnet from grain boundary migration shows similar zoning as the UHPM phase of garnet growth, suggesting it occurred simultaneously. Grain boundary migration does not result in significant strain so is rather a mechanism of re-equilibration.

Intergranular pressure solution in garnet will only accommodate significant strain in the whole rock if garnet is a load-bearing mineral. As a result, it also relies on the deformation of quartz/coesite, allowing it to become load-bearing. Even though pressure solution in garnet can take place at low stresses, garnetite layers can only act as weak zones if extreme amounts of undersaturated fluids are present. The boudinaged nature of the garnetite suggests that it was relatively strong, so even a highly localized fluid cannot turn garnetite into a weak layer.

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MELTING OF AN OVERCOOLED HETEROGENEOUS MANTLE, EQUATORIAL MID-ATLANTIC RIDGE

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Keywords: *mantle heterogeneity, cold spot, mid-ocean ridge, ridge-transform intersection, isotope, equatorial Atlantic*

The equatorial Mid-Atlantic Ridge (MAR) is characterised by a set of long fracture zones cumulatively offsetting the ridge by more than 2000 km. The Romanche Fracture Zone is the longest (950 km; Heezen et al, 1963), corresponding to an age contrast of ca. 50 My (assuming a 17mm/yr average spreading-range; Cande et al., 1988). This geotectonic setting is associated to a regional thermal minimum, which makes the equatorial MAR a particularly interesting place to study the lithological and chemical variability under mid-ocean ridges in a changing mantle temperature regime.
Here we study the eastern ridge-transform intersection of the Romanche FZ where the regional minimum is overprinted by a strong cold-edge effect. Approaching this region, the lithospheric thickness increases from the axis centre to the transform and large areas of mantle-derived peridotite are exposed over a crustal stretch for about 50 km (Bonatti et al., 2001; Ligi et al., 2005, 2011). Chemical analyses suggest an extremely low melting degree of the upper mantle in this region (Schilling et al., 1994), leading to a continuous decreasing of the magmatism from the center of the ridge towards the amagmatic region at the ridge-transform intersection. Along this trend, basalt compositions change from N-MORB to alkaline-basalts, with an enrichment in incompatible elements and water (Bonatti et al., 1993; Ligi et al., 2005). This transition occurring in a low degree melting region, leads us to believe that a low solidus component is present in the depleted mantle screen (Brunelli et al., 2018). We present a Sr-Nd-Pb and Hf isotope study of basalts recovered along the eastern Romanche axis and intersection. It appears that a decrease in the mantle temperature influences directly the basalt compositional variability by enabling a dissociation of the heterogeneities present in the depleted mantle through low degrees of melting.

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DECODING MONAZITE TEXTURES USING INTEGRATED LA-ICP-MS MAPPING AND PHASE EQUILIBRIA MODELLING: INSIGHTS INTO THE TIMESCALES OF MID-CRUSTAL METAMORPHISM

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Keywords: *monazite, granulite-facies metamorphism, LA-ICP-MS raster mapping*

Meta Incognita Peninsula, located on south-east Baffin Island, Arctic Canada, exposes upper-plate supracrustal rocks metamorphosed at granulite-facies conditions during the Himalayan-scale Paleoproterozoic Trans-Hudson Orogen (Weller & St-Onge, 2017). Two migmatitic metasedimentary samples from the region were selected for analysis, to investigate metamorphic processes operating at mid-crustal levels during orogenesis. Phase equilibria modelling indicates peak pressure–temperature conditions ~7 kbar and 850 °C, and *in situ* U–Pb monazite dating reveals a complex history of crystallisation from 1870 to 1740 Ma. To interpret the latter dataset, 4 µm-resolution laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) mapping of monazite was applied, to quantitatively determine the spatial variation in trace element chemistry. The maps unequivocally demarcate growth zones, some of which were cryptic with conventional imaging, allowing the complex U–Pb dataset to be decoded. The evolving monazite chemistry is interpreted using melt-reintegrated phase diagrams, which quantify the abundance of influential trace element hosts such as garnet and plagioclase, to determine that granulite-facies metamorphism occurred over ~40 Myr in the region.

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GRANULITE-AMPHIBOLITE TRANSITIONS: QUANTIFYING FLUID INGRESS IN HIGH-GRADE METAMORPHIC TERRAINS AND ITS EFFECTS ON CRUSTAL RHEOLOGY

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Keywords: *retrograde metamorphism, fluid flow, rheology, Trans-Hudson orogen*

The retrograde transition from granulite- to amphibolite-facies mineral assemblages is an important control on the strength of the lower continental crust. However, our current understanding of the source and mechanism of fluid ingress – required to catalyse this transition – is poor. The relative contributions of fluid channelisation, grain boundary diffusion and volume diffusion as pervasive hydration mechanisms are unclear. Moreover, different granulite terrains show strongly heterogeneous relationships between deformation, rehydration and retrogression. Controls on the rates and length scales of fluid flow through granulite rocks need to be investigated if we are to understand the effects of fluid ingress on crustal rheology.

In this study, we analysed a portion of the Superior craton crystalline basement in northern Quebec, Canada, which was metamorphosed at granulite-facies conditions in the Archaean and later retrogressed to amphibolite facies during the middle Palaeoproterozoic Trans-Hudson orogen (St-Onge & Lucas, 1995). This retrogression occurred in association with the development of an overlying thrust for retrogression of the underlying basement. The basal décollement to the overlying thrust belt likely acted as a fluid conduit from which fluids percolated into the basement (St-Onge & Lucas, 1995). The aim of this study is to assess the fluid budget required to hydrate the retrogressed basement using integrated microstructural analysis and phase equilibria modelling. This, when combined with observed length scales and the timescale of metamorphism, will provide insights into the mechanism(s) of fluid infiltration.

Petrographic observations on samples from the footwall crystalline basement in northern Quebec indicate that rocks with a strong deformation fabric contain more hydrated assemblages, suggesting that deformation assists fluid flow through granulite rocks. However, retrogression from granulite- to amphibolite-facies assemblages also occurs in samples devoid of clear deformation fabrics, which suggests fluid can permeate granulite rocks (up to a certain distance) in the absence of deformation. Here, we present models of the structurally-bound hydration of key basement samples. We also provide updated constraints on the pressure-temperature conditions, water activities and fluid budget of the granulite-amphibolite transition at varying distances below the proposed fluid source.

belt, which is thought to be the fluid source

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