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Abstracts and field trip guide



Wrocław, Poland, 25-28 August 2015

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## 2<sup>nd</sup> European Mantle Workshop

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## **Mineralogical Society of Poland**



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Wrocław, 25-28 August 2015

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#### Preface

#### 2<sup>nd</sup> European Mantle Workshop

The first European Mantle Workshop (EMAW) was held in 2007, in Ferrara, Italy. Since then, a large number of studies have been published that have contributed towards a far better understanding of the processes that have taken place in the Lithospheric Mantle beneath Europe. Consequently, this second EMAW, in Wroclaw, Poland, where ongoing research and new perspectives about the European Lithospheric Mantle can be discussed, is both necessary and inevitable.

Significant advancements in-situ analytical methods, such as LA-ICP-MS, has made it possible to both study in detail and better understand metasomatic processes and, in particular, to identify the metasomatic agents; whether they were fluids, melts or carbonates. Due to in-situ analytical methods, it has become possible to identify how melt percolation affects and changes the composition and possibly the nature of the lithospheric mantle. Apart from the chromatographic effect, as described, amongst other, by Menzies (1983) and Dawson (1984), processes such as refertilization have now been recognized in xenoliths and orogenic peridotites from many places.

In the past, trace element analysis was generally only possible on clinopyroxene and garnet. The substantial improvement of in-situ analytical instruments, such as LA-ICP-MS, has made routine accurate analyses of olivine and orthopyroxene also possible. Consequently, our understanding of the distribution and behavior of trace elements in these minerals has greatly improved; for example, trace element compositions in olivine have been used to define new geothermometers (De Hoog et al., 2010).

The possibility to analyze whole-rock and in situ PGE and Os isotope concentrations provides an additional powerful tool for establishing the age of metasomatism or the age of stabilization of the lithosphere.

The study of the European lithospheric mantle, as can be judged from the abstracts in the present issue, is an ongoing process. New results from studies that have taken advantage of state-of-the-art analytical instruments are being added to the already existing data-base, contributing towards a better understanding of the evolution of this part of the Earth. In recent years, an increasing number of outstanding papers have appeared, providing details that have helped our understanding of the nature of the Lithospheric Mantle beneath Central Europe, an area that was until now rather poorly studied.

The abstracts in this volume cover issues concerning the European Lithospheric Mantle that range from petrology, geochemistry and radiogenic isotopes to geophysics, as well other topics dealing with the Upper Mantle in general.

Welcome to the 2<sup>nd</sup> European Mantle Workshop!

Magdalena Matusiak-Małek Theodoros Ntaflos Jacek Puziewicz

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2<sup>nd</sup> European Mantle Workshop

Invited lectures



MINERALOGICAL SOCIETY OF POLAND POLSKIE TOWARZYSTWO MINERALOGICZNE



#### European Orogenic Lherzolites: prisitine or refertilized?

Jean-Louis BODINIER

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Orogenic peridotites display structural, petrological and geochemical characteristics which encompass the deformation styles and compositions expected for subcontinental lithospheric mantle and shallow asthenospheric mantle. In the past, the ambiguous character of these rocks led to somewhat conflicting views on their origin. Recent studies tend to converge on the idea that the orogenic peridotites represent thinned and/or rejuvenated lithospheric mantle, thermally eroded by asthenospheric mantle in various tectonic settings (postcollisional, back-arc, and continental rifting). Lithospheric rejuvenation is marked by annealing of deformation microstructures, overgrowth of mineral grains and km-scale modal/chemical variations resulting from partial melt redistribution.

From top to base of eroded lithosphere, melt processes vary from refertilization of aged, refractory (harzburgite) lithosphere to partial melting of previously refertilized material (lherzolite & websterite). Both processes are associated with narrow fronts where major microstructural, modal and chemical variations occur within a few meters to tens of meters. Melting and refertilization fronts display striking resemblances (e.g., annealing of textures and small-scale chemical heterogeneities) but also significant differences. The melting front observed in Ronda is a clear-cut structure that can be followed over > 10 km in the massif, suggesting that is formation was thermally-controlled at regional scale. In contrast, the refertilization front of Lherz is extremely convoluted, suggesting its formation by coalescence of relatively narrow ( $\leq 10$  m) melt infiltration channels. Refertilization and melting fonts are considered as the upper and lower boundaries of transient, moving asthenosphere-lithosphere transition zones during thermo-mechanical erosion of the lithospheric mantle by upwelling asthenosphere. Further complexity arises during the waning stages of lithospheric erosion - upon conductive cooling - when partially molten lithosphere is traversed by the receding melting/refertilization fronts.

Igneous fertilization has been invoked for virtually all types of tectonically emplaced and oceanic mantle rocks for at least 30 years. However, the number of reported cases involving orogenic lherzolites (see review by Bodinier, Godard 2014) has increased exponentially over the last decade, to such a degree that it seems logical to consider this process as the main cause of the fertile compositions observed in these rocks. Altogether, these studies indicate that the (re)fertilization of mantle rocks may occur regionally at the interface between partially molten asthenospheric (or 'asthenospherized') mantle and colder lithospheric domains, at depths ranges from the stability field of garnet to that of plagioclase.

However, several intriguing questions remain unanswered, among which:

- How can igneous refertilization account for the observation that in most orogenic peridotites the most fertile lherzolites converge towards almost identical compositions

comparable to those suggested for Primitive Mantle?

- Is there any causal relationship between igneous refertilization, the mafic (pyroxenite) layers that are ubiquitous in fertile peridotite, and certain forms of mantle metasomatism ascribed to small volume melts/fluids?

- Is there any indication that the refertilization also affected the lithospheric mantle sampled by xenoliths, particularly the off-craton SCLM that has been through one or more orogenic cycles? In other words, are the fertile xenoliths pristine or secondarily refertilized?

Recent data provide some clues to answer these questions, at least tentatively.

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## The origin and evolution of the lithospheric mantle beneath the Siberian craton

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#### Introduction

The formation of the stable continental blocks known as cratons involves not only crustal processes, but the welding of crustal rocks to a section of melt-depleted lithospheric mantle with high Mg/Fe ratios and low Ca and Al contents that can extend 100-200 km into the asthenosphere. Many cratons and their underlying lithospheric mantle keels formed in the Archean, i.e. before 2.5 Ga, which has given rise to the idea that cratons can only form in the Archean when mantle temperatures were high enough to allow the high degrees of melt extraction recorded by cratonic peridotites (e.g. Herzberg, Rudnick 2012). Many large cratonic regions, however, for example in Siberia and South America, have not been studied in sufficient detail to document the mode and timing of their cratonization.



Fig. 1. Simplified geological map of the sampling area

The Siberian craton is one of the largest on Earth (>4 million km<sup>2</sup>; Fig. 1). Most of its surface is covered by Phanerozoic sedimentary rocks and by 250 Ma old basaltic rocks (traps) in its NW part. Precambrian basement rocks (mainly ~2 Ga and 2.8-3 Ga; Rosen 2002) are exposed on the Anabar shield in the north and the Aldan shield in its SW corner.

Some of the first data on cratonic mantle were reported for xenoliths from Siberia (Sobolev 1977), yet the craton composition is hard to constrain because few kimberlite pipes contain peridotite

xenoliths suitable for petro-geochemical studies. Until recently, much of what we know about the Siberian cratonic mantle was based on data for a suite of altered xenoliths from the Udachnaya kimberlite in the central craton (Pearson et al. 1995; Boyd et al. 1997). Here

we present a summary of recent work on new extensive collections of large and fresh peridotite xenoliths from the Udachnaya and Obnazhennaya kimberlites (Fig. 1).

#### Composition and formation of the lithospheric mantle in the Siberian craton

Remarkably fresh peridotite xenoliths spanning a P-T range from  $\leq 2.5$  to 6.6 GPa and 720 to 1320°C were recovered from deep levels of the Udachnaya diamond mine. Unlike most published data on cratonic peridotite xenoliths, low-opx spinel harzburgites from Udachnaya define clear trends on major oxide co-variation plots that appear to have recorded their melting conditions. Based on experimental data on melting of fertile peridotites, the lithospheric mantle in the central Siberian craton formed by ~40% of polybaric melting between 7–4 GPa and  $\leq 1-3$  GPa, possibly in upwelling asthenosphere with potential T of 1550–1600°C. About <sup>1</sup>/<sub>4</sub> of the xenoliths show enrichments in silica (opx) that cannot be produced by dry or hydrous melting of fertile mantle at 1-7 GPa, but may stem from melting of hybrid sources or post-melting enrichments (Doucet et al. 2012).

Some coarse and deformed garnet peridotites from Udachnaya are similar in modal, major and trace element compositions to the low-opx spinel harzburgites and may be near-pristine melting residues; their garnets may be residual phases that survived partial melting. The majority of the garnet peridotites experienced modal metasomatism, which produced enrichments in Fe, Ti, Al, Ca, Si and precipitated HREE-rich garnets. The coexisting cpx may record ingress and percolation of kimberlites and related liquids into peridotites shortly before the eruption (Doucet et al. 2013). The mantle beneath Udachnaya has a complex geotherm due to thermal perturbations related to magmatic activity before the intrusion of the kimberlite magmas (Goncharov et al. 2012).

Several lines of evidence indicate that the lithospheric mantle beneath the NW Siberian craton is thinner than in the center and has been extensively re-worked. Most samples in this study, and many Obnazhennaya peridotites in general, show a combination of relatively low  $Al_2O_3$  (0.1-2%) with very high CaO (2-4%), hence high Ca/Al, which is unusual for peridotite xenoliths in Siberia and elsewhere. Peridotites with low contents of both  $Al_2O_3$  and CaO (0.1-0.8%) are very rare; their relatively low Mg# (0.89-0.92) and highly variable Os contents suggest they may have formed in melt migration channels rather than as residues of partial melt extraction. Some garnet peridotites contain as much as 2.7-8.0%  $Al_2O_3$  and 3.2-5.5% CaO with a continuous transition to websterites. We attribute these modal and chemical trends to widespread metasomatism by carbonate-rich melts.

#### The age of the lithospheric mantle in the Siberian craton

Published Os isotope data have shown that the mantle beneath Udachnaya contains rare Archean components, like megacrystalline dunites and eclogites (e.g. Pearson et al. 1995). Yet, our new data show that the most common Re-Os  $T_{RD}$  ages for refractory Udachnaya peridotites (Ionov et al. submitted) as well as some Lu-Hf age estimates (Doucet et al. 2015) are close to 2 Ga suggesting that the major part of the lithospheric mantle in the central Siberian craton formed in the Paleoproterozoic rather than in the Archean.

Re-Os  $T_{RD}$  ages for refractory peridotite xenoliths from Obnazhennaya (Ionov et al. submitted) show bi-modal distribution. The highest Re-Os  $T_{RD}$  ages, from 2.6 to 2.9 Ga, are shown by some Ca-rich (2.0-3.2% CaO) peridotites while the other samples yield lower  $T_{RD}$  ages from 1.65 to 2.3 Ga. We interpret these results as evidence for a two-stage formation of the lithospheric mantle: at 2.6-2.9 Ga and at ~2 Ga. The peridotites formed at the two stages show similar chemical compositions. The enrichments in Ca may have taken place either at the end of the Archean melting event or later.

Os isotopic compositions were also reported for basalt-hosted spinel peridotite xenoliths from the Tokinsky Stanovik Range (Tok) on the Aldan shield (Fig. 1). These rocks are mainly refractory harzburgites that represent the uppermost, largely reworked mantle from the SE margin of the craton and yield Proterozoic ( $\leq 2$  Ga) ages (Ionov et al. 2006). Their lithospheric roots may have been largely removed, like in the North China craton.

The combined Re-Os age data on the xenoliths from Obnazhennaya and Udachnaya suggest that the lithospheric mantle beneath the Siberian craton took a long time to form, from the late Archean to the Paleoproterozoic. The Proterozoic event involved either generation of new lithosphere and its mixing and stacking with the old one or delamination of parts of the Archean lithosphere by mantle upwelling and their replacement by younger melting residues. The new data for the Siberian craton strongly suggest that the formation of cratonic lithospheric mantle was not completed in the Archean as previously thought based primarily on data for cratons in southern Africa, but continued well into the Paleoproterozoic when the Siberian craton was definitively stabilized at ~2 Ga.

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POLSKIE TOWARZYSTWO MINERALOGICZNE



#### Halogens in the Earth mantle: What we know and what we don't

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Water is probably the most abundant and the most important volatile component in the deep Earth. Numerous studies investigated its role in Earth's mantle. However, there are other important volatile elements (e.g., C, S, N, or the halogens F, Cl, Br and I) in the mantle which may have similar effects on mantle mineral properties and melting processes, but there is scant data on this. Recently, however, interest in the role of halogens in the mantle has increased and several new studies report new data on halogen partitioning and incorporation of halogens in nominally anhydrous minerals (NAM) like olivine or pyroxene. However, little is known about the effect of halogens on melting relations of mantle rocks or their influence on mineral stability in the mantle. In this talk I will present some new experimental data on halogen-bearing humite group minerals in the Earth's mantle, and discuss new analytical results on halogens in naturally occurring mantle minerals.

2<sup>nd</sup> European Mantle Workshop

## Oral and poster contributions



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#### Occurrence and potential origin of "Mantle Hydrocarbon"

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#### Introduction

Since mantle is one of the largest reservoirs for deeply buried carbon in the Earth. In order to investigate the total carbon cycle and the Earth's chemical component, the potential occurrence and containing factors of such heavy hydrocarbon using mantle peridotite and cumulate samples will be discuss on the presentation.

#### Instructions to Authors

There are some samples of mantle-derived peridotite including oranic matters. Sugisaki and Mimura (1994) found that the most ultramafic xenoliths and some orogenic peridotites contain heavy hydrocarbon matters (up to  $C_{33}$  n-alkans) and they named such organic matter as the "mantle hydrocarbon". They carefully analyzed more than 200 of many kinds of plutonic rocks such as samples; peridotite, ultramafic cumulates, gabbro and granite from over 50 localities from all over the world. In addition to the observations of natural samples, some high-pressure experiments were taken and demonstrated abiotic formation of hydrocarbon (up to C32 *n*-alkane: McCollom, Seewald 2006) and other relevant molecules 30 during the Fischer-Tropsch Type reaction.

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## Re-Os and Lu-Hf isotopic systematics of mafic layers from the Horoman Complex, Japan

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#### Introduction

Detailed elemental and isotopic studies of interlayered mantle sections composed from peridotite and mafic rocks (pyroxenite, gabbro) provide insights into Earth's mantle heterogeneity and the processes of melt-rock reactions between peridotite and infiltrated melts in various geotectonic settings. The Re-Os and Lu-Hf isotopic systematics are very helpful to give an explanation of the origin, evolution and age of the mafic layers and their relationship with host peridotites (e.g., Pearson, Nowell 2004; van Acken et al. 2010). In this contribution, layered sections of peridotite-gabbro I and peridotite-gabbro II from the Horoman Complex (Japan) were analyzed for their major/trace element contents together with Re-Os and Lu-Hf isotopic compositions.

#### Geology of the Horoman Complex

The Horoman Complex is the peridotite massif derived from shallow oceanic mantle settings located at the northern Japan (Hokkaido). It consists of various lithological types of layered ultramafic and mafic rocks including plagioclase lherzolite, lherzolite, harzburgite and dunite interlayered with mafic layers of variable thickness (several centimetres to a few meters) with "gabbroic" mineralogy (e.g. Takazawa et al. 1999; Malaviarachchi et al. 2010). The Horoman peridotites represent residues after partial melting in the garnet stability field at a MORB settings and later metasomatized/refertilized in a suprasubduction zone mantle wedge (e.g. Yoshikawa, Nakamura 2000; Malaviarachchi et al., 2010). Among the mafic layers, four different types (Gabbro I-IV) with different mineralogy and chemistry can be distinguished as a result of their different origin and melt sources (Takazawa et al. 1999).

#### **Results and Discussion**

Major element compositions of thin-layer Type I and II gabbros and associated peridotites are similar to those reported by previous studies (Takazawa et al., 1999; Malaviarachchi et al. 2010) with the highest  $Al_2O_3$  contents (11.6–13.2 wt. %) found in thin-layered Type I gabbros and massive Type II gabbro. Thin-layered Type II gabbros are characteristic by their lower  $Al_2O_3$  and CaO values (7.1–11.0 and 5.8–12.8 wt. %,

respectively). The Type I gabbros exhibit highly LREE-depleted patterns with  $La_N/Yb_N$  between 0.03 and 0.2 paralleled with low abundances of large ion lithophile elements (LILE). In contrast, Type II gabbros are characterized by less pronounced LREE depletions ( $La_N/Yb_N = 0.5-0.7$ ) coupled with highly positive Eu (Eu/Eu\* = 1.3–1.6), Pb and Sr anomalies. Interlayered peridotites show highly variable trace element concentrations reflected by mildly LREE-depleted to slightly LREE-enriched patterns.

Studied gabbros show variable whole-rock Lu-Hf concentrations and Hf isotopic compositions. The Type I gabbros yield significantly higher Lu-Hf contents of 0.07–0.55 and 0.26–3.2 ppm, respectively in comparison to the Type II gabbros with Lu and Hf values at range from 0.02 to 0.04 and 0.03 to 0.07 ppm, respectively. This different composition is reflected also by <sup>176</sup>Hf/<sup>177</sup>Hf ratios and  $\epsilon_{\rm Hf}$  values. While present-day  $\epsilon_{\rm Hf}$  values of the Type I gabbros varies from +13.7 to +48.1, the Type II gabbros exhibit generally more radiogenic  $\epsilon_{\rm Hf}$  between +40.4 and +117. The Re-Os systematics of the studied mafic layers partially followed Lu-Hf composition with divergent compositions of the Type I and II gabbros. The former type is characterized by high Re contents in the range of 0.35 and 1.9 ppb paralleled by radiogenic <sup>187</sup>Os/<sup>188</sup>Os values between 0.2465 and 0.6108 and high <sup>187</sup>Re/<sup>188</sup>Os ratios of 8.28–29.5. In comparison, the latter type exhibit significantly lower Re concentrations (0.026–0.50 ppb) and consequently less radiogenic <sup>187</sup>Os/<sup>188</sup>Os and lower <sup>187</sup>Re/<sup>188</sup>Os ratios in the range of 0.1349–0.3277 and 0.211–2.85, respectively.

Our new data on mafic layers from the Horoman Complex suggests different sources and/or evolution of the parental melts of the Type I and II gabbros. While the Type I gabbros display trace element signatures similar to MORB-related melt sources, their Hf-Os isotopic compositions argue for significant contribution of the crustal material and/or long term (~1 Ga) isolated Hf-Os evolution. Conversely, trace element and Os-Hf compositions of the Type II gabbros may be best explained by their crystallization from the MORB-related melts at shallow depths. Very low Lu-Hf contents paralleled by highly radiogenic Hf isotopic composition of the major part of the Type II gabbros requires highly depleted melt source.

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#### CT scanning of Spinel-Pyroxene Clusters in Mantle Peridotite Xenoliths from the Massif Central, France and Lanzarote, Canary Islands

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#### Introduction

This study investigates spinel-pyroxene clusters which are intergrowths of spinel, orthopyroxene and clinopyroxene in mantle xenoliths. Studied samples are from two localities in different tectonic settings: (1) the Massif Central, France, an uplifted plateau associated with Tertiary-Quaternary volcanic activity on continental lithosphere; (2) Lanzarote in the Canary Islands, an oceanic intraplate volcanic island built on old (Jurassic) oceanic lithosphere. Spinel-pyroxene clusters are considered to be the product of garnet breakdown as a result of pressure reduction. The phase transition from the garnet stability field to the spinel stability field is represented by the equation olivine + garnet =orthopyroxene + clinopyroxene + spinel (Smith 1977). The presence of spinel-pyroxene clusters is documented in several localities worldwide, (Smith 1977; Lenoir et al. 2000; Falus et al. 2000; Neumann et al 1995; Ghosh et al. 2013). Mercier and Nicolas (1975) proposed that these clusters were produced by exsolution from orthopyroxene. Smith (1977) cited several studies where there is a record of the garnet – olivine reaction, with spinel-pyroxene forming coronas around garnets when in contact with olivine. Transition from garnet to spinel is possible by an increase in temperature or a pressure decrease. Mantle convection or a rising diapir thus would provide a mechanism for changes in pressure in the upper mantle. Smith (1977) concluded that the spinel-pyroxene cluster texture reflects transport of a garnet peridotite through the garnet-spinel transition and that mantle convection occurred at a depth <90 km.

#### Methodology

X-Ray computed tomography (CT) is a non-destructive technique in which a series of 2D images (radiographs) characterising variations of X-Ray interaction due to density differences of the subject matter, when combined provide a high resolution 3D visualisation of an object. Fourteen spinel peridotite xenoliths have been cored and scanned using micro-computed tomography ( $\mu$ -CT). Some samples contained spinel-pyroxene clusters whereas others (also from the Massif Central) did not. Sections of the rock cores and individual clusters have been isolated and extracted from the 3D dataset for textural analysis at greater magnification and resolution.

#### Discussion

The  $\mu$ -CT data from Lanzarote and Massif Central has revealed a range of cluster textures from relatively small <2 mm blebs which can be either spatially concentrated or

distributed throughout the rock (with preferred orientation), to large 4-12 mm individual clusters with complex vermicular textures. Fig 1 displays large relatively circular spinel structure 8mm in diameter and flattened in one axis 4mm in thickness. Coarse-grained individual spinel grains are randomly scattered throughout the rock with no preferred orientation. Fig 2 also displays a large spinel structure but with a complex vermicular texture. Again the spinel structure is largely circular with one shortened axis. Samples from Massif Central display similar textures as seen in the Lanzarote samples with individual spinel sites displaying complex vermicular texture in random orientation with the exception of sample MB64 where the large spinel structures display a strong preferred orientation. A BSE (fig. 3) image of a Lanzarote sample has revealed a metasomatic reaction rim surrounding the spinel-pyroxene clusters. Figure 4 is a 3D rendered volume of a whole rock core segmented with both the spinel phase (red) and a selected portion of the silicate phase (green) in which individual blebs of spinel display a lower density silicate phase 'halo' surrounding the spinel and represent the products of metasomatic reactions.





Figure 1. Image of spinel peridotite core with a large individual cluster (8mm), spinel shows a complex



Figure 3. BSE (EC3) image of a spinelpyroxene cluster with metasomatic reaction rim and spinel displaying

Figure 2. Image of an individual cluster (> 12mm), spinel shows a complex vermicular texture.



Figure 4. 3D rendered volume of a peridotite with metasomatic reaction rim (green) surrounding spinel (red) in a spinel-pyroxene cluster.

#### Conclusion

There is a clear distinction in spinel textures displayed in the samples with and without spinel-pyroxene clusters. The large individual spinel clusters with complex vermicular texture in themselves appear to display no evidence of deformation and show that locally the spinel is highly concentrated. The metasomatic reactions displayed around the spinel-pyroxene clusters would suggest that this process occurred after formation of the cluster texture. No metasomatic reaction halos were detected from the  $\mu$ -CT data for samples from the Massif Central. We agree with the conclusion of Smith (1977) that spinel–pyroxene textures preserve evidence of a transition of shallow lithospheric mantle from the garnet stability field to the spinel stability field. We would therefore predict that such textures would only occur in the mantle beneath regions that show tectonic evidence of thinning of the lithospheric mantle.

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## Water diffusion by asthenospheric domain entrained in the lithospheric mantle of Lianshan (Subei Basin, Eastern China)

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The effects of mantle melting and the subsequent re-equilibration processes in the region of the Subei Basin (Eastern China) are here explored through the study of major and trace (including H) element distributions among minerals entrained in xenoliths from Lianshan Cainozoic basalts. They are anhydrous, medium/coarse-grained sp-bearing lherzolite (cpx-rich lh; lh and cpx-poor lh) and harzburgites. The cpx-rich lh do not record textural and chemical metasomatic efffects and are close in composition to Primitive Mantle (PM). In turn, cpx-poor lh (and lh) and harzburgites, record the circulation of a silicate melt (with crustal components) in a variably depleted mantle sector well before the entrapment of the xenoliths by the host basalt. The temperatures, determined with both olsp and cpx-opx geothermometer, are fairly constant from harzburgites to cpx-rich lh and never exceed 1021°C . Measured mineral water contents indicate that the whole rock contains, on average, 19+7 ppm of H<sub>2</sub>O without any systematic variation among rock types nor correlation with Al<sub>2</sub>O<sub>3</sub>, light-REE and Yb (or Y) contents of cpx. On the basis of water contents of primary melts we calculate the water contents of the fertile mantle between 328 and 1440 ppm. Considering these estimates Lianshan cpx-rich lh (<3% of PM partial melting) have significantly lower water contents with respect to the theoretical values. Based on these petrographic and geochemical features, we suggest that cpx-rich lh constitute fragment of upwelling fertile asthenosphere, which caused the removal/erosion of the lowermost part of lithospheric mantle. This asthenosphere portion may have been incorporated in the lithospheric region (represented by cpx-poor lh and harzburgites) since Jurassic and it may have progressively cooled down after one (or more) partial melting episodes. The water depletion can be accounted for a continuous loss by diffusion during the subsolidus chemico-physical readjustment, well after (>5My, based on modelled H<sub>2</sub>O solid-solid diffusion rate) the occurrence of the last melting episode.

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## Geochemistry of magmatic rocks of Euganean Hills (Padua, Italy) and Berici Hills (Vicenza, Italy)

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#### Abstract

The Tertiary Magmatic Province of Veneto, in the North-East of Italy represents the most important magmatic province of the Adria Plate and is composed of the Marosticano, Lessini Hills, Berici Hills and Euganei Hills. Interestingly, only in the Euganean zone, trachitic, rhyolitic and latitic rocks were produced.

For this project, specimens have been collected from both open and closed quarries, localized in the whole Euganei Hills, and from the eastern and southern part of the Berici Hills in order to reconstruct the age, origin and evolution of the Euganean magmas.

Using optical microscopy together with XRF and ICP-MS spectrometers, the following rock-types have been identified: basanite, basalt, basaltic andesite, basaltic trachyandesite, trachyandesite, trachyte e rhyolite. <sup>40</sup>Ar/<sup>39</sup>Ar radioisotopic dating showed that all the magmas were emplaced at about 32 Ma. Moreover, Sr-Nd-Pb isotope analysis showed that the basaltic specimens display DMM and HIMU signatures (this latter is more important in alkaline basalts). According to the geochemical configuration, already analyzed by Beccaluva (2007), it has been thought that the lithospheric mantle of the Adria plate had been enriched by metasomatizing agents with HIMU isotopic signatures. Therefore, the sub-lithospheric originated metasomatizing component may have accumulated with more efficiency in the lower lithosphere. EC-AFC modeling shows that trachytic, rhyolitic and latitic magmas (i.e., the evolved ones) could be the result of a contamination of the initial magma with continental crustal rocks.

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# Variation of chemical composition of sulfides from spinel peridotite xenoliths from Krzeniów and Wilcza Góra basanites, Lower Silesia (SW Poland)

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The basanites from Krzeniów (19.57 Ma) and Wilcza Góra (20.07 Ma; K-Ar ages by Birkenmajer et al. 2007) in SW Poland belong to the Lower Silesian part of the Cenozoic Central European Volcanic Province (CEVP). Basanites form volcanic plugs located in the Złotoryja-Jawor volcanic complex and are rich in peridotitic mantle xenoliths, predominantly of harzburgitic composition. Those from Krzeniów contain no hydrous phases, whereas most xenoliths from Wilcza Góra contain small amounts (<1.6 vol.%) of amphibole. For this study 3 harzburgite xenoliths from Wilcza Góra and 2 harzburgites from Krzeniów were selected.

Three types of sulfide assemblages have been distinguished basing on their location within the xenoliths: (1) singular, anhedral grains enclosed in silicate phases (commonly in pyroxenes, rarely in olivine) up to 15  $\mu$ m in diameter, of composition of pentlandite. Scarcely, pentlandite is associated with Ni-pyrrhotite within the same grain; (2) small (< 5  $\mu$ m in diameter) grains along inclusion trails located close to silicate grain margins, also having the composition of pentlandite; and (3) rounded sulfide blebs occurring in the fine-grained intergranular aggregates of silicate and oxide minerals; these are the most abundant. The studied rocks can be classified into two groups basing on the bulk composition of sulfide blebs from intergranular aggregates: (A) containing sulfides which are Fe-rich (from 38.63 to 42.49 wt.% Fe) and Ni-poor (from 21.46 to 25.90 wt.% Ni), which comprises harzburgites MM99 and MM113 from Wilcza Góra, (B) containing sulfides which are Fe-poor (from 21.75 to 30.48 wt.% Fe) and Ni-rich (from 32.93 to 45.09 wt.% Ni), which comprises harzburgite WLK1 from Wilcza Góra and harzburgites K1/11/14/1 and K6 from Krzeniów.

Fine-grained aggregates of group A consist of clinopyroxene + spinel + feldspar + sulfides and supposedly originated by external melt infiltration (Matusiak-Małek et al. 2013). This type of aggregates contains anhedral, rounded, randomly distributed pentlandite + Ni-pyrrhotite polyphase grains. Pentlandite forms irregular domains within a grain and/or rim around grain core, composed by Ni-pyrrhotite and pentlandite "flame-like" intergrowths.

Fine-grained aggregates of group B consist of clinopyroxene + olivine  $\pm$  spinel  $\pm$  glass  $\pm$  feldspar  $\pm$  sulfides (pentlandite + Ni-pyrrhotite). Those occurring in the Krzeniów samples originated by external melt infiltration, whereas those from Wilcza Góra samples resulted from decompression melting of clinopyroxene with or without external melt supply (Matusiak-Małek et al. 2013). Sulfides reside in aggregates consisting of clinopyroxene +

spinel + glass. The polyphase grains consist of pentlandite + Ni-pyrrhotite or pentlandite + chalcopyrite). Pentlandite forms irregular domains and/or rims around cores consisting of Ni-pyrrhotite and pentlandite intergrowths. Chalcopyrite occurs as domains in or rims around pentlandite polyphase grains. Pentlandite occurs also as monophase grains.

The Lower Silesian-Upper Lusatian domain of European subcontinental lithospheric mantle is dominated by harzburgites containing relatively little aluminium (Puziewicz et al. 2015) which record relatively high degrees of melt extraction (20-30 %). These rocks were overprinted by silicate-carbonate melt metasomatism, mostly at the time of Cenozoic volcanism. Our data show that most of sulfides occur in the fine-grained interstitial aggregates (related to the syn-volcanic metasomatism) and have preserved rounded shapes typical for sulfide liquid with a minimum surface area (Skinner and Peck, 1969) and thus are of metasomatic origin. The sulfides enclosed in the silicates are compositionally similar to the metasomatic ones, which suggests that their origin is also related to the syn-volcanic metasomatic event.

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#### Mafic and ultramafic cumulates from the eastern part of Central European Volcanic Province – xenolithic insight into lower crust

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Xenoliths of not-mantle-derived, mafic and ultramafic rocks give insight into structure and composition of lower crust and crust/mantle boundary. Xenoliths of this type have been scarcely described from Polish part of the Cenozoic Central European Volcanic Province and a coherent interpretation has never been made. In this study we present data on notmantle-derived xenoliths from five outcrops of volcanic rocks in the Złotoryja-Jawor Volcanic Complex in Lower Silesia (SW Poland). The latter is one of the five Cenozoic "complexes" forming the easternmost part of the Central European Volcanic Province (Puziewicz et al. 2015).

The texture of studied xenoliths is typically cumulative but in some samples it is blurred by recrystallization. The studied xenoliths are either plagioclase-free (clinopyroxenites, websterites, wehrlite) or plagioclase-bearing (anorthosite, gabbros, and norite). Besides the rock-forming phases, the xenoliths occasionally contain spinel, sulfides and amphibole. The xenoliths are characterized by strong variability in modal composition and chemical composition of minerals The mineral grains are usually zoned and chemical equilibrium between phases is scarce.

Plagioclase-free rocks contain clinopyroxene which has the composition of diopside with occasionally elevated Al, Ti and Cr contents. It's mg# usually varies from 0.89 to 0.79, but in diopside from Ostrzyca it is as low as 0.55. It is usually slightly to moderately enriched in LREE relative to primitive mantle; the REE patterns are concave, and the normalized values vary significantly between localities. It shows negative Sr and Ti anomalies. However, clinopyroxene from Mnisza Górka clinopyroxenite is depleted in majority of trace elements, including LREE. Orthopyroxene is Al-rich enstatite with mg# varying from 0.85 down to 0.75. Amphibole occur exclusively in clinopyroxenite from Wilcza Góra and has a composition of pargasite and mg# around 0.75. Olivine forming wehrlite contains ~82% of forsterite, while NiO content is around 0.17 wt.%. Opaques are ilmenite - Ti-magnetite solid solution and/or sulfides.

Plagioclase-bearing rocks contain clinopyroxene which also has composition of diopside, but its mg# is lower (0.68-0.88). It is typically LREE enriched and shows negative Eu, Ti and Sr anomalies. Strongly heterogeneous (mg#=0.60-0.75) orthopyroxene occurs only in norite from Wilcza Góra. Fo- and NiO-poor (62-69% and 0.04-0.10 wt.%, respectively) olivine occurs in gabbro from Winna Góra. Feldspar is typically plagioclase  $(An_{30-60})$ , but in rims the composition grades towards ternary feldspar (Or up to 45%).

Plagioclase is LREE enriched and shows strong positive Eu anomaly. Composition of opaques is similar to that in plagioclase-free rocks.

Ratios between A<sup>IV</sup> and Al<sup>VI</sup> in clinopyroxene suggest that PI-bearing rocks crystallized in different conditions than pyroxenites (Aoki, Shiba 1976). Calculations of trace element composition of melt in equilibrium with clinopyroxene from websterite and clinopyroxenites show that rocks from Wilcza Góra and Grodziec are precipitates from alkaline melt, while clinopyroxenite from Mnisza Górka has affinity to much more depleted melt, possibly of tholeiitic affinity. Precipitation of tholeiitic magma in Bohemian Massif was so far described only from Steinberg in SE Germany (Kukuła et al., submitted) and from Dobovičky in Eger Graben (Ackerman et al. 2012).

Wehrlites, websterites and clinopyroxenites showing cumulative textures were described from the Księginki nephelinite (SW Poland) and were interpreted as mantle precipitates from host volcanic rocks (Puziewicz et al. 2011). Composition of the plagioclase-free suite in our study is similar to that from Księginki and therefore we suggest that formation of cumulates of host rocks is widespread in northern part Bohemian Massif. This type of cumulates were not reported from south-west part of Bohemian Massif, most probably due to a fact that they were not a scope of any study.

The Ostrzyca Proboszczowicka basanite carries significant number of clinopyroxene megacrysts which were also interpreted as fragments of coarse-grained, crustal cumulates of host magma (Lipa et al. 2014). The composition of clinopyroxene forming the Ostrzyca clinopyroxenite differs from that of megacrysts by lower mg# (0.55 vs. 0.61-0.70), lower Na contents (0.03 vs. 0.08-0.12 a.pfu) and significant negative Eu anomaly. This suggests that the clinopyroxenite might have been formed at later stages of host magma crystallization, after formation of megacrysts. Fractional crystallization of alkaline magma may be also an explanation for formation of significant number of gabbroic rocks in Wilcza Góra and Winna Góra.

Our study shows that composition of lower crust beneath Northern Part of Bohemian Massif was strongly modified beneath each volcanic complex. Until now no xenolithic samples of metamorphic lower crust (granulites, eclogites) were stated. Further petrological studies and their comparison with geophysical data are required to explain this phenomena and construct detailed cross-section of lower crust in this area.

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#### Ureilite meteorites: Extra-terrestrial mantle samples

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What does the mantle of another planet look like? We can get an insight from ultramafic meteorites known as Ureilites which are derived from the restitic mantle of an unknown differentiated asteroid. They are mostly dominated by olivine and pigeonite with subordinate augite, as well as minor carbon phases and metal/sulphide. Their modal abundances range from peridotite to pyroxenite, and their bulk silicate rock mg#s (i.e., corrected for metal/sulphide abundances) range from 74 to 92, much wider than the range found in terrestrial peridotite samples. This wide compositional variation correlates with variations in  $\Delta^{17}$ O values and is considered to have been inherited from the accretion of the parent asteroid from the primordial solar nebula, rather than being produced by different extents of partial melting.

Correlations between bulk rock mg# and moderately incompatible oxides such as CaO and TiO<sub>2</sub> are weak and slightly positive, in contrast to the strong negative correlations shown by terrestrial peridotites. All ureilite bulk rock compositions show LREE-depletion, as do their silicate minerals, indicating removal of a silicate partial melt. The asteroid on which ureilites formed was more reduced than the Earth, leading to Eu being commonly divalent. Plagioclase was probably present in the original parent asteroid but has been completely removed by silicate partial melting which gave rise to trachyandesitic melts. As partial melting was taking place, the original asteroid suffered a catastrophic destruction probably by impact with another asteroidal body. This gave rise to extensive shock metamorphism and reverse zoned olivines with Mg-rich reduced rims laced with native iron. A daughter asteroid later formed from the remnants of the disrupted original body. This destruction, however, preserved evidence of the processes which had been occurring during the early phase of asteroidal differentiation and mantle formation.
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# Carbon isotopic signature of orogenic peridotites from the Ulten Zone (Italy): tracer for carbon sources in subduction zones?

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The origin and cycling of carbon (C) within the Earth's mantle and its isotopic variability are still under debate. The occurrence of dolomite in ultramafic rocks of the Ulten Zone (UZ) tectonic unit (Eastern Alps, Italy) has been reported previously (Sapienza et al., 2009), thus, the UZ ultramafics represent a natural laboratory to study the sources, storage and recycling of carbon in subduction-modified lithospheric mantle. This is of particular importance to the terrestrial C-cycle referring to the fate of carbon in subduction-related environments.

Ultramafic rocks of the UZ consist of orogenic peridotites from a supra-subduction zone mantle wedge that have been captured by a down-going subducting crustal slab. Thereby, coarse spinel-bearing lherzolite was deformed into porphyroclastic garnet-amphibole harzburgite. During the Late Paleozoic Variscan orogeny, exhumation of UZ peridotites led to their deformation into fine-grained garnet-bearing and amphibole-rich mylonitic peridotite (Scambelluri et al. 2006). Due to their multi-stage tectonic history, UZ orogenic peridotites show a large variety regarding grain-size, mineral assemblage, texture and retrogression, indicating that they experienced several petrological processes if a common protolith is assumed.

The presence of hydrous minerals such as amphibole, phlogopite, chlorite and serpentine as well as of dolomite as a C-carrier has been described in earlier studies (Marocchi et al. 2007; Sapienza et al. 2009). These phases have been postulated to be of metasomatic origin. The occurrence of such metasomatic phases requires the infiltration of UZ peridotites by CHO-bearing metasomatic agents, such as crust-derived fluids released during subduction-related dehydration and/or melting and exhumation. While the hydrous metasomatic phases are widespread in UZ peridotites, dolomite has been detected rarely either as disseminated grains or rare porphyroclasts. Locally, large aggregates of dolomite crystals occur (Lo Pò et al., this issue). A link between the occurrence of dolomite and any other particular petrological feature has not been identified and samples that are dolomite-free on thin-section scale haven been shown to be compositionally indistinguishable from dolomite-bearing varieties (Sapienza et al., 2009). However, in the majority of UZ peridotites dolomite is not optically detectable. Thus, the question arises if dolomite is widespread in all UZ peridotites, regardless of their petrographic variety and provenance within the mantle wedge, and which carbon isotopic signature characterizes these rocks.

To address these questions we will present a systematic study of whole-rock (WR) C-content and carbon isotopic data for UZ peridotites combined with their detailed petrography. Preliminary analyses of WR C-content and carbon isotope systematics have been carried out at the University of Ferrara using EA-IRMS. The peridotite samples investigated so far cover a wide range of mineral assemblage, grain size, texture and retrogression and do not contain optically detectable carbonate. UZ peridotites display homogeneous C-concentrations (0.06 wt-% to 0.08 wt-%) and hence a constant carbonate mode, regardless of petrographic features. This confirms the presence of carbonate as a low-volume accessory phase and indicates that UZ peridotites acted as a carbon trap even though carbonate is not optically apparent. It seems that carbon, if indeed mobilized from the subducting slab, was fixed within the peridotitic mantle wedge in form of carbonate. The associated carbon isotopic composition is characterized by high variability with  $\delta^{13}$ C ranging between -17.17 ‰ and -11.12 ‰ (relative to PDB). Overall, the variability and the light carbon isotopic signature of these rocks relative to the primitive mantle ( $\sim -5$  ‰) argue against a simplistic model of crustal C-recycling into the mantle via subduction, requiring the occurrence of more complex fractionation processes that might be related to interaction with metasomatic fluids and/or degassing.

We will discuss the results of a systematic study of WR C-content and carbon isotopic compositions of UZ peridotites and a potential relation to particular petrographic features. The integrated study of petrographic information, C-concentrations and carbon isotopic signatures will enhance our understanding of the origin of different C-sources that interact with the mantle wedge in collisional subduction zone settings.

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### Mantle refertilization by melts of crustal-derived garnet pyroxenite

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Geochemical studies of primitive basalts have documented the presence of crustalderived garnet pyroxenite in their mantle sources. The processes whereby melts with the signature of garnet pyroxenite are produced in the mantle are, however, poorly understood and somewhat controversial. Here we investigate a natural example of the interaction between melts of garnet pyroxenite derived from recycled plagioclase-rich crust and surrounding mantle in the Ronda peridotite massif. Melting of garnet pyroxenite at  $\sim 1.5$ GPa generated spinel websterite residues with MREE/HREE fractionation and preserved the positive Eu anomaly of their garnet pyroxenite precursor in whole-rock and clinopyroxene. Reaction of melts from garnet pyroxenite with depleted surrounding peridotite generated secondary fertile spinel lherzolite. These secondary lherzolites differ from common spinel lherzolite from Ronda and elsewhere by their lower-Mg# in clinopyroxene, orthopyroxene and olivine, lower-Cr# in spinel and higher whole-rock Al<sub>2</sub>O<sub>3</sub>, CaO, Sm/Yb and FeO2 at a given SiO2. Remarkably, secondary spinel lherzolite shows the geochemical signature of ghost plagioclase in the form of positive Eu and Sr anomalies in whole-rock and clinopyroxene, reflecting the transfer of a low-pressure crustal imprint from recycled pyroxenite to hybridized peridotite. Garnet pyroxenite melting and melt-peridotite interaction, as shown in the Ronda massif, may explain how the signature of subducted or delaminated crust is transferred to the mantle and how a garnet pyroxenite component is introduced into the source region of basalts. The efficiency of these processes in conveying the geochemical imprint of crustal-derived garnet pyroxenite to extruded lavas depends on the reactivity of pyroxenite melt with peridotite and the mantle permeability, which may be controlled by prior refertilization reactions similar to those documented in the Ronda massif. Highly fertile heterogeneities produced by pyroxenite-peridotite interaction, such as secondary spinel lherzolite in Ronda, may nucleate magmatic channels that remain chemically isolated from the ambient mantle and act as preferential pathways for melts with the signature of recycled crust.

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### Phase velocities of Rayleigh and Love waves in central and northern Europe from automated, broadband, inter-station measurements – Implications for the lithosphere-astenosphere structure on both side of the Transeuropean Suture Zone

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#### Abstract

Ireland

The increasingly dense coverage of Europe with permanent and temporary broadband seismic stations makes it possible to image its lithosphere and asthenosphere structure in great detail, provided that structural information can be extracted effectively from the very large volumes of data. In a new implementation of the classical two-station method, Rayleigh and Love dispersion curves are determined by cross-correlation of seismograms from a pair of stations. Between 5 and 3000 single-event dispersion curves with error estimates. In total, around 63000 Rayleigh- and 27500 Love-wave dispersion curves between 10 s and 350 s have been determined, with standard deviations lower than 2 % and standard errors lower than 0.5 %. Using our large new dataset, we construct phase-velocity maps for central and northern Europe. According to checkerboard tests, the lateral resolution in central Europe is  $\leq 150$  km.

The new, broad-band, phase-velocity dataset offers abundant, valuable information on the structure of the crust and upper mantle beneath Europe. In our contribution we present and discuss results, which shed new light on the lithosphere-asthenosphere structure across the Transeuropean Suture Zone spanning from the Variscan European Platform towards the Proterozoic East European Platform. Comparison of regional surface-wave tomography with independent data on sediment thickness in North-German Basin and Polish Trough (from a compilation of deep seismic sounding results) confirms the accuracy of the imaging using our short-period, phase-velocity measurements. The region of the Tornquist-Teisseyre Zone is associated with a stronger lateral contrast in the lithospheric thickness from the East European Platform towards the southwest compared to the region across the Sorgenfrei-Tornquist Zone as can be clearly seen from the longer periods.

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# Insight into the shallow lithosphere structure and magmatic plumbing system beneath the Tristan da Cunha hot spot from geophysical and petrological studies

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#### Abstract

According to classical plume theory, the Tristan da Cunha plume is thought to have played a major role in the rifting of the South Atlantic margins and the creation of the aseismic Walvis Ridge by impinging at the base of the continental lithosphere shortly before or during the breakup of the South Atlantic margins. However, Tristan da Cunha is enigmatic as it cannot be clearly identified as a deep-rooted hot spot, but may instead be related to a more shallow feature in the mantle that could actually have been caused by the opening of the South Atlantic. The equivocal character of Tristan da Cunha is largely due to a lack of geophysical and petrological data in this region.

We therefore staged a multi-disciplinary geophysical study of the region by acquiring passive marine electromagnetic and seismic data, and bathymetric data within the framework of the SPP1375 South Atlantic Margin Processes and Links with onshore Evolution (SAMPLE) funded by the German Science foundation. The experiment included two expeditions onboard the German R/V MARIA S. MERIAN in 2012 and 2013. In addition to the geophysical work, a landing party collected samples for petrological studies.

In our contribution we present first results on the shallow lithosphere structure beneath the Tristan da Cunha archipelago derived from geophysical studies. These results are combined with results from thermobarometric analyses of basanitic/ankaramitic rocks that represent the main rock type on the island. The more evolved products of the eruption in 1962, (trachyandesites), were also studied to include the full range of magma compositions. Clinopyroxene-melt thermobarometry yielded crystallization pressures between 4 and 14 kbar, corresponding to depths of 12-42 km, whereby the youngest and most evolved rocks erupted from the shallowest depth. Olivine-, clinopyroxene-, and plagioclase-melt thermometry yielded magmatic temperatures of 1100° - 1320°C. The Moho below the archipelago is at approximately 11-12 km depth based on the receiver function method at two island stations and ocean-bottom seismometers. Therefore the petrologic depth estimates demonstrate that magmas erupted from a plumbing system in the uppermost mantle.

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### Seismic model of the lower crust, uppermost mantle and LAB in Poland

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#### Abstract

The area of Poland covers a complicated contact between three continental scale tectonic units: Precambrian East European Craton (EEC) to the northeast, Variscan West European Platform (WEP) terranes to the southwest and younger Carpathian arc in the south. The Trans-European suture zone (TESZ) between EEC and WEP is a major crustal-scale feature, which appears to be a deep-seated boundary reaching at least down to a depth of about 200 km. In Poland the southwestern edge of the EEC (paleocontinent Baltica) is fault-bounded the Teisseyre-Tornquist Zone (TTZ) which is continued in Scandinavia along Sorgenfrei-Tornquist Zone (STZ). Its structure and evolution are still the important tectonic problems in Europe north of Alps. Recently presented high-resolution 3D seismic model for the area of Poland could be useful for geophysical and geological studies, tectonic correlations and petrophysical interpretations.

The three layer crystalline crust – upper, middle and lower, shows great variations both in thickness and average velocity. In general crustal layers in the EEC are thicker than in the area of WEP. In the TESZ the lower crust has very high seismic velocity (>7.0 km s<sup>-1</sup>), which may be explained by the presence of metamorphic sequences in the transition from lower crust to upper mantle (Fig.1). In the past it was interpreted as intracontinental rift-conditioned graben structure with the phase transformations of the type basalt-eclogit or gabbro-eclogit. High-velocity lower crust was observed also in Germany, where it terminates abruptly at the Elbe line. The depth of the Moho discontinuity across the TESZ is changing from 43–45 km in the EEC to the 28–32 km beneath WEP, and take place over a short lateral distance of less than 100 km width. Cratonic areas are generally characterized by high mantle velocities (>8.2 km s<sup>-1</sup>), while Phanerozoic areas are characterized by velocities of ~8.0 km s<sup>-1</sup>.

The lithosphere-asthenosphere boundary (LAB) is recently investigated effectively using seismic methods because their deep penetration and relatively good resolution (Wilde-Piórko et al., 2010; Grad et al., 2015). The thickest lithosphere, to more than 200 km is observed under "cold" Precambrian shields and platforms, while the thinnest lithosphere of 50-100 km was found under "hot" oceans and oceanic and continental rifts. In Poland seismic lithosphere thickness for the EEC is about 200 km, while it is only 90 km in the Palaeozoic platform (PP). Using ambient noise analysis from experiment "13 BB star" in northern Poland new model of *S*-wave mantle velocity will be presented. National Science Centre Poland provided financial support for experiment and this work by NCN grant DEC-2011/02/A/ST10/00284.



Fig. 1. Compilation of crustal and upper mantle seismic models in the transition from the East European craton to the Palaeozoic platform. Two-dimensional P-wave velocity model of the crust and lower lithosphere along profile P4 was derived by forward 2D ray-tracing modelling (Grad et al., 2003). The lithosphere-asthenosphere boundary (LAB) was obtained from relative P-residuals (Świeczak et al., 2004) and mantle boundaries "410" and "660" km were taken from 1D mantle models and a receiver function study (Wilde-Piórko et al., 2010). TESZ - Trans-European Suture zone. The thick solid lines are seismic boundaries and numbers are P-wave velocities (in km s<sup>-1</sup>). Dotted line ellipse in TESZ shows zone of high seismic P-wave velocities in the lower crust and uppermost mantle. No vertical exaggeration for the model.

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# Super-Reducing Conditions in the Upper Mantle Beneath the Lower Galilee (Israel)

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The lower limit of oxygen fugacity ( $fO_2$ ) in the upper mantle commonly is assumed to approximate that of the iron-wustite (IW) buffer. However, the occurrence of moissanite (SiC) and other highly reduced phases in kimberlites, and in peridotites from major suture zones, implies the action of processes that can produce and preserve local volumes with  $fO_2$ orders of magnitude below the IW buffer. Over the past 14 years, Shefa Yamim's exploration program in the Lower Galilee area of northern Israel has led to the discovery, in volcanic rocks and secondary alluvial deposits, of an unusual association of xenocryst minerals. This includes, *inter alia*, diamond, zircon, rutile, ilmenite, garnet, corundum (sapphire, ruby and non-gem corundum (NGC)) and the largest known crystals (4.1 mm) of natural moissanite. The relationships among these xenocrysts are not yet clear; we report here initial findings on the non-gem corundum and moissanite in the primary occurrences.

The colourless to pale brown NGC "megacrysts" are granular aggregates with irregular melt pockets along grain boundaries. The melt pockets contain a unique mineral assemblage indicative of very low oxygen fugacity ( $fO_2$ ), including *inter alia* native Fe, Ti and Si and Fe<sub>3</sub>Si. The NGC contains essentially no Cr or Fe, but high levels of Ti (up to 2.8 wt% expressed as TiO<sub>2</sub>). It also shows striking, highly irregular CL patterns; very bright CL correlates with low Ti, and highest Ti contents correlate with dark CL the CL. Ti contents increase toward the melt pockets, and stoichiometry suggests the substitution of Ti<sup>3+</sup> in the corundum, which in turn requires very low  $fO_2$ .

It is not yet clear whether the melt pockets represent melts residual after the precipitation of corundum, or the introduction of a melt phase into pre-existing corundum. However, the presence of native Ti in the melt pockets and other inclusions in the NGC indicate  $fO_2 > 8$  log units below the I-W buffer. These  $fO_2$  levels are low enough to stabilize moissanite (SiC), and suggest a genetic link between the SiC and the reduced melts trapped within the NGC. In addition, corundum has been found in globules of Si metal, enclosed in SiC crystals. The processes that have generated these super-reducing conditions, and the role of corundum crystallization in these processes, remain unclear; the Mt Carmel mineral associations thus hold the keys to some important petrological problems.

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# An overview of the mantle xenoliths from Loch Roag, Northwest Scotland (the margin of the North Atlantic Craton)

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At Loch Roag, on the western edge of the Outer Hebridean island of Lewis, a vertical ENE-WSW trending monchiquite dyke (50-150cm wide) cross-cuts Archaean-Palaeoproterozoic Lewisian gneisses. This fine-grained and aphanitic dyke has been dated to  $45.2 \pm 0.2$  Ma (Faithfull *et al.*, 2012) and is thus the youngest known magmatic intrusion in the British Isles, intruded some ~10 Ma later than the initial opening of the North Atlantic. It was discovered in the late 1970s during quarrying to widen a farm track. Aside from its recent age, the dyke has other features that mark it as unique in the British Isles, if not in western Europe. Axial portions of the dyke carry an assemblage of mantle and lower crustal xenoliths (including shonkinites (syenites), anorthoclasites, anorthosites, glimmerites, mafic granulites, pyroxenites, wehrlites and spinel lherzolites) which are distinct from those known from any other UK xenolith site, and megacrysts including gem quality sapphires (Upton et al. 1983; Menzies et al. 1987). More than 300 specimens were collected in the 1980s (exhausting the currently exposed portions of the dyke) and are now curated. For the purposes of this presentation, we will primarily focus on the spinel lherzolites.

The spinel lherzolite xenoliths display a range of textures, from sub-equigranular and granoblastic, to porphyroblastic. Whole-rock analyses of xenolith samples were originally presented by Hunter and Upton (1987), and further bulk geochemical analysis has been conducted by Hughes et al. (2015), including platinum-group elements (PGE) and Au. Bulk PGE abundances are equivalent to estimates of 'primitive upper mantle' and are notably Ptrich. Cu abundances are elevated above cratonic or Archaean-Proterozoic mantle peridotite compositions worldwide and currently available in the published literature. The xenoliths are also light REE enriched and depleted in Nb, Ta and Ti. Thus the Loch Roag xenoliths are enriched relative to cratonic lithospheric mantle, probably because of their position on the margin of the North Atlantic Craton.

Crystal sizes are typically 1-2mm but orthopyroxene porphyroblasts may be up to 10mm and olivine compositions range  $Fo_{92}$  to  $Fo_{88}$  (Upton et al. 2011). 'Primary' clinopyroxene compositions indicate a cryptic metasomatism event (Hughes et al. 2015). Sulphides are abundant and may be categorized into distinct 'groups' according to their petrographic setting within the xenoliths and trace element composition. For example, lherzolite xenoliths demonstrate modal metasomatism in the form of corroded grains of

spinel mantled by anorthoclase-pyroxene symplectites. In these, the pyroxenes adjacent to the spinel-anorthoclase pairs are enriched in Na. Feldspars range from potassic-oligoclase to anorthoclase, and spinel has a wide range of  $Cr_2O_3$  contents, from 6.2–31.4 wt.%. Crucially, rounded 'droplets' of base metal sulphides, enriched in PGE and bearing PtS (cooperite) are found strictly within these symplectites, indicating the same metasomatic event was responsible for PGE enrichment (particularly Pt) of this portion of the SCLM. Similar PGE-rich sulphide droplets have rounded inclusions of CaCO<sub>3</sub>, possibly indicating a carbonatitic metasomatic agent, as supported by the xenolith's light REE enrichment and other isotopic evidence. A model-age of ~2.5 Ga was obtained from the metasomatised rocks by Long et al. (1991), suggesting that the Loch Roag-type lherzolite protolith is Archaean-Palaeoproterozoic, unlike other mantle xenoliths from western Europe south of Scandinavia where the SCLM has experienced different Phanerozoic orogenic events.

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# Range of the high-velocity upper mantle in the NW Poland determined from deep seismic soundings

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#### Abstract

The net of wide angle reflection and refraction (WARR) profiles acquired on the territory of Poland in the frames of LT-7, POLONAISE'97, CELEBRATION 2000 and SUDETS 2003 projects detected the existence of high upper mantle velocities (HVUM, Vp~8.3 km/s) in the western part of the country. Based on the obtained velocity models it was possible to approximate the range of the HVUM to NE, which already at the first glance was coinciding with the edge of the East European Craton (EEC). The depth of the Moho discontinuity, which is the top limitation of the HVUM, decreases from ~40 km in the NE part to ~32 km in the SE part. From two velocity models of the P4 and S01 profiles it is possible to determine the thickness of the HVUM as  $\sim$ 5-12 km; ; below it, there is a next mantle layer, whose velocities were determined as ~8.15 km/s from dynamic modeling of reflected waves for profile P4, or as <8.0 km/s from modeling of both reflected and refracted waves for profile S01. The velocities observed on the NW-SE oriented profiles P1, TTZ-CEL03 and CEL04, amounting to ~8.35-8.4 km/s, are higher than those on the SW-NE oriented profiles LT-7, P2, P4, S01. The upper mantle velocities observed on SUDETS 2003 profiles to the south of the HVUM, namely S01 and others, are <8.0 km/s. On the other hand, velocities observed on the profile P3 located parallel to the edge but on the EEC are ~8.1 km/s. The recognition of the range, thickness and velocity distribution of the HVUM could be a great contribution to our understanding of complex tectonic scenario of the area. Interesting could also be a comparison of the range of the HVUM with the Large Igneous Province (LIP) postulated in this area (Doblas et al. 1998 and De Boorder 2013).

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# Highly siderophile element and Re–Os isotopic compositions of Mohelno-Biskoupky peridotite, Bohemian Massif, Czech Republic

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#### Introduction

Peridotites occurring in orogenic massifs provide important insights into geochemical processes of the Earth's upper mantle by providing direct evidence of mantle evolution throughout Earth history. It has been previously demonstrated by (Medaris, et al., 1990) that the uppermost tectonic unit of the Moldanubian Zone in the Bohemian Massif - the Gföhl Nappe - hosts a variety of peridotites that originated from different sources.

The Gföhl Unit consists of HT-HP felsic rocks (gneiss, granulite) accompanied by abundant bodies of peridotites that have different sources, histories and P-T-t paths. Based on major and trace elements, P–T conditions and cooling rates, three types of peridotites were identified (Medaris et al., 2005), representing (I.) suboceanic lithosphere and asthenosphere, (II.) subcontinental lithosphere, and possible (III.) ultramafic cumulate complexes. We investigated major/trace element compositions in parallel with highly siderophile element (HSE) distributions and Os isotope compositions in "Type I" rapidly cooled garnet and spinel peridotites from Mohelno and Biskoupky, equilibrated in low P–T regime and most likely representing suboceanic mantle lithosphere (Medaris et al. 2005).

#### **Results and Discussion**

The Mohelno-Biskoupky peridotites (spinel- and garnet-bearing lherzolite and harzburgite) show two different types of rare earth element (REE) patterns: (i) peridotites showing significant depletion in the light REE ( $La_N/Yb_N = 0.2-0.6$ ) coupled with weak positive Eu anomaly, and (ii) peridotites with LREE enrichment ( $La_N/Yb_N$  between 2.4 and 3.7), paralleled by a significantly positive Eu anomaly and U-shaped profile of the REE. Concerning HSE distribution, most samples have uniform iridium-group element (I-PGE: Os-Ir-Ru) contents similar to PUM estimates (Becker et al. 2006) with no obvious fractionation ( $Ru_N/Ir_N = 0.9-1.1$ ). Platinum and Pd contents are variable, but generally significantly lower than PUM, as a result of variable degrees of partial melting. In contrast, Re contents vary from 157 to 400 ppt and are not depleted to a similar degree despite incompatible behavior of Re during mantle melting compared with Pd-Pt. However, variable Re contents found in Mohelno-Biskoupky peridotites may be a result of melt-rock interaction and/or metasomatic overprint. A significant scatter in <sup>187</sup>Os/<sup>188</sup>Os ratios (0.1196–0.1333;  $\gamma_{Os}$  from –5.0 to +5.5, calculated at 330 Ma) could be explained by combined process of partial melting, melt-rock reactions and/or metasomatism by slabderived fluid/melt rich in radiogenic Os. The Re depletion model ages (T<sub>RD</sub>) calculated using the PUM estimate range from 0.5 to 1.1 Ga. These results are similar to other massive peridotites from the Bohemian Massif (Ackerman et al. 2013; Medaris et al. 2014), but are resolvedly younger than those of peridotites from lower Austria in the southern Bohemian Massif (Becker et al. 2001). The addition of Re and/or radiogenic Os could shift Re–Os model ages in peridotites towards younger ages. Based on the described behavior of the trace elements and HSE distribution, it is likely that Mohelno-Biskoupky peridotite body underwent partial melting and subsequent refertilization by basaltic melts, the pattern of which is usually recorded by orogenic lherzolites rather than abyssal peridotites.

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### East Thessaly metaophiolites interpreted through the serpentinitesubduction channel exhumation model

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The metaophiolites of East Thessaly extend from the foothills of Mt. Olympus up to the regions of Pelion and north Othris. They are commonly found in the form of deformed thrust sheets, often with cataclastic features, and in some cases as tectono-sedimentary brecciated ophiolitic mélange formations. These metaophiolites mainly consist of serpentinites which include a remarkable network of variably thick dykes (metagabbros, metadolerites, pyroxenites and rodingites), metagabbroic and metabasitic rocks in the form blocks or small irregular bodies, chromitites and ophicalcites. The East Thessaly metaophiolites have been overthrusted above Pelagonian basement marbles, limestones, amphibolites and greenschists (Pe-Piper, Piper 2002) and in some cases above Late Cretaceous to Eocene carbonate sedimentary rocks and flysch. East Thessaly region also includes a high-pressure blueschist metamorphic unit, the Makrynitsa-Ambelakia unit, consisting of marbles, schists quartzites serpentinites and meta-mafic rocks.

Many scenarios, in the past decades, have been proposed in order to explain the derivation of the southwest Balkan Jurassic ophiolites and their emplacement onto the Pelagonian microcontinent (e.g. Pe-Piper, Piper 2002; Smith, Rassios 2003; Robertson 2012; Bortolotti et al. 2013). Most researchers agree with the setting of two separate microoceans bounding the Pelagonian microcontinent, namely the Vardar Ocean to the east and the Pindos Ocean to the west. On the other hand, there seems to be little agreement in interpreting the formation and emplacement mechanisms of the Hellenic ophiolites, since there are controversies concerning the relationships between the western and eastern Hellenic ophiolites (e.g. Smith, Rassios 2003; Robertson 2012; Papanikolaou 2009; Bortolotti et al. 2013 and references therein).

In the context of this long lasting debate it is important to interpret the formation and emplacement processes of the East Thessaly metaophiolites, since they have been emplaced onto basement rocks of the Pelagonian microcontinent. Their geological features are different from those observed in other Hellenic ophiolitic occurrences (e.g. Othris, Pindos, Koziakas) that correspond to almost complete ophiolitic sequences. In contrast, the East Thessaly metaophiolites lack upper-section gabbroic rocks, sheeted dykes or pillow lavas. Instead, metagabbros, metadolerites and pyroxenites are enveloped within highly deformed and imbricated serpentinized harzburgites and serpentinites. Geochemical and mineral chemistry data indicate that these rocks have been affected by subduction related processes (Koutsovitis et al. 2013; Magganas, Koutsovitis 2015). These geological features, as well as the geochemical data, suggest that the formation and emplacement of the East Thessaly metaophiolites can be interpreted through the serpentinite-subduction channel exhumation model (Guillot et al. 2009). In this scenario, during the closure of the Mesozoic Neotethyan oceanic basin, the adjacent to the slab partial melts and peridotitic residues of the mantle wedge were incorporated into the exhumed serpentinite blocks. This physical mechanism was facilitated by the mantle corner flow which was advected towards the subduction channel in the wedge corner (Guillot et al. 2009; Long, Wirth 2013). Circulation of hydrothermal fluids of oceanic and/or subducted slab origin affected parts of the exhumed mafic-ultramafic rocks forming rodingites and also ophicalcites (Koutsovitis et al. 2013).

The high-pressure metamorphic rocks of the Makrynitsa-Ambelakia Unit, the East Thessaly metaophiolites, as well as the high-pressure metamorphic rocks and metaophiolites from the island of Evia and from the Cyclades, seem to form a distinct exhumation belt. These formations may be associated with the closure of either the Pindos and/or Vardar oceanic basins. Geochemical and isotopic data may prove very useful in resolving this issue, since the initial geometry of exhumed ophiolitic rocks is generally considered difficult to reconstruct. The mineral chemistry and geochemistry of the mafic and ultramafic rocks from the metaophiolitic occurrences in south Thessaly (Eretria, Aerino, Velestino) are comparable with those from the Othris ophiolite complex, which represents parts of upper mantle wedge rocks in a intraoceanic subduction setting of the Pindos microocean (Koutsovitis et al. 2013; Magganas, Koutsovitis 2015). However, this assumption cannot be applied for the other metaophiolite occurrences of east Thessaly and therefore further research is required.

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MINERALOGICAL SOCIETY OF POLAND POLSKIE TOWARZYSTWO MINERALOGICZNE



# Peridotitic xenoliths from the Bramberg alkali basalt (Hassberge, Bavaria, Germany)

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Bramberg hill is situated 2 km north-west of Bramberg village (Hassberge, Bavaria, Germany) and belongs to Heldburger Gangschar subset of the Central European Volcanic Province. It is a well preserved volcanic cone (494 m asl), composed of relatively rich alkali basalt (SiO<sub>2</sub> 48 wt %, < 1 % of nepheline in CIPW norm) which contains 5 – 8 cm peridotitic xenoliths. Our study based on characterization of 7 xenoliths.

We classified xenoliths into 3 groups. Group A1 (xenoliths 3146, 3149) is characterized by the highest Fo content (90.56 - 91.06 % Fo, 0.38 - 0.44 wt. %, Fig. 1) in olivine I. Clinopyroxene I has mg# 0.91 - 0.92, Al 0.16 - 0.19 a pfu. Mg# in orthopyroxene I is 0.91 - 0.92, Al 0.12 - 0.14. Spinel I has cr# 0.24 - 0.26 and mg# 0.70 - 0.73. The clinopyroxene REE patterns of group A1 are constant in Heavy REE (HREE) and slightly depleted from Sm to Pr with enrichment in Ce and La (Fig. 2). The orthopyroxene REE patterns are depleted relative to PM and follow a shape of clinopyroxene patterns.

Group A2 (xenoliths 3145, 3150, 3151, 3153) has lower Fo content (89.91 - 90.64 % Fo, 0.32 - 0.44 wt. % NiO, Fig. 1) in olivine I than group A1. Clinopyroxene I exhibits negative correlation between mg# (0.90 - 0.92) and A1 (0.13 - 0.26 a pfu). Orthopyroxene I follows clinopyroxene I trend (mg# 0.90 - 0.92, Al 0.10 - 0.18). Spinel I exhibits variation in chemical composition (cr# 0.13 - 0.39 and mg# 0.58 - 0.75). The REE patterns of clinopyroxene exhibit strong, constant enrichment in LREE (Fig. 2). Three type of REE patterns occur in orthopyroxene: U-shaped, shallow U-shaped and depleted from Lu to La pattern.

Group B (xenolith 3152a) has the lowest Fo content (87.35 - 88.33 % Fo, 0.35 - 0.39 wt. % NiO, Fig. 1). Clinopyroxene I and orthopyroxene have mg# 0.88 - 0.90 and 0.88 - 0.89 respectively. Cr# in spinel I is 0.49 and mg# 0.50 - 0.52. The group B xenolith is characterized by presence of carbonates (up to 0.5 mm grains) in interstices or intergranular aggregates. They also occur as a irregular, lobed or oval grains. Composition of carbonates is CaO 50.6 - 61.0 wt.%, MgO 2.1 - 10.6 wt.%, FeO 0.8 - 3.2 wt. %. Group B clinopyroxene REE patterns exhibit enrichment from Lu to La, inflected at Ce (Fig. 2). Orthopyroxene REE patterns are depleted form Lu to La or wavy.

The Bramberg peridotites record the combined alkaline and carbonate-rich melt metasomatism and are similar to that of Zinst, Hirschentanz and Teichelberg (Ackerman et al. 2013). The Bramberg and NE Bavarian peridotites differ significantly from those forming the Lower Silesian – Upper Lusatian domain of European subcontinental

lithospheric mantle, which are significantly less aluminous (Puziewicz et al. 2015). We speculate that the Bavarian xenoliths come from another lithospheric mantle domain, which is located beneath SW Bohemian Massif and E Bavaria.



Fig. 1. Primitive mantle (McDonough & Sun 1995) normalized REE patterns of clinopyroxene I.



Fig. 2. Chemical composition of olivine: Fo vs. NiO content.

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# Clinopyroxene megacrysts from Alter Hutberg and Georgenberg in Upper Lusatia (SE Germany) – preliminary data

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The Cenozoic Lusatian Volcanic Field (Upper Lusatia, SE Germany) is situated at the NE termination of the Eger Rift in the Bohemian Massif (Büchner et al. 2015). It belongs to numerous occurrences of alkaline volcanic rocks forming the Central European Volcanic Province. Some of the lavas of Lusatian Volcanic Field contain mantle xenoliths and clinopyroxene megacrysts. In this abstract we present the data on clinopyroxene megacrysts from two basanite lava occurrences in this area: Alter Hutberg located 1 km to the west of Ostritz and Georgenberg situated 7 km to the east of Löbau.

Clinopyroxene megacrysts of size from 0.5 cm up to 2 cm occur in both localities. They are brownish-green, brown or translucent. Some of studied samples reveal sector- or oscillatory zoning. Alter Hutberg megacrysts are characterized by relatively high Mg# (0.77-0.83), Cr content up to 0.016 atoms per formula unit (a pfu), Na on the level from 0.032 to 0.045 a pfu and Ca 0.89-0.91 a pfu. They are classified as diopside. The REE patterns reveal slight enrichment in HREE ( $2 \times PM$ ) and stronger enrichment in LREE (to 14 x PM for Nd) with characteristic deflection for La-Ce-Pr. The TE plots are characterized by depletion in Rb, Ba, U and Pb; the concentrations of the remaining elements vary from 1 to 13 x PM. Strong negative Pb anomaly and small negative U, Sr and Zr anomalies are present.

Georgenberg clinopyroxenes are also diopsides, but are significantly different. Their Mg# ranges between 0.65 and 0.75, Cr is below 0.001 a pfu, Na reaches 0.07 a pfu and Ca varies between 0.89 and 0.93 a pfu. The exception is spongy megacryst 3318b with Mg# from 0.81 to 0.86, Cr content up to 0.016 a pfu, Na varying between 0.03 and 0.04 a pfu and Ca concentrations on the level of 0.90-0.91 a pfu. Moreover, these megacrysts contain abundant of inclusions of anhedral spinel (magnetite and titanomagnetite up to 3 mm in length) and rounded sulfides (pyrrhotite 20-75  $\mu$ m in diameter).

Alter Hutberg and Georgenberg clinopyroxene megacrysts are distinctly different and based on the Mg# they can be divided into three groups: 1) spongy megacryst 3318b from Georgenberg with the highest Mg# (to 0.86); 2) Alter Hutberg megacrysts (Mg# 0.77-0.83); 3) Georgenberg megacrysts (Mg# 0.65-0.75). They are probably cumulates, but represent different depths of crystallization and diverse stages of evolution of parental melt. Compared to megacrysts from Księginki nephelinite from the Lusatian Volcanic Field (Puziewicz et al., 2011) they have less Mg, but the Ca content is quite similar. The crystallization from host nephelinite as local coarse-grained cumulates in mantle conditions is suggested for megacrysts from Księginki (Puziewicz et al., 2011). Alter Hutberg and

3318b Georgenberg megacrysts can originate from similar or shallower level of mantle, but Georgenberg diopsides may be derived from crustal depths.

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### Constraints on the geochemical properties and processes of the upper mantle beneath the northernmost part of the Pannonian Basin

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Peridotite xenoliths hosted by Plio-Pleistocene alkali basalts have been widely studied throughout the Carpathian-Pannonian region in the past few decades. The northernmost occurrence among these is the Nógrád-Gömör Volcanic Field, where there are only a few publications focusing on petrography and geochemistry, and even recent studies involving crystal preferred orientation (Liptai et al., 2013) and water content of nominally anhydrous mantle minerals used samples only from the central and southern part of the volcanic field. The main goal of this study is to characterise the geochemical signatures of xenoliths collected from the northern and central parts (including localities not previously described) and to compare the results with recent data from the central and southern parts.

Some xenoliths from the new locations contain a significant amount of amphibole, indicating modal metasomatism, whereas it has not been found in samples from the central part. In addition, some of the samples also show cryptic metasomatism detectable as Feenrichment, leading to a decrease in the Mg# of olivine and pyroxenes. These metasomatic effects appear independent of sampling sites, but are strongest in xenoliths from the locality closest to the central part of the Nógrád-Gömör Volcanic Field, where cryptic (and stealth) metasomatism showing similar patterns has been previously described (Patkó et al., 2013). Equilibrium temperatures calculated from major-element data are between 845 and 1025 °C which, using the appropriate heat flow value for the area, gives an approximate estimation of 40-50 km for depth of origin. These results coincide with the depth range previously estimated for the central part, suggesting a common relationship between the geochemical processes leading to cryptic metasomatism in both areas. The presence of amphibole, however, as well as the lack of correlation between amphibole content and Fe-enrichment suggest that at least two distinct metasomatic processes affected the upper mantle beneath the northern part of the volcanic field.

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### Dolomite in three textural sites from the Ulten Zone peridotites (Italy): a petrographic and microstructural report

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The Variscan Ulten Zone (Eastern Alps, Italy) is a high-grade unit of continental crust containing lenses of mantle wedge affected by partial melting and metasomatic processes (Scambelluri et al. 2006; Marocchi et al. 2009). In particular, the occurrence of amphibole + dolomite assemblages in garnet and spinel stability fields indicates that influx of C-O-H fluids persisted from pressure peak to retrograde conditions (Sapienza et al. 2009). Despite the overall low modal abundance of dolomite in the Ulten Zone ultramafics (Förster et al. 2015, this issue), locally dolomite forms mm-sized porphyroclasts.

This contribution focuses on the petrographic and microstructural features of a spinelgarnet-amphibole harzburgite showing a polycrystalline aggregate of dolomite. This aggregate (length around 5 cm) consists of differently oriented crystals with an average grain size of 500  $\mu$ m, decreasing towards the contact with the matrix. The dolomite aggregate overprints a previous foliation delineated by flattened olivine and elongated amphibole. The texture of the matrix ranges from granoblastic to porphyroclastic, the latter defined by olivine and amphibole around amphibole porphyroclasts. Apatite is usually located in reaction zone within the host amphibole-harzburgite.

Dolomite can be also found as inclusion into amphibole and olivine and as intertistial grains disseminated throughout the matrix. The contacts between interstitial dolomite and the harzburgitic matrix are curvilinear to embayed, suggesting a reactive percolation of C-O-H fluids through the matrix mineral boundaries.

The dolomite observed in the three microstructural sites may belong to different generations, pointing to a multistage metasomatism involving C-bearing fluids. Whereas dolomite inclusions crystallized before or during the matrix formation, dolomite aggregate and interstitial grains belong to a late stage. The occurrence of apatite as reaction product suggests that the metasomatic agent was Ca- and P-rich.

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# Simulating reactive melt transport in the oceanic mantle lithosphere – a thermodynamic approach

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The oceanic mantle lithosphere is commonly interpreted as the melt-depleted residue left after the extraction of igneous oceanic crust from the upwelling asthenosphere at midocean ridges. This model predicts that a) fractional melts formed in the upwelling mantle are efficiently isolated, aggregated, and extracted to form basaltic crust, and b) the residual lithosphere is upward depleted and its degree of depletion is proportional with the amplitude of decompression. Such a scenario is, however, unrealistic because the lengthscale of heterogeneities observed in oceanic peridotite series is shorter than the depth interval of melt depletion predicted by polybaric melting models, and the concentration of incompatible elements in these peridotites is too high for a given MgO content to result by melt depletion alone (e.g. Elthon 1992). Petrographic observations and geochemical data indicate that melt-rock reaction must be ubiquitous and capable of generating locally diverse peridotite series at oceanic spreading centers and transform faults, and contributes to the compositional diversity of MORBs (e.g. Collier, Kelemen 2010). Whereas the principles governing reactive melt transport are well established by basic theories and models, studies quantifying the physical conditions and mechanisms creating heterogeneities in the oceanic lithosphere are limited (Collier, Kelemen 2010, Kelemen 1990).

To gain a better quantitative understanding of how reactive melt infiltration acts to modify the composition of oceanic mantle lithosphere, here we simulate 1-D melt-rock reactions using Adiabat\_1ph (Smith, Asimow 2005) running with the pMELTS thermodynamic database (Ghiorso et al. 2002). In our model, aggregate liquids that result from polybaric near-fractional melting of peridotites upwelling at oceanic spreading centers percolate the mantle section of the overlying thermal boundary layer, reacting with residual harzburgites under constraints of local geothermal gradients and melt/rock ratios. We prescribe the thickness, geothermal gradient and initial composition of the lithosphere using a spreading rate-dependent 2-D thermal model, and handle the process of melt-rock reaction as a combination of continuous fractional crystallization of basalt and harzburgite assimilation under predefined P-T constraints.

We first demonstrate that reactive percolation of basaltic melts through depleted harzburgites readily generates the dunite-(wehrlite)-harzburgite-lherzolite spectrum observed in the abyssal mantle and ophiolites, and that the amplitude of transformations is a function of thermal boundary layer thickness and amount of available melt. We then evaluate the extent to which the major and trace element variability in the melts and oceanic mantle lithosphere can be influenced by different mechanisms of melt transport. Our results show that, if associated with cooling, distributed porous melt percolation (simulated by incremental addition of the same amount of melt) more efficiently converts harzburgites into fertile lherzolites and creates more pronounced compositional gradients in the abyssal mantle than imparted during channelized melt influx (simulated as batch addition of large amounts of melt) under otherwise identical circumstances. To remain within the MORB trend, reacted melts must be released from dunite channels, before orthopyroxene saturation occurs. Further reaction with harzburgite causes liquids to evolve toward boninite-like compositions. As reaction progresses with decreasing temperature, the chance of such liquids to erupt diminishes rapidly, because reactive melts freeze in rapidly after the point of clinopyroxene precipitation maximum. This prevents such boninite-like liquids to become globally important MORB end-members.

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### Subcreted oceanic crust melting beneath the Southeastern-Carpathians: evidence from garnet pyroxenite xenoliths from Quaternary basalts of the Perşani Mts.

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A wealth of ultramafic xenoliths hosted in Quaternary alkali basalts erupted in the Perşani Mts. of the Southeastern–Carpathians, Romania, provide insight into the deep lithospheric processes shaping the south-eastern part of the Carpathian–Pannonian region. Here, abundant peridotite xenoliths have been studied extensively; they document the mantle's thermal state prior to eruption as well as its melting, metasomatism, and deformation history (Vaselli et al. 1995, Chalot-Prat, Boullier 1997, Falus et al. 2011). In contrast, the origin and significance of less-common pyroxenite xenoliths have not been addressed yet. Using petrographic and geochemical data from rare garnet pyroxenite xenoliths, we refine the current view on the thermal state of the shallow mantle beneath the region and identify an altered oceanic crust component in the lower lithosphere.

We constrain the geotherm beneath the Persani Mts. by combining major and trace element thermobarometry on twenty garnet clinopyroxenites and garnet websterites. Twopyroxene thermometry and garnet-pyroxene barometry indicate that these xenoliths equilibrated at T = 800-1050 °C and P = 8-12 kbar. The temperature interval overlaps with that obtained from peridotites in previous studies and thus suggests that all pyroxenites represent—as revealed by few composite xenoliths—veins and dykes in the peridotitedominated mantle lithosphere. In addition, thermobarometry on garnet pyroxenites constrains the extraction depth of peridotite xenoliths as well, suggesting that all observed xenoliths originate from the near-Moho mantle at 30-42 km depths. The conductive geotherm defined by xenolith P-T data corresponds to an elevated heat flux of  $\sim 100 \text{ mW/m}^2$  and coincides with the conductive geotherm imposed by the same tectonothermal event that generated the host alkali basalts at the base of lithosphere (60-70 km) at a potential temperature of  $\sim$ 1350 °C (Harangi et al., 2013 updated with our own estimates). For the estimated lithospheric thickness, the transition from any stable continental conductive geotherm to the estimated  $100 \text{ mW/m}^2$  geotherm is accomplished in less than 10 Ma, regardless of the invoked geodynamic scenario. Thus it is plausible that the xenoliths record the thermal perturbation induced by the asthenosphere upwelling accompanying the ongoing foundering of the Vrancea seismogenic block (Seghedi et al., 2011). The pyroxenites, however, do not bear signs of heating; instead, microtextural features such as garnet coronas around spinels as well as chemical zonation of pyroxenes indicate cooling. Therefore, it is likely that the pyroxenites formed in response of the above-mentioned tectonothermal event, i.e. the melts from which they originate were products of fusion ultimately triggered by the sinking Vrancea block. In order to constrain

the source of these melts, we have carried out O, Sr, and Nd isotope analyses on minerals making up the garnet pyroxenites. <sup>143/144</sup>Nd (0.51179–0.51295) and <sup>87/86</sup>Sr (0.7032–0.7088) isotope systematics indicate multiple subducted crustal components in the source, while the range of  $\delta^{18}$ O values (3.5–6.7‰) strongly suggests that at least one of these components must have been a hydrothermally altered oceanic crust. Therefore it is plausible that the observed pyroxenites represent reaction products between silicic—probably dacitic—melts resulted from the partial fusion of a subducted oceanic crust and ancient lithospheric mantle peridotites through which they percolated. One possibility is that this crust represents leftover fragments of the steepening oceanic Vrancea slab, as suggested by seismic data (Bokelmann, Rodler 2014). Alternatively, the involved oceanic crust may represent relics of an ancient subducted slab accreted to the lower lithosphere, which partially melted during the invoked recent tectonothermal event. Distinguishing the two possibilities requires further investigations.

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# Surface metasomatic reaction between host basanites and mantle peridotite xenoliths from Moesian Platform

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### Introduction

Variations in the chemical composition of ultramafic xenoliths brought to the surface by magmas are thought to reflect chemical heterogeneity in the lithosphere. In many studies it is assumed that the effect of interaction between xenoliths and host basalt is minimal, and thus bulk and cryptic metasomatism of the xenoliths are generally attributed to processes that occurred in the upper mantle, prior to their incorporation into the host magma. However, some studies (e.g. Klügel 1998, 2001; Shaw et al. 2006) have shown that mantle xenoliths may react with their host melts, causing effects which are very difficult to distinguish from the supposed metasomatism occurring in the mantle. According to Klügel (1998), xenolith-host reaction may take place over years to decades in the mantle reservoirs or during residence in a crustal chamber. Scambelluri et al. (2009) suggested that modification can start immediately before and/or during xenolith entrainment in the host magma. Experimental work by Shaw and Dingwell (2008) explored the possibility of textural modifications of xenoliths during magma cooling at the Earth's surface, however, they concluded that most changes occur during transport. No detailed study exists of the possible modification of mantle xenoliths near or at Earth's surface. Here, we present a detailed study of mineralogical and chemical reactions of peridotite xenoliths during magma transport and cooling at the Earth's surface. Our results demonstrate that such reactions, although starting at the time of entrainment of xenoliths at mantle depths, were completed mostly during their residence in the magma on the surface.

#### Results

The xenoliths were collected across three large basanite domes from the Moesian Platform (North Bulgaria) which enable us to differentiate the reactions at different cooling rates and to distinguish transformation during transport from that during surface cooling. Most of the xenoliths have been percolated to various degrees by melts and vapor along networks of fractures and grain boundaries, forming irregular veinlets and pools of glass or trails of melt inclusions and sulfides within their constituent minerals. In addition, constituent minerals in contact with the fractures, veinlets and pools and host rocks show variable reaction phenomena and chemical interaction which strongly depend on their position in the dome structure. Location of the xenolith within the interior or carapace of

the dome is easily recognized by the changes of groundmass texture and size and composition of minerals in the host basanites. Spinel lherzolite xenoliths from the finegrained brecciated carapace of the domes show very thin fine-grained reaction rims around orthopyroxene, thin diffusion zones around spinel and olivine and thin (10-30 µm) clear rims around clinopyroxene. The reactions are limited mostly to the contact of the xenoliths. Modeling of concentration profiles of xenolith's olivine suggests a very short residence time of 1-3 days in the lavas and, therefore, rapid ascent rate at velocities around 0.5-1.5 km/h. Clinopyroxene in these xenoliths is always strongly depleted in LREE and Sr. Most xenoliths from the interiors of the domes are strongly affected by the host basanites. This is recorded in the wider reaction rims around orthopyroxene leading up to its entire consumption, transformation of spinel into chromite, and Fe-Mg diffusion profiles in olivine up to 400 µm long. Calculations from the olivine diffusion profiles indicate interdiffusion time up to 200 days. Times obtained from Ca concentrations from the carapace and interior are from 8 to >700 days, respectively. The clinopyroxene is variably enriched in LREE and Sr, from slightly enriched with respect to the depleted xenoliths in the nonveined xenoliths to complete equilibrated with the host basanites in the highly veined and fractured xenoliths. The enriched clinopyroxene exhibit sieve-textured zones of different thicknesses and show extremely large intra- and inter-grain compositional variations, reaching more than 200 ppm Sr within a single grain.

#### Conclusions

Our study demonstrates that chemical and mineral modification, although starting at the time of entrainment of xenoliths at mantle depths, was completed mostly during their emplacement on the surface. Post-entrainment interaction was facilitated by the access of the infiltrating melt and fluid between primary grains and fractures. Large variations of the chemical composition of the clinopyroxene reflect a prolonged disequilibrium process related to changing composition during crystallization of the host magma. Residence of xenoliths in slow cooling thick domes, dikes and lava flows may result in partial or total resetting of their mineral, chemical and isotopic compositions.

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### Evolution and differentiation of sulphur in sub arc environment

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Sulphur solubility and speciation are two key factors controlling the distribution of chalcophile elements and formation of magmatic ore deposits. Understanding speciation controls through the subduction zone environment remains one of the major challenges in Earth science. High sulphur concentrations in arc magmas (>1000ppm) are often explained by the presence of sulphate (S<sup>6+</sup>) related to the prevalence of oxidizing conditions in shallow magma chambers. However, the behavior of sulphur in magmatic systems at mid to deep crustal conditions (>5kbar) has yet to be investigated. Natural samples representing these pressures are rare and previously experiments have illustrated the technical challenges, particularly of oxygen fugacity ( $fO_2$ ) control at high-pressures conditions.

Recent studies (Klimm et al. 2012) suggest the transition from S<sup>2-</sup> to S<sup>6+</sup> takes place in oxygen fugacity window of  $\Delta$ FMQ 0 to +2 at 1000°C and 2kbar. In this study, we explore the behavior of sulphur at pressures of 10 and 15kbar and temperatures 850-950°C, simulating the lower crustal environment. High-pressure piston cylinder experiments were carried out using synthetic basaltic andesite from Laguna del Maule (Chile). The starting composition was doped with S (3000ppm), Cl (1500ppm) and 5.5wt.% H<sub>2</sub>O representing concentrations estimated for deep hydrous arc magmas. 1.5 wt.% carbon was added using carbonated Ca(OH)<sub>2</sub>. Oxygen fugacities were from  $\Delta$ FMQ -0.5 to +5.5 imposed using the new solid oxygen buffer technique of Matjuschkin et al. (2015).

Experimental results suggest a strong control of  $fO_2$  over phase relations. Reduced experiments at  $\Delta$ FMQ -0.5 and +1 exhibit 1-3wt.% higher concentrations of Al<sub>2</sub>O<sub>3</sub> and CaO in the melt compared to more oxidized experiments, due to the suppression of plagioclase crystallization. Pyrrhotite (FeS) was found to be stable at  $fO_2$  up to  $\Delta$ FMQ +3, whereas Ssolubility markedly increased at  $\Delta$ FMQ+1, suggesting the presence of additional S<sup>6+</sup> component in the melt. The 'sulphate only' stability field was only achieved at  $\Delta$ FMQ +5.5 and demonstrates that the S<sup>2-</sup> to S<sup>6+</sup> transitions at 10 and 15kbar requires a higher level of oxidation than suggested for 2kbar (Klimm et al. 2012).

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### Enrichment processes in the Patagonian lithospheric mantle

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Several mantle xenolith suites entrained in basalts from back arc mafic plateau in Patagonia were investigated. They appear to be affected by both depletion processes due to melt extraction and enrichment processes. These latter are related to metasomatic and refertilization melts that, migrating through the mantle, change its composition adding geochemical elements to the existing paragenesis or crystallizing new phases (mostly hydrated and clinopyroxene). The fluids responsible for the mantle enrichment have been linked to subduction (Stern et al. 1989; Kilian et al. 1998; Laurora et al. 2001; Kilian, Stern 2002; Rivalenti et al. 2007; Faccini et al. 2013), plume-related (Bjerg et al. 2005) geodynamics, and ascribed to silicate (Kempton et al. 1999; Stern et al. 1999) and carbonanititic (Gorring, Kay 2000) melts.

Estancia Sol de Mayo (ESM) anhydrous mantle xenoliths from Central Patagonia were recently studied by Melchiorre et al. (2015). They are entrained in post-plateau alkaline lavas belonging to Meseta Lago Buenos Aires, characterized by a coarse-grained protogranular texture, devoid of any evident modal metasomatism and equilibrated at T of 1003–1040 °C. Though no correlation between petrography of the mineral phases and their geochemistry has been observed, it is important to highlight the presence of two and three texturally different clinopyroxenes and orthopyroxenes: the first occurs as both protogranular (cpx1) and texturally related to spinel (cpx2); the second as large protogranular crystals with exsolution lamellae (opx2) and finally as small grains arranged in a vein (opx3).

Major element composition of cpx and opx of ESM highlights two different trends characterized by i) high  $Al_2O_3$  content at almost constant mg# and ii) a slight increase in  $Al_2O_3$  content with decreasing mg#. Cpx are LREE enriched and characterized by prominent to slightly negative Nb, Zr and Ti anomalies. Partial melting modeling using both major and trace elements indicates a melting degree between ~5% and ~13% (up to ~23% according to major element modeling) for lherzolites and between ~20% and ~30% for harzburgites (down to ~5% according to trace element modeling).

La/Yb and  $Al_2O_3$ , as well as Sr and  $Al_2O_3$  show negative correlation pointing to a refertilization event affecting the ESM lithospheric mantle domain. The presence of opx arranged in vein, as well as the similarity between the geochemical features of the ESM cpx and those from Northern Patagonia pyroxenites, point to a transitional alkaline/subalkaline melt as refertilizing agent. When comparing the ESM mantle xenoliths with those from Central and Northern Patagonian suites, similar trends can be recognized. This suggests that the  $Al_2O_3$  enrichment through refertilization is a common process in the Patagonian lithospheric mantle, as also indicated by the widespread negative correlation between La/Yb - Sr and  $Al_2O_3$ . The most likely melt responsible for this event vary in composition from alkaline/subalkaline transitional to tholeiitic melts. In addition to this, another enrichment process can be envisaged for the Patagonian subcontinental lithospheric mantle, linked to alkaline metasomatism.

Sr-Nd systematic performed on samples from several localities show a large range of both isotopic ratios. Mixing calculations allow to assess that up to 4% of an EM II component is needed to account for the most radiogenic samples.

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### Highly siderophile elements and Os isotope composition of recycled mantle pyroxenites: a case study from the Ligurian mantle section (N Apennine, Italy)

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Crust-derived mantle pyroxenites are believed to be significant components of OIB-MORB sources. Recycled pyroxenites record processes such as partial melting, migration of pyroxenite-derived melts and variable extents of melt/peridotite reaction. In particular, melting of second-stage pyroxenites formed by reaction of eclogite-derived melts with ascending peridotite within mantle plumes are thought to provide a significant contribution to OIB petrogenesis (e.g. Sobolev et al. 2005; Lambart et al. 2012).

Although the presence of a pyroxenite component may contribute to the radiogenic <sup>187</sup>Os and <sup>186</sup>Os signatures within the sources of oceanic basalts, the highly siderophile element (HSE) signatures of mantle pyroxenites are not well constrained and well understood. Here, we present HSE (Os, Ir, Pt, Pd, Re) and <sup>187</sup>Os compositions of thirteen garnet pyroxenites and two lherzolites from the External Ligurian ophiolites.

This pyroxenite-peridotite sequence provides a snapshot on the evolution of recycled mafic crust within the mantle. The pyroxenites include Mg-rich, Al-poor garnet websterites and three types of garnet clinopyroxenites which were recognized on the basis of wholerock and clinopyroxene REE geochemistry. Type-A and Type-B are strongly LREEdepleted and display flat and HREE-enriched whole-rock patterns, respectively. Type-C have moderate LREE depletion and lower HREE contents with respect to Type-A-B. Small to distinct Eu positive anomalies characterize Type-A and Type-C garnet clinopyroxenites. In the previously reconstructed scenario (Montanini et al., 2012 and Montanini and Tribuzio, submitted), a rifting-related event of Mesozoic age caused melting of eclogites originated from an heterogeneous MORB-type gabbroic sequence. The garnet clinopyroxenites originated by crystallization of eclogite-derived melts that experienced negligible interaction with the host peridotites. The garnet websterites, on the other hand, were interpreted as the reactions products of eclogite-derived melts and peridotites, thereby giving rise to hybrid, second-stage pyroxenites with a crustal geochemical fingerprint. The mafic precursors underwent a long-lived evolution of recycling into the mantle (1.5-1.0 Ga), with no evidence for substantial fractionation affecting the Lu/Hf and Sm/Nd isotopic systems.

The Ligurian peridotites show typical mantle-like concentrations and flat CI-chondritenormalised HSE patterns, in accordance with their lithophile major and trace element composition close to PM. The pyroxenites display large concentration ranges and significant differences between the different pyroxenite types recognized on the basis of lithophile elements. All the pyroxenites are significantly but variably depleted in Os and Ir and enriched in the incompatible HSE (Pt, Pd and Re) with respect to the host peridotites. As a whole, only Os and Ir abundances and Re/Os ratios are correlated with Al<sub>2</sub>O<sub>3</sub> and Mg# values.

Type-A pyroxenites exhibit lower Os, Ir, but higher Pt, Pd concentrations and flatter Pd-Re segments when compared to the associated Type-B pyroxenites. Type-C pyroxenites show heterogeneous HSE compositions. They have Os-Ir contents similar or higher than Type-B pyroxenites, whereas the Pd-Re segments range from flat to negatively sloping. Distinct Pt-Pd enrichment is observed in two out of four Type-C pyroxenites. The Mg-rich websterites have HSE patterns broadly similar to Type-A but are significantly enriched in Os and Ir by ca. a factor 10.

The External Ligurian mantle sequence shows small scale (centimetre to metre-scale) Os isotopic heterogeneities. The initial <sup>187</sup>Os/<sup>188</sup>Os ratios recalculated for the age of the partial melting event inferred from Nd-Hf isotope systematics (220 Ma) are unradiogenic to slightly radiogenic in the peridotites (0.124-0.134) and vary from moderately to highly radiogenic in the pyroxenites (0.149-2.190), corresponding to  $\gamma_{Os}$  of + 17 to +1628. Interestingly, the least radiogenic <sup>187</sup>Os signatures of the pyroxenite suite are observed in the Mg-rich websterites, which are the most likely pyroxenites in our suite to partly carry a peridotite signature.

We show that crust-derived mantle pyroxenites may display a large range of highly siderophile elements signatures, as well as Os isotope ratios, which may be related to heterogeneity of crustal protoliths, age of recycling, interaction with the host peridotites and late-stage melt percolation during the decompression history. They would likely contribute to small and large-scale geochemical and isotopic heterogeneities of the Earth's mantle and more specifically partly explain for the large range of <sup>187</sup>Os-<sup>186</sup>Os isotopic signatures in OIBs and MORBs.

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# Petrology and geochemistry of the peridotite and pyroxenite xenoliths from selected outcrops of the Złotoryja Volcanic Field (SW Poland)

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The Złotoryja Volcanic Field is one of the two largest concentrations of the Cenozoic basaltoides in Lower Silesia (SW Poland). Those rocks belong to the Central European Volcanic Province which is part of the Circum-Mediterranean Anorogenic Cenozoic Igneous province (Ladenberger et al. 2006; Badura et al. 2006; Lustrino, Wilson 2007).

The area studied spreads between Złotoryja, Świerzawa and Jawor and covers about 560 km<sup>2</sup>. More than 54 volcanic outcrops occur in this area, the current studies were focused only on seven chosen places. The peridotite and pyroxenite xenoliths were found only in five exposures (Wołek Hill (WH), Muchowskie Wzgórza (MW), Owczarek (O), Wilcza Góra (WG) and Jeziorna (J)). In the two remaining occurrences Czartowska Skała (CzS) and Kozia Góra (KG) only the crustal xenoliths and rare pyroxenites were recognized (Nowak 2012). The studied outcrops differ in the age – from Oligocen (MW) to Miocen (WG) (Badura et al. 2006), and in the form of the volcanic body (necks, lava flows and dykes).



Fig. 1. Simplified sketch of the area studied

From the collected ca. 600 xenoliths – peridotite xenoliths are more than 60% and pyroxenite about 5%. The rest of the collected samples consist of ultramafic cumulates (5%), megacrysts (4%) and crustal xenoliths (20%). The number of the collected xenoliths differ between individual outcrops. Most of the xenoliths were collected at WH and WG; smaller number of samples were collected at CzS, KG and J. In most of the outcrops the peridotite xenoliths dominated over pyroxenites and cumulates, except of Owczarek (O)

where pyroxenites constitute ca. 43% of the collected material. Xenoliths size ranges from less than 1 cm to 28 cm – but larger xenoliths (> 5cm) occur only at Wołek Hill (WH).

Petrographic observations where performed in 91 thin-sections from 74 xenolith samples (Nowak 2012). The microprobe measurements were performed in Warsaw, Hannover and Touluse (more than 30 thin-sections). The LA-ICP-MS measurements were made in Touluse and Cracow (11 thin-sections). Seven xenoliths where measured using whole-rock analyses (ACME Canada) and 5 isotopic measurements of mineral separates (Cpx, Amph) where also obtained (TIMS Poznań).

According to the mineral modal compositions most of the samples are harzburgites (67%), but dunites (22%) and wehrlites (11%) also occur. According to the structural classification (Mercier, Nicolas 1975), the dominant are protogranular structure (more than 60% of the samples) and porphyroclastic (ca. 34%), eqiugranular (5%) is less common. Based on petrographic observations and chemical compositions the minerals inside peridotite xenoliths could be classified on six different groups (main minerals, metasomatised minerals, intergrowths, melt pockets, host-rock interactions and minerals related with weathering). Based on thermodynamic calculation peridotite xenoliths originate from depth not exceeding 50 km.

Studied pyroxenite xenoliths belong to clinopyroxenites (78%) and Ol-bearing clinopyroxenites (22%), one sample from WG could be described as Amph-bearing clinopyroxenite. Two types of structures can be distinguished in pyroxenites: coarse and fine-grained, most of Cpx in clinopyroxenites display spongy texture.

Ultramafic cumulates divide into Ol-bearing (almost pure dunites) and Cpx-enriched (wehrlites), and they contain the same minerals like peridotite xenoliths. Chemically cumulates are strongly enriched in iron. Amph, Cpx and Feld were recognized as megacrysts.

Based on whole information from studied xenoliths it seems that lithospheric mantle was strongly depleted. Changes related to modal metasomatism are only limited to two occurrences (WH and WG). The modal metasomatism is related to infiltration and propagation of Cenozic lavas and strongly visible in the youngest rocks. Many xenoliths show overlapping of different processes related to magma ascent and storage.

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POLSKIE TOWARZYSTWO MINERALOGICZNE



#### Origin and geochemistry of the Cenozoic alkali basalts in SW Poland

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Cenozoic lava flows and necks belonging to the Central European Volcanic Province are widespread in Lower Silesia in SW Poland. They occur in the NE part of the Variscan Bohemian Massif (Sudetes and Fore-Sudetic Block). Part of the lavas occurs at the NE prolongation of the Ohře (Eger) Rift into Poland (westernmost part of Lower Silesia), whereas those situated in the central and eastern parts of Lower Silesia are distant from the Rift. Samples from 22 outcrops show that, besides one site consisting of basaltic trachyandesites, the majority of the lavas are nephelinites and basanites, with eruption ages ranging from 31 to 4.5 Ma ago.

The nephelinites and basanites have Mg# varying from 54 to 63 and from 62 to 71 respectively. They have low total alkalis that range from 3.5 to 6.3 wt% and Ba/Ce ratios that vary between 4.5 and 6.5, which are consistent with the mean OIB ratio of 4.5. The radiogenic Sr and Nd isotopic ratios have values similar to HIMU (0.703115-0.703867 and 0.512780-0.513015 respectively)

The calculated melt segregation temperatures for basanites range between 1550 and 1580 °C (Herzberg, Asimow 2008), which correspond mantle potential temperatures around 1480 °C that is higher than the mantle ambient temperature estimated to be 1400 °C. Pressure estimates for the segregated melts are 3 GPa, which correspond depths of approximately 100 km (Scarrow, Cox 1995).

The nephelinites could not be modelled using the same approach. Their chemical characteristics show that the source has been affected by  $CO_2$  metasomatism.

The estimated high temperatures at low pressures (~100 km) point to a thermal anomaly underneath the studied area, which coincides with the postulated low-velocity material underneath Europe (Hoernle et al. 1995). This could be attributed to local small "finger-like" plume activity causing alkaline volcanism (Granet et al. 1995). However not everywhere in Europe the alkali basalts are related to plumes. For example Ali and Ntaflos, 2011 have shown that in Styrian Basin, Austria, the mantle potential temperature is below 1400°C and that lithospheric attenuation is responsible for the generation of the alkali basalts. It is therefore evident that thermal anomalies are not widespread everywhere underneath Europe but there are small low-velocity bodies causing the alkaline volcanism. This could be valid at least for SW Poland.

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### Geodynamic and geophysical consequences of *stealth(y)* mantle metasomatism

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The metasomatised lithospheric mantle is a palimpsest, recording the multiple fluid events that have affected that domain since it formed. Interpreting this complex record and tracking specific episodes and processes is a key to reconstructing lithosphere evolution through time, and also the nature of the volatile flux from the deep Earth over time.

Metasomatism affects not only the geochemical characteristics of the lithospheric mantle, but also its physical parameters (and hence geophysical signatures) including density, seismic response and thermal and electrical characteristics.

The concept of <u>"stealth</u>" metasomatism has been introduced (O'Reilly, Griffin 2012) to highlight the "deceptive" addition to lithospheric mantle rock-types of new phases (e.g. garnet and/or clinopyroxene) indistinguishable mineralogically from common mantle-peridotite phase assemblages.

*Recognition of stealth metasomatism reflects* the increasing awareness of the importance of refertilisation of ancient refractory mantle regions by metasomatic fluid fronts in modifying the composition (and physical properties) of mantle domains. Recognition of stealth metasomatism is critical to unravelling the geochemical and geodynamic evolution of the lithospheric mantle, and realistically estimating composition (and change with time) of primitive ancient subcontinental lithospheric mantle (SCLM).

Primitive Archean lithospheric mantle is highly magnesian and has a relatively low density (~3.31 g/cm3) compared to fertile mantle (~3.37 g/cm3). The resulting contrasts in seismic response become measurable if metasomatised regions are on the scale of tens to hundreds of km (Griffin et al. 2014). Metasomatic refertilisation of the cratonic SCLM not only increases its density, but also strongly affects its rheology. Thermal changes are caused by advective transfer of heat by relatively hot metasomatising fluids and by the influx of heat-producing elements (K, U, Th) that accompanies some types of metasomatism. The heat produced by radioactive decay of these elements can raise the local heat flow by 50-70% compared to the normal reduced mantle heat flow. The origins of significantly contrasting *electromagnetic (MT) responses* in the lithospheric mantle have not yet been satisfactorily identified. Fluid-related recrystallisation demonstrated in microstructural studies may result in significant H contents in mantle minerals and may affect electrical conductivity. The key to understanding the electromagnetic signals from the mantle lies in identifying the nature of fluids and their distribution and thus is closely connected with a full understanding of metasomatic processes and fluid movement in the mantle.

Recognition of *stealth metasomatism* coupled with geodynamic modelling using mineral physics for exploring nanoscale fluid flow mechanisms is the key to interpreting physical-property data (seismic, magnetotelluric) of lithospheric and convecting mantle.

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## Mineralogical, microstructural and geochemical variability of lithospheric mantle beneath the Middle Atlas (Morocco)

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In the North-Eastern part of Africa, the Middle Atlas volcanic province is one of the largest and youngest volcanic fields in Morocco. It roughly coincides with the maximum of lithospheric thinning beneath continental Morocco. In this region, several strombolian cones and maars provide numerous crustal and mantle xenoliths. Peridotites and a few pyroxenites from the two main mantle xenolith localities, the BouIbalghatene and Tafraoute maars, have been investigated for their mineralogy, microstructure and whole-rock and mineral compositions. Bou Ibalghatene is located in the center of the volcanic province, in the tabular Middle Atlas, whereas Tafraoute is situated 45 km away, on the North Middle Atlas Fault that separates the tabular Middle Atlas to the North-West from the folded Middle Atlas to the South-East. Several studies were devoted to mantle xenoliths from the Bou Ibalghatene maar (e.g., Raffone et al. 2009; Witting et al. 2010) whereas the recent work of El Messbahi et al. (in press) was the first one devoted to samples from the Tafraoute maar.

The Boulbalghatene and Tafraoute mantle xenoliths show contrasting records of lithospheric mantle evolution. Our study reveals that those brought to the surface by the Tafraoute maar differ from the Bou Ibalghatene suite in several respects. The Tafraoute samples show a variety of microstructures - coarse-equant, porphyroclastic, granular, and mylonitic - recording different stages of deformation associated with decompression and lithospheric thinning. In the Bou Ibalghatene suite, the different microstructures are largely obscured by annealing and secondary grain growth, and the mylonites are absent.

The Bou Ibalghatene and Tafraout xenoliths suites both record infiltration of sublithospheric melts that are akin to the Middle Atlas volcanism but were differentiated to variable degrees as a result of interactions with lithospheric mantle. However, while the BouIbalghatene mantle was densely traversed by high melt fractions, the Tafraoute suite records heterogeneous infiltration of smaller melt fractions. As a consequence the lithospheric mantle beneath Bou Ibalghatene was strongly modified by melt–rock interactions in the Cenozoic whereas the Tafraoute mantle preserves the record of extensional lithospheric thinning, most likely related to Mesozoic rifting.

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# Petrological features of Antarctica lithospheric mantle, new insights from anhydrous mantle xenoliths: re-fertlization, garnet signature and metasomatism.

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A petrological study of two mantle xenolith suites from Northern Victoria Land (NVL) have been carried out in order to characterize a large portion of the lithospheric mantle beneath the West Antartict Rift System from Mt. Melbourne (74°21'S 164°42'E) to Handler Ridge (HR) (72°31' 167°18'E). Samples are anhydrous lherzolites, although few harzburgites and wehrlites are also found. GP peridotites vary from protogranular to porphyroclastic in texture, while in HR medium to coarse or fine-grained equigranular texture prevails. Based on mineral major and trace element petrological modeling, this mantle domain may represent a residuum after ~10 to 20% of partial melting. Overprinted on this event at GP there are evidence for the percolation of a tholeiitic and an alkaline melts, most probably affecting the mantle domain in different times. The first event increases the  $Al_2O_3$  content in opx and cpx and modifies the REE content in cpx, leaving a garnet signature. The good matching with trace element content in cpx phenocryst from Ferrar and Karoo tholeiites allow to ascribe this refertilization event to Jurassic time. The second event is associated with the alkaline Cenozoic magmatism related to the WARS opening and it is responsible for the presence of rare, LREE-enriched, secondary cpx and alkali-rich glassy patches. The mg# values (mg# ol=87.5-91.0) and the high variable cpx HREE contents (Y<sub>N</sub>=1.76-11.45) of the HR reflect a fertile to moderate residual mantle segment. The presence of SiO<sub>2</sub>-rich glass and rare, trace element-enriched secondary cpx suggest that HR population was also affected by melt interaction, most probably of alkaline affinity. Both HR and GP peridotites are thermal constrained at 950-980 °C, with redox conditions close to the QFM buffer, and the tendency for GP population towards more reduction conditions (~ -1.04 log units below QFM, on average). Compared with hydrated mantle xenoliths from nearby localities, GP and HR xenolith suites present higher T and comparable oxidized conditions.

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### Refertilization of the mantle lithosphere during passive rifting in the Ligurian Tethys: insights from the W. Alps - N. Apennines peridotites

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#### Aim

This work deals with the process of refertilization (i.e., enrichment of basaltic components) of mantle peridotites from the Ligurian ophiolites by melt infiltration, melt/peridotite interaction and melt interstitial crystallization.

Our present knowledge (Piccardo 2014, 2015; Piccardo et al. 2014; and references therein) evidence that refertilization of, and melt stagnation/storage within the shallow mantle lithosphere was an integral part of the "hidden magmatism" which characterized the magmatic stage of the passive rifting in the Jurassic Ligurian Tethys.

#### The magmatic rifting stage

This magmatic rifting stage consisted of:

1) Early porous flow percolation through the mantle lithosphere of silica-undersaturated, unmixed single melt increments, formed by fractional melting of the asthenosphere under spinel-facies conditions, that caused melt/peridotite reactive interaction (by means of pyroxene dissolving / olivine precipitating reactions) at spinel-peridotite facies conditions;

2) Increasing pyroxene dissolution into the percolating melts, whose compositions were modified to silica-(orthopyroxene-)saturated, derivative compositions during the reactive melt migration towards shallower, plagioclase-peridotite facies, lithospheric levels;

3) melt/peridotite interaction (by means of olivine dissolving / pyroxenes precipitating reactions) and melt interstitial crystallization of these silica-saturated liquids within preexisting reactive spinel harzburgites and dunites, that were enriched of basaltic components in the form of magmatic pyroxenes (mostly orthopyroxene) and plagioclase.

Depending on type and modal proportion of the added magmatic phases, the composition of host peridotites were modified to a suite of ultramafic/mafic rocks that were significantly enriched of orthopyroxene(minor clinopyroxene) and plagioclase with respect to the known spinel-facies mantle peridotites, both fertile and variably refractory residua.

In the Ligurian mantle peridotites, the most common melt-impregnated rock types are plagioclase(+orthopyroxene)-enriched peridotites (plg < 10% by volume), that are abundant as km-scale masses. The addition of the gabbroic minerals was, in places, rather abundant. The pre-existing peridotites were transformed into opx-rich gabbroic and pyroxenitic rocks (Piccardo 2015), i.e.,: 1) olivine-bearing(rich), orthopyroxene-rich mela-gabbro-norites [mafic gabbros, with plg >> 10% by volume]; 2) olivine-bearing(rich), plagioclase-bearing websterites [opx-rich pyroxenites, with plg < 10% and opx > 40% by volume].

The percolating/impregnating melts locally ponded forming decametric pods of coarsegranular/ pegmatoid olivine-free, opx-rich gabbro-norites (Piccardo, Guarnieri 2011).

Impregnated peridotites and gabbro-norites show highly anothitic (An 86.4-90.0) plagioclases and Mg-rich pyroxenes (Cpx Mg# 90.5-93.7; Opx Mg# 91.8), that are strongly depleted in Na, Ti, Zr, Y, Sr and LREE compositions, with respect to corresponding minerals of oceanic/ophiolitic MORB olivine gabbros. Mineral compositions suggests that they crystallized from basaltic liquids significantly different from any erupted MORB.

Calculated liquids in equilibrium with REE compositions of clinopyroxenes of reactive and impregnated peridotites fit with modelled REE compositions of liquids in equilibrium with cpx after 5-7% of fractional melting degrees of a spinel-facies DM mantle source.

#### The rheological consequence of the syn-rift lithosphere refertilization

Melt/peridotite interaction and melt refertilization of mantle lithosphere occurred along the axial zone of rifting, where asthenosphere upwelled passively during lithosphere thinning, attaining melting conditions on decompression, under spinel-facies conditions.

Estimated equilibration T indicate that both reactive sp peridotites and plg-enriched peridotites of the melt-percolated column were equilibrated with the percolating melts and attained T higher than 1200°C. Accordingly, the mantle lithosphere was asthenospherized (Bodinier, Godard 2003) by melt thermal advection and storage (Piccardo et al. 2014).

During the pre-oceanic rifting, the extending mantle lithosphere underwent relevant compositional and rheological modifications along the axial zone of the passive extension.

#### The geodynamic relevance of the syn-rift lithosphere refertilization

Numerical and analogue modeling of continental extension in the Ligurian Tethys realm evidenced that, during passive rifting: 1) an axial lithospheric mantle column (WLM) is formed, with significantly weakened rheological characteristics (Corti et al. 2007), and 2) melt thermal advection of hot liquids infiltrating from asthenosphere results in a decrease in total strength from 10 to 1 TN m-1 as orders of magnitude (Ranalli et al. 2007).

Accordingly, the syn-rif magmatic stage formed a rheological softened/weakened axial zone in the lithosphere between the future continental margins that played a determinant geodynamic role in the evolution of continental drifting, promoting chemical/mechanical erosion, faster drifting and spreading. The softened/weakened axial zone of the lithosphere may have represented a preferential way for the active upwelling of deeper/ hotter asthenosphere causing change from passive rifting to an active mid-oceanic ridge system.

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#### Subcontinental lithospheric mantle beneath Central Europe: v. 2.0

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The information on the lithology of subcontinental lithospheric mantle (SCLM) beneath Variscan orogen in Europe comes from the xenoliths entrained in the volcanic eruptions active in Cenozoic in the foreland of the growing Alpine orogen. The "sampling" of xenoliths by erupting lava is accidental, and the xenoliths from each volcano come from various depths in SCLM. However, the xenolith occurrences are relatively common in the area of European Variscan orogen. The comparison of rocks forming the individual xenolith suites shows systematic regional-scale variations of SCLM beneath the Variscan part of continent.

Recent studies of the Wrocław group revealed the strongly depleted SCLM domain beneath Lower-Silesia and Upper Lusatia. The SCLM in this domain consists mostly of harzburgites, which have been subjected to 20 - 30 % melt extraction ("A" peridotites of Matusiak-Małek et al. 2014, and Puziewicz et al. 2015). These rocks are poor in aluminium, which content in orthopyroxene is typically < 0.10 atoms pfu (corresponding to ca. 2.5 wt. % Al<sub>2</sub>O<sub>3</sub>). Clinopyroxene is absent or its volume is below 5 vol. %. The mineral is typically characterised by deep negative Zr-Hf anomaly. Clinopyroxene and probably most of spinel are metasomatic additions. The Lower Silesian – Upper Lusatian harzburgites were subjected to chromatographic style metasomatism by mixed carbonatite-silicate trace element characteristics. The last metasomatic event in the Lower Silesia – Upper Lusatia was syn-volcanic, related to migration of alkaline lavas through the SCLM. It was rather high-temperature one and lead to slight enrichment of harzburgitic protolith in iron ("Fe-metasomatism"). The record of this metasomatism is locally intense.

The Lower Silesian – Upper Lusatian domain of European SCLM borders to the SW with the South Bohemian-East Bavarian domain. The latter is less depleted (lherzolites are more common, orthopyroxene is more aluminous, no Zr-Hf anomaly occurs in clinopyroxene; e.g. Ackerman et al. 2013). The western extent of the Lower Silesian – Upper Lusatian domain is not defined precisely as yet.

The Lower Silesian – Upper Lusatian domain of European SCLM is located within the Saxo-Thuringian subduction-collision system of the Variscan orogen in Europe. In the area of the Bohemian Massif the lithospheric roots of Variscan subduction-collision systems (Saxo-Thuringian, Rheno-Hercynian and Massif Central-Moldanubian) have different

seismic anisotropy (e. g. Babuška, Plomerová 2013), which probably reflects their differing provenance and geological history. One of the possible explanations of the depleted nature of the Lower Silesian – Upper Lusatian domain is that it represents an old depleted fragment of lithospheric mantle docked in the growing orogen within the Saxo-Thuringian subduction-collision system. However, the Lower Silesian – Upper Lusatian domain is relatively close to the NE termination of the Variscan orogen at its contact with Baltica, and some of the seismic models show the prolongation of Baltica lower crust und upper SCLM to the north-eastern margins of the Bohemian Massif (e. g. Grad et al. 2003). Thus, it is possible that the SCLM occurring currently in the Lower Silesian – Upper Lusatian domain is a remnant of the Baltica mantle wedge active in the Variscan times. Further studies integrating petrological xenolith observations with large-scale geophysical observation of the SCLM in the region are necessary to reveal the origin of SCLM in the region.

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MINERALOGICAL SOCIETY OF POLAND POLSKIE TOWARZYSTWO MINERALOGICZNE



### First insights into the mantle underneath south Libya: Evidence from basalts and their xenoliths in the Jabal Eghei area

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The Jabal Eghei area is the southernmost volcanic provinces of the Libyan volcanic field. K/Ar ages suggest that two distinct volcanic events occurred in this area, from ~16 to ~5 Ma and from 4 to  $\leq$ 1 Ma (Radivojević et al. 2015). During the first event transitional to mildly alkaline basaltic lava flows formed, whereas the younger event brought to the surface low-volume basanites, mostly in form of spatter to scoria cone facies. Some of these basanite lavas host cm-dm size mantle xenoliths.

Olivine (ol) from the transitional basalts and those from the basanites range in composition  $Fo_{83}$ - $Fo_{>90}$  and  $Fo_{83}$  to  $Fo_{>90}$ , respectively. Clinopyroxene (cpx) from these two groups of basalts mostly correspond to diopside. The concentrations of Cr and Ni in the transitional basalts and the basanites mostly range between 210-430 ppm and 121-305 ppm, and 310-670 ppm and 250-483 ppm, respectively. Primitive mantle- and chondrite-normalized multivariant spider diagrams have generally subparallel, incompatible trace element-enriched patterns, with the most enriched pattern shown by the basanites. A combination of higher Mg#, Cr and Ni contents with higher incompatible trace element concentrations in the basanites rule out a possibility that they are linked by differentiation processes to the transitional basalts. The REE variations observed in the transitional basalts and basanites can be achieved by batch melting of similar, garnet-bearing, primitive mantle-like source. Calculated low degrees of melting ( $\leq 1\%$ ) for the most enriched by incompatible elements.

Upper mantle xenoliths that are found in the above described basanites are predominantly fresh anhydrous cpx-rich lherzolites, except one sample which can be classified as cpx-poor lherzolite. The xenoliths are texturally distinguished into two groups - undeformed protogranular xenoliths and deformed, mostly porphyroclastic to equigranular types. Major element mineral compositions of ol, ortopyroxene (opx), cpx and spinel generally indicate that subcontinental mantle underneath this region is remarkably fertile. The major element composition of the silicates correlates with texture, revealing that the undeformed xenoliths possess more depleted signatures. In addition, estimated equilibration temperatures are slightly higher for the protogranular types (Radivojević et al. 2014). Whole rock contents of MgO, Al<sub>2</sub>O<sub>3</sub> and CaO are ranging 43.24-35.06 wt.%, 1.46-3.94 wt.%, and 0.82-3.99 wt.%, respectively. The MgO contents exhibit strong negative correlations with Al<sub>2</sub>O<sub>3</sub> and CaO contents, and weaker negative correlations with SiO<sub>2</sub> and TiO<sub>2</sub>. Ni and Co correlate positively with MgO, whereas Sc, V, Y and heavy rare earth

element (HREE) concentrations display negative correlations with MgO contents. Whole rock geochemistry also correlates with texture, hence, the lowest HREE contents (~0.3 x chondrite) is shown by the protogranular cpx-poor lherzolite. Other trace elements, including light rare earth elements (LREE) display complex relationships with MgO contents. Namely, the patterns vary from LREE-depleted, flat to variously LREE-enriched. LA-ICP-MS trace element analyses of cpx show that HREE contents range from 5 to 11 x chondrite, with the lowest values found in the sample that was previously recognized as most depleted cpx-poor lherzolite sample is assumed to have undergone 8-9 % of fractional melting, whereas the rest of samples record lower degrees of depletion from 6.5 to 2%. The LREE patterns of cpx's are also variable, thus, most samples are variously LREE-depleted, some display spoon shaped patterns, some are highly LREE-depleted, and only few samples are LREE-enriched.

These first data indicate that the mantle beneath the Jabal Eghei area is similar with mantle segments beneath other regions in Libya e.g., Gahryan (Beccaluva et al. 2008) and Wau en Namus (Miller et al. 2012). It certainly underwent complex melting (depletion) and enrichment episodes and elucidating these processes more in detail will be done in the near future.

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## Geochemistry and tectonic significance of Iherzolites from New Caledonia Ophiolite

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The association of rocks with contrasting geodynamic affinities is a quite common feature in ophiolites and it has been documented in several ophiolitic complexes, such as Pindos (Greece), and Lycian and Antalya ophiolites (Turkey) (Saccani, Photiades 2004; Aldanmaz et al. 2009).

New Caledonia hosts one of the World's largest ultramafic terrane termed "Peridotite Nappe" belonging to an "atypical" ophiolitic sequence of presumed Late Cretaceous- Early Eocene age. It is dominated by mantle lithologies, mostly harzburgite and minor spinel and plagioclase lherzolite, together with some mafic and ultramafic cumulates. Despite their ultra-depleted nature, some efforts were devoted to characterize the mantle rocks from a geochemical point of view. A supra-subduction affinity is generally accepted for harzburgites (Marchesi et al. 2009; Ulrich et al. 2010); in contrast, the origin and evolution of lherzolites still remain a matter of debate. This presentation will focus on the petrological and geochemical characterization of the lherzolitic rocks.

Lherzolites are mainly found in northern massifs, where spinel lherzolites extensively crop out in association with minor plagioclase lherzolites. These rocks are low-strain porphyroclastic tectonites, locally grading into protomylonite.

They likely record an asthenospheric HT origin followed by sub-solidus re-equilibration, which is also testified by geothermometric estimates (870-1080°C and 830-980°C for porphyroclastic assemblages and recrystallization in the spinel facies, respectively).

Spinel lherzolites are relatively undepleted, as attested by the presence of 7-8 vol% of Na and Al-rich clinopyroxene (up to 0.8 wt% Na<sub>2</sub>O; 3.1-6.7 wt% Al<sub>2</sub>O<sub>3</sub>), low Fo in olivine (88.5-90.0 mol%) and Cr# in spinel ([100 • Cr/(Cr+Al)]= 13-17).

Major element mineral compositions (e.g. Mg# (Ol) vs Cr# (Spl), Cr# (Spl) vs Mg# (Spl)) coupled with Cpx and whole-rock REE geochemistry show that the lherzolites are akin to abyssal peridotites. In particular, the spinel lherzolites have REE patterns characterized by MREE and HREE enrichment over LREE (Nd<sub>N</sub>/Sm<sub>N</sub> = 0.18-0.27, Nd<sub>N</sub>/Yb<sub>N</sub> = 0.02-0.70) for Yb<sub>N</sub> = 1.0-1.3. The REE patterns of clinopyroxenes have strong LREE depletion (Nd<sub>N</sub>/Yb<sub>N</sub> = 0.001-0.05) and nearly flat HREE segments for Yb<sub>N</sub> = 5.5-5.9.

Melting modelling based on REE compositions of Cpx and whole-rock indicate that HREE patterns can be explained by 8-10% fractional melting of a DMM source in the

spinel stability field. However, slight MREE/HREE fractionation suggest that melting may have initiated at higher pressure, in the garnet stability field.

Whole-rock Nd isotope ratios ( $\varepsilon_{Nd} = 6.98-11.86$ ) also suggest derivation from a relatively homogenous MORB-type depleted mantle that experienced a recent depletion event, leading to variable <sup>147</sup>Sm/<sup>144</sup>Nd ratios.

The aforementioned features point out an origin in a spreading ridge environment, probably related to pre-Early Eocene marginal basin development within the Southeast Gondwana margin.

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### Multiple metasomatic events within the SCLM beneath the French Massif Central: part A

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#### Introduction

Tertiary and Quaternary volcanism of the French Massif Central has sampled the underlying subcontinental lithospheric mantle (SCLM) in form of mantle xenoliths. Several studies have demonstrated the existence of two geochemically and texturally distinct mantle domains lying north and south of 45°30', respectively(Lenoir et al. 2000; Downes et al. 2003). These two mantle domains are also characterized by different redox states (Uenver-Thiele et al. 2014) and metasomatic overprints.

Major and trace element analyses of clinopyroxene from 91 xenoliths from 39 localities indicate multiple types of enrichment in LREE, MREE and HSFE. Based upon REE patterns of clinopyroxene, our suite of samples can be subdivided into four major groups A, B, C and D. Group A and B are less affected by metasomatism whilst Group C and D experienced stronger metasomatic overprints recorded by LREE, MREE and other elements like Sr, Zr or Hf. Those signatures occur regionally as well as locally, which implies variations in metasomatism with depth, rock type and/or texture. Although, cryptic metasomatism is common, samples from only a few localities exhibit modal addition of amphibole or clinopyroxene. However, no significant differences in REE signatures are apparent between amphibole-bearing and anhydrous xenoliths. On the other hand, significant enrichments are observed in samples with clinopyroxene addition. Northern domain clinopyroxenes stand out not only by their tick-shaped REE patterns (Group D), but also because some samples exhibit two clinopyroxene populations with significantly different Zr/Hf, Lu/Hf, Ti/Eu and REE signatures. These clinopyroxenes represent snapshots of different types of metasomatic agents (silicate or carbonatite) and/or variable effects of percolating melt or fluid interacting with peridotite wallrock.

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#### Subduction initiation, recycling of lower continental crust, and intracrustal emplacement of subcontinental lithospheric mantle in the westernmost Mediterranean

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#### Abstract

The geochemistry of high-Mg pyroxenite dykes in the Ronda peridotite (S Spain) shows that the subcontinental lithospheric mantle in the westernmost Mediterranean evolved above a subducting slab shortly before its intracrustal emplacement. We present new Sr-Nd-Pb isotopic data of crustal rocks in the western Betics that might account for the isotopic signature of Ronda high-Mg pyroxenite. We show that lower crustal garnet granulites from the Alpujarride complex, which overly the peridotites, account for the characteristic relatively high 207Pb-208Pb/204Pb and low 206Pb/204Pb subduction component of Ronda high-Mg Ronda pyroxenite indicates that the peridotites in the westernmost Mediterranean were placed in a forearc position above a newly initiated subduction zone, followed by underthrusting of the lower crust. This possibly occurred during the late Oligocene due to the inversion of an extensional back-arc continental basin. As subduction progressed, the thinned subcontinental mantle was emplaced over the foreland following its collision with the trench.



Fig. 1. Geological map of the westernmost Betic belt showing sample location. Inset shows the location of the Betic-Rif orogenic belt in the westernmost Mediterranean: 1- Neogene sediments; 2- South-Iberian domain; 3- Maghrebian domain; 4- Flysch Trough domain; 5- Alboran domain.

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#### Melting and refertilization of the Subcontinental Lithospheric Mantle during Rifting: the record of the Beni Bousera peridotite (Rif Belt, Morocco)

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#### Abstract

Correlations between major and minor transition elements in tectonically-emplaced orogenic peridotites are generally ascribed to variable degrees of melt extraction or igneous refertilization processes superimposed on melting depletion events. In order to elucidate how melt depletion and refertilization are recorded in the subcontinental lithospheric mantle, we analyzed a large geochemical database of peridotites from the four tectonometamorphic domains of the Beni Bousera orogenic massif (Rif Belt, NE Morocco; Fig. 1). From SW to NE these domains are: Garnet and Spinel mylonites; Ariègite subfacies domain; Ariègite-Seiland domain; and Seiland subfacies domain. Our study reveals that variations in major elements and modal compositions of lherzolites, as well as the LREEdepleted patterns of their clinopyroxenes, are the result of different mechanism involving melt-rock reactions of pyroxenite-derived and under-saturated silicate melts with refractory, residual lithospheric mantle. We propose that Beni Bousera lherzolites were formed by refertilization processes after residues of partial melting (harzburgites and depleted lherzolites) that existed previous to the current zonation by domains of the massif. We can distinguish at least two distinct near solidus, melt-rock reactions associated to the development of the domains: (1) pyroxene precipitation at expenses of olivine dissolution, mainly recorded in the Ariègite domain; and (2) dissolution of orthopyroxene at expenses of clinopyroxene, with minor olivine dissolution, affecting mainly the Ariègite-Seiland and Seiland domains. We conclude that the Beni Bousera tectono-metamorphic zoning records different refertilization processes, associated with the thermomechanical erosion and rejuvenation of the subcontinental lithospheric mantle by asthenosphere upwelling in the westernmost Mediterranean.



Fig. 1. Simplified map of the Rif-Betic mountain belt showing the location of the Beni Bousera (BB) and Ronda (R) peridotite bodies

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### PASSEQ 2006-2008: What passive seismic experiment can tell us about the mantle in Central Europe?

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#### Abstract

PASSEQ 2006-2008 project (PASsive Seismic Experiment in Trans-European Suture Zone) aimed at understanding the deep seismic structure around the transition between the old Proterozoic platform of northern and eastern Europe and the younger Phanerozoic platform in Central Europe (Wilde-Piórko et al. 2008). The experiment could be executed thanks to a big international effort of 17 institutions from Europe and the USA. A total of 139 three-component temporary short-period and 49 temporary broad-band seismic stations provided continuous recordings from May 2006 to June 2008, along about 1200 km long and 400 km wide array running from Germany through the Czech Republic and Poland to Lithuania. The array also included permanent stations of the national observatories from the area of experiment. The configuration of the seismic network was a compromise among needs of different seismic methods. Data from the dense array of stations will allow us to map the upper mantle structure, e.g., the contrast, sharpness and topography of seismic discontinuities, with much higher resolution than it was possible up to now.

The inversion of teleseismic P-waves residuals resulted in  $V_P$  variations up to about  $\pm 3$  % with respect to the reference IASP91 model in the upper mantle (Janutyte et al., 2015). To the west of the Trans-European Suture Zone (TESZ) beneath the eastern part of the Bohemian Massif, the Sudetes Mountains and the Eger Rift, the negative anomalies are observed from a depth of at least 70 km. Generally, under the Variscides the average depth of the seismic lithosphere-asthenosphere boundary (LAB) is about 100 km and beneath the East European Craton (EEC) is not observed. However, beneath Lithuania the thickness of lithosphere is about 300 km or more. Beneath the TESZ, the LAB is at a depth of 150–180 km and in the southern part is shallower, most probably due to younger tectonic settings. The similar features are observed from an automated technique for the measurement of inter-station phase velocities of the fundamental-mode surface waves (Soomro et al. 2015).

A large new data set of P-receiver functions is used to map the 410 km and 660 km discontinuities in the mantle (Knapmeyer-Endrun et al. 2013). Significantly shorter travel times for conversions of seismic waves at both discontinuities within the East European

Craton (EEC) are observed, caused by the high velocities of the cratonic root. However, the differential travel time across the mantle transition zone (MTZ) is normal to only slightly raised due to the reference IASP91 model. No trace of a discontinuity at 520 km depth was found, which indicates a rather dry MTZ beneath the western edge of the craton. Only more recent tectonic events, related to Alpine subduction and Quarternary volcanism in the Eifel area, can be traced.

The analysis of splitting of teleseismic shear waves shows lateral variations of the delay times of the slow split shear waves and orientations of the polarized fast shear waves in the mantle across the PASSEQ array, as well as back-azimuth dependences of measurements at individual stations (Vecsey et al. 2014). The distinct regionalization of the splitting parameters in the Phanerozoic part of Europe (particularly in the Bohemian Massif) correlates with the large-scale tectonics. The variations of anisotropic parameters around the TESZ and in the EEC are smooth and of a transitional character. The authors suggest a southwestward continuation of the Precambrian mantle lithosphere beneath the TESZ and the adjacent Phanerozoic part of Europe.

Joint inversions of independent datasets can provide more realistic 3-D models of the upper mantle than single methods. We will present the summary of results obtained from analysis of data recorded during the seismic experiment PASSEQ 2006-2008.



Fig. 1. The fast shear-wave polarization azimuths as bars/arrows with length proportional to the split delay time: (left) averages calculated separately for waves arriving from the west and from the northeast; (right) evaluated for three events from the NE back azimuths. Complementary measurements at stations equipped with 2–3 s seismometers are shown in light-grey colour (Vecsey et al., 2014).

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MINERALOGICAL SOCIETY OF POLAND POLSKIE TOWARZYSTWO MINERALOGICZNE



## The origin of the non-serpentine phases from the Ślęża Ophiolite (SW Poland)

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The Gogołów-Jordanów Serpentinite Massif (GJSM) is a peridotitic member of the Variscan Ślęża Ophiolite in SW Poland. The latter is situated in the NE part of the Bohemian Massif in Central Europe. The GJSM consists of highly serpentinized harzburgites. The rocks occurring in its eastern part are completely serpentinized whereas those from the western part contain chromite and relics of olivine and clinopyroxene. The non-serpentine silicate phases form variable microstructures, e.g. clinopyroxene-spinel symplectites and elongated clinopyroxene grains surrounded by olivine. The clinopyroxene (Mg# = 0.91-0.93, Al<sub>2</sub>O<sub>3</sub> = 2.2-4.0 wt.%, Cr<sub>2</sub>O<sub>3</sub> = 0.8-1.4 wt.%) is depleted in Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu relative to chondrite. Olivine (Fo<sub>90.0-92.2</sub>) contains 0.3-0.5 wt.% NiO and 0.1-0.3 wt.% MnO. Moreover, low-Al and -Cr clinopyroxene (Mg# = 0.96-0.98, Al<sub>2</sub>O<sub>3</sub> = 0.2-0.4 wt.%, Cr<sub>2</sub>O<sub>3</sub> = 0.1-0.2 wt.%) and low-Ni olivine (NiO = 0.2 wt.%) occur as pseudomorphs after bastites or mesh textures. The chromite occurs in chromitites and in serpentinites. The chromite from chromititic schlieren (Cr# = 0.5-0.6, TiO<sub>2</sub> <0.2 wt.%) is depleted in PGE relative to chondrite. The single angular chromite grains dispersed in serpentinites have major element composition similar to the chromitite ones.

The primary peridotites have been serpentinized in two episodes: first, low-T serpentinization occurred due to ocean floor metamorphism and produced pseudomorphic, lizardite serpentinite, the second, higher-T serpentinization occurred at the orogenic stage and produced antigorite serpentinites without pseudomorphic textures. The non-serpentine phases occur mainly down to 1.5 km below paleo-Moho. Clinopyroxene has the mode of occurrence and composition similar to grains originated due to melt-percolation in abyssal peridotites (cf. Seyler 2007). The pseudomorphic low-Al and -Cr clinopyroxene originated due to deserpentisation. The same refers to low-Ni olivine. The chromite from chromities has the composition similar to those originating in shallow mantle zone of ophiolites due to basaltic melt migration through harzburgites (Arai et al. 2004). Its composition is typical for chromites occurring in the back-arc setting (Wojtulek et al. 2015) and indicates that Ślęża is a SSZ type ophiolite. The single chromite grains from serpentinites reveal a composition similar to that of chromite from depleted abyssal spinel harzburgites (cf. Famous F.Z. "B", Bouvet F.Z. 54°27'S 1°37'E, South-West Indian Ridge; Dick and Bullen, 1984). Its angular form could be also an indicator of harzburgitic origin (Matsumoto 2001).

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### Metasomatic processes as revealed by trace element and redox signatures of the SCLM beneath the Massif Central, France: part B

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#### Introduction

Mantle peridotites brought to the surface by Tertiary and Quaternary volcanism in the French Massif Central provide an unique view into the underlying subcontinental lithospheric mantle (SCLM), including its oxidation state. Two different mantle domains, lying N and S of  $45^{\circ}30'$ , respectively, have been identified, based upon differences in geochemistry, texture and oxidation state (Lenoir et al. 2000; Downes et al. 2003; Uenver-Thiele et al. 2014). The northern domain is generally more oxidized than the south and the degree of oxidation is controlled by the  $fO_2$  of migrating metasomatic agents (fluid or melt). We have undertaken a study to link the geochemical signatures of clinopyroxene (cpx) with redox data (Uenver-Thiele et al. 2014) from the same xenoliths to further characterize the different metasomatic agents that have overprinted the SCLM under the Massif Central.

Our samples can be subdivided into four groups according to their REE signatures. Cryptic metasomatism has caused variable degrees of LREE and MREE enrichment, whilst the presence of amphibole does not correlate with such enrichment. Differing rock types, textures and degrees of melt extraction between samples obscure any general relationship between  $fO_2$  and REE enrichment. But, for a given locality a link between increasing  $fO_2$  and LREE enrichment is apparent. Amphibole-bearing samples do not exhibit the highest  $fO_2$  ( $\Delta \log fO_2 \sim FMQ+0.6 \pm 0.3$ ), whereas a wehrlite and 2 samples having experienced carbonatite metasomatism record  $\Delta \log fO_2 \ge FMQ+1$ . Other samples have interacted with silicate-rich melts/fluids and have  $\Delta \log fO_2$  ranging from FMQ+0.5 to  $\ge FMQ+1$ . Evidence for the mobility of V during even cryptic metasomatism may compromise the use of V/Sc or V/Ga ratios as redox proxies for peridotites.

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#### Petrology and geochemistry of the back-arc lithospheric mantle beneath the Payenia volcanic province (La Pampa, Argentina)

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Insights into the petrochemical composition and evolution of the lithospheric mantle beneath the Payenia volcanic province (PVP) (Mendoza and La Pampa provinces, central-western Argentina) are provided thanks to the characterization of mantle xenoliths hosted in Pleistocene basaltic rocks from the Agua Poca and Huanul volcanoes. The PVP is related to the mantle wedge of the Argentine back-arc area in correspondence to the Transitional Southern Volcanic Zone. Agua Poca is a pyroclastic cone formed 0.6 Ma and located in the eastern PVP at 37°01'S and 68°07'W, at about 530 km east of the Chilean trench. The Cerro Huanul is instead located in the southern part of PVP, at 37°17'S and 68°32'W, about 480 km east of the Chilean trench. It is a shield volcano crowned by a ring of lava 3.9 km in diameter and 20 m height. Inside this ring, there are various heights formed by pyroclastic cones and a lava flow. The latter contains ultramafic xenoliths mostly smaller than 5 cm. According to K-Ar dating, Huanul volcanic rocks are  $0.84 \pm 0.05$  Ma (Bertotto et al. 2006).

The studied mantle xenoliths from both the localities are mainly anhydrous spinel lherzolites, with very subordinate amounts of harzburgites, wehrlites and pyroxenites. Most of the peridotites show porphyroclastic texture, whereas pyroxenites are equigranular.

These lithologies show highly variable equilibrium temperatures ranging from 780°C to 1080°C at ~1.0 to 2.0 GPa, with the relevant exception of two peridotite samples from Huanul, reaching 1200°C of equilibrium T. This constitutes evidence that the studied ultramafic xenoliths are representative of a large portion of the lithospheric mantle column. Major element mineral composition of Agua Poca and Huanul spinel lherzolites is characterized by fertile character, as evidenced by low Fo in olivine, large Al content in pyroxenes and spinel, large Na in clinopyroxene. CI-normalised REE patterns of lherzolite clinopyroxenes are LREE depleted with flat M-HREE region at ~10 xCI (see also Bertotto et al. 2013). They also show extreme depletion in highly incompatible elements such as Nb, Ta, U and Th. REE whole rock and clinopyroxene composition indicate that lherzolites can be considered to be refractory residua after 1% to 7%, non-modal, near-fractional melting of a spinel-facies Primitive Mantle. These estimates are consisting with those obtained by

means of spinel composition. Isotope composition of clinopyroxene separates from Agua Poca samples is characterized by low radiogenic Sr and large radiogenic Nd. As a whole, all the petrochemical data converge in indicating that most of the mantle column of this sector of PVP consists of rocks belonging to Depleted Mantle reservoir.

Spinel harzburgites show bulk and trace element composition characterized by LREEenrichment over HREE. These enrichments are the evidence of interaction of the mantle peridotite with LREE-enriched melts, which induced the development of transient chemical gradients, but that locally was also able to induce a complete metasomatic overprint of the trace element composition. The Sr and Nd isotopic composition of clinopyroxenes from Agua Poca harzburgites lies very close to the DM field, thus not evidencing any clear geochemical fingerprint imparted by contributions from slab-derived crustal components.

A banded websterites from Agua Poca shows peculiar major and trace element composition. In particular, REE patterns are characterized by slight LREE depletion (La down to 0.8 xCI) and flat HREE, with the content of these latter down to 3 xCI. Isotope composition of the websterite clinopyroxene exhibits very low radiogenic Sr, similar to DM. Also the Nd isotope composition in the pyroxenite slab at the contact with the peridotite is very close to that of the Agua Poca lherzolites, but it becomes markedly more enriched in radiogenic Nd in the central part of pyroxenite. As a whole, the geochemical data suggests a derivation of the parent melt by partial melting of an ultra-depleted DM.

In conclusion, the lithospheric mantle beneath the PVP is apparently dominated by a DM reservoir, which melted, according to Nd and Re-Os systematic (Schilling et al. 2008), in Proterozoic times. Both pyroxenites and metasomatised harzburgites so far investigated do not provide any clear evidence of the presence of slab-derived crustal components in the migrating melts. The petrochemical features of the Payenia lithospheric mantle are significantly different with respect to that documented for the Patagonian back-arc region, where the lithospheric mantle column is mainly constituted by harzburgite and/or strongly metasomatised by multiple events of melt migration, sometimes bearing evidence of slab-derived components. Thus, the results of this study point to a significantly different geodynamic evolution for Payenia and Patagonian mantle domains.

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### Multiple refertilisation of a strongly refractory mantle column in the extra-Andean back-arc (Paso de Indios, Argentina)

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In the central part of the Chubut province, close to the village of Paso de Indios, there are several outcrops of Cenozoic basalts carrying spinel-facies mantle xenoliths. In this area, located in the extra-Andean back-arc, basaltic necks and dikes outcrop between  $43^{\circ}$   $36' - 43^{\circ}$  50' S and  $68^{\circ}$   $53' - 69^{\circ}$  02' W, along with remnants of lava flows, being divided in two groups of Paleocene and Eocene age. This volcanism was generated by extensional tectonic related to an episode of transform plate margin that affected the southern sector of South America western margin from the Paleocene to the Oligocene, as the Aluk plate detached and a slab window opened beneath the study area.

In this contribution, the petrochemical processes experienced by mantle xenoliths hosted in Eocene basalts belonging to the Matilde lava flow, the Leon volcano and the Chenque dike, are presented and discussed.

The studied samples are mainly spinel-facies harzburgites and clinopyroxene(Cpx)-poor lherzolites, with some dunites. The Chenque xenoliths mainly display porphyroclastic to equigranular texture, whereas those from Matilde and Leon volcanoes have coarse-granular to porphyroclastic textures. Estimated equilibrium temperatures based on pyroxenes solvus range from 800 to 940°C.

The overall refractory character of the mineral assemblages is matched by the major element mineral compositions, which are mostly Al-poor and Mg-and-Cr-rich. Spinel composition is consistent with melt extraction from 8 to 14% for Chenque and Leon samples, and from 14 to 18% for the Matilde ones. The estimated degree of partial melting rises up to 24% considering the literature spinel data. However, the occurrence of melt-related open-system processes is suggested by local trends of positive correlation between Na and Cr# in Cpx, being fully confirmed by the trace element compositions. In particular, the Matilde harzburgites ubiquitously show Cpx with transient U-shaped REE patterns. The LREE fractionation is very strong, with La<sub>N</sub> up to 100 and REE patterns minimum in the M-HREE region between 0.1-1 xCI. The HREE level content (Lu<sub>N</sub> down to 1 xCI) is

consistent with 20-23% fractional melting of spinel DM. V-to-U-shaped REE patterns are also shown by Chenque Iherzolites and harzburgites. Their M/HREE are significantly more fractionated than that expected in residue after spinel-facies basalt removal, thus suggesting an onset of the partial melting process at garnet facies conditions. Other Chenque Iherzolites experienced a more pronounced refertilisation process led by LREE-enriched to LREE-depleted melts. The latter gave rise to peculiar, transient LREE-depleted sinusoidal patterns in Cpxs through reaction with the depleted ambient peridotite. A refertilised geochemical composition is also shown by the Leon samples, with harzburgite Cpxs resulting enriched in highly-incompatible elements such as U, Th, Sr and LREE.

The data presented in this study, in combination with those from the literature, allow us to conclude that the shallow mantle column beneath Paso de Indios was strongly refractory in origin, being successively affected by multiple events of melt migration. These letter, however, were able to produce only an incomplete refertilisation of the depleted protoliths, which still record geochemical gradients developed during the interaction with both LREE-enriched and LREE-depleted migrating melts. These petrochemical features make the Paso de Indios mantle column a unique study case in the Patagonian region, where the composition of the shallow mantle is usually completely overprinted by multiple stages of melt/fluid migration.

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#### LAM U-Pb zircon Early Jurassic exhumation age of the Finero Phlogopite Peridotite (Ivrea-Verbano Zone, Western Alps) and its geodynamic consequences

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A new LA-ICP-HRMS investigation of transparent zircons, unzoned and smoky at cathodoluminescence (CL), separated from chromitite layers segregated in mantle dunite bodies belonging to the Phlogopite Peridotite unit (hereafter PP) of the Finero Complex (Ivrea –Verbano Zone, Southern Alps) provides single-spot <sup>206</sup>Pb/<sup>238</sup>U Lower Jurassic ages between 200 to 180 Ma, with a pronounced peak at ~190 Ma. Relevant exception is represented by two pinky zircons showing relics of zoning at CL, with darker cores that give Triassic ages from 240 to 230 Ma.

The presence of continental crust component(s) evidenced by the negative  $\epsilon$ Hf of the zircons, the strict similarity of the trace element contents shown by clinopyroxenes and amphiboles from chromitites and the phlogopite harzburgites and pyroxenites hosting the dunite bodies, as well as the complete to partial disappearance of olivine replaced by orthopyroxene, indicate that the parent melts of the chromitites had a cognate origin with the hydrous LILE-enriched silica-saturated melts responsible of the pervasive metasomatism recorded by the Finero mantle sequence.

The combination of our data with those reported in literature for the PP chromitite zircons determines a large age interval ranging from 290 to 180 Ma. However, zircon populations with different U-Pb ages show  $\epsilon$ Hf very similar to that found in this study.

The latter evidence, together with the rejuvenation of the ages with the disappearing of the internal structures suggest that the large age variability is the result of a prolonged residence at mantle/lower crustal depths of the PP, characterised by progressive re-equilibration stages of the U-Pb zircon system.

Thus, it is here proposed that the segregation of the zircon-bearing chromitite layers was related to the pervasive metasomatic event, which occurred at ~290 Ma or before. Successively, the U-Pb zircon system remained virtually unperturbed until Middle Triassic, when the area was affected by at least two main magmatic cycles with tholeiitic to Na-alkaline geochemical affinity associated to tectonic instability. The consequent thermal perturbations induced re-equilibration stages of the chromitite zircons, which ended with the Early Jurassic exhumation documented by the U-Pb ages of chromitite zircons of this

study. Our data are in agreement with the interpretation that the Early Jurassic extensional tectonics was characterised by an important reheating event at 190 Ma, possibly due to lithospheric hyperextension.

Such a scenario considers that the PP unit resided at mantle depths during Early Permian, being possibly emplaced at crustal levels only thanks to trans-lithospheric faults during the Early Jurassic. This evolution is completely different with respect to the present day interpretation of the geodynamic history of the mantle bodies in the Val Sesia area, which are believed to have been emplaced within the continental crust, as part of accretionary prisms, since the end of the Variscan orogeny or before. This evidence confirms that the northernmost part of the Ivrea-Verbano Zone underwent peculiar Paleozoic to Mesozoic geodynamic processes, thus unravelling important additional complexities to the interpretation of the geodynamic evolution of the area now related to the Southern Alps.

2<sup>nd</sup> European Mantle Workshop

Field trip guide


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# Cenozoic alkaline lavas in SW Poland and their mantle xenoliths Introduction to the field trip

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#### **Introduction**

Sudetes and Fore-Sudetic Block form the NE margin of the Variscan Bohemian Massif, the easternmost part of Variscan basement in Europe. This area was the place of intense volcanic activity during Cenozoic. The volcanism was related to the formation of European Cenozoic Rift System in the foreland of the growing Alpine orogen, and resulted in the numerous occurrences of alkaline volcanic rocks, forming the Central European Volcanic Province. The easternmost of the Cenozoic rifts – the Eger (Ohře) Rift – is located in the western part of the Bohemian Massif (Ulrych et al. 2011). Its northern prolongation stretches to SW Poland, to the corner of Lower Silesia bordering with Czech Republic and Germany. In this area volcanic rocks form the Lubań-Frydlant volcanic complex, which is the part of the Lausitz Volcanic Field (Büchner et al. 2015). Cenozoic volcanic rocks occur also along the system of NW-SE directed faults (Labe-Odra Fault System) in Lower Silesia, and are grouped in the four "volcanic complexes": Złotoryja-Jawor, Niemcza-Strzelin, Lądek Zdrój and Niemodlin (Puziewicz et al. 2015).

Most of the alkaline lavas occurring in Lower Silesia have composition of basanites, nephelinites and alkali basalts. These rocks are poor in potassium, usually strongly LREE enriched, and typically contain no hydrous phases. They come from asthenospheric or mixed asthenospheric-lithospheric mantle sources (Ladenberger et al. 2006, Ntaflos et al. this volume). Some of them carry mantle-derived peridotitic and pyroxenitic xenoliths of various size, which enable the insight into the lithology of underlying subcontinental lithospheric mantle.

During this field trip we will visit the Oligocene and Lower Miocene basanites and nephelinite in the western part of Lower Silesia (Fig. 1). The first stop – Wilcza Góra – is one of the few sites in the region in which the peridotitic xenoliths contains sparse amphibole. The second stop – Krzeniów – offers abundant peridotite xenoliths, which partly escaped the syn-volcanic metasomatism by the lavas migrating through the SCLM. From Krzeniów we will move to Grodziec castle, which Medieval walls and towers contain impressive collection of mantle xenoliths. All these stops are located in the Złotoryja-Jawor "volcanic complex". Our last stop – Księginki – belongs to the Lubań-Frydlant complex and offers the set of xenoliths which typically are strongly affected by mantle syn-volcanic metasomatism



Fig. 1. Outcrops of Cenozoic volcanic rocks of eastern part of Central European Volcanic Province with places visited during field trip. The inset shows the location of the Eger (Ohře) Rift in the Bohemian Massif (after Ulrych et al. 2011)

### Stop 1: Wilcza Góra



Fig.2. Wilcza Góra hill with "basaltic rose" on the top. (Fot. M. Matusiak-Małek)

Ar method for 20.07±0.9 Ma (Birkenmajer et al. 2007). In the basanite numerous xenoliths of mafic, ultramafic and crustal rocks occur. Collecting of the xenoliths is possible in the lowest part of the working quarry. In the following text the crustal xenoliths are not included.

The Wilcza Góra hill (367 m asl) is located ca. 2 km south from Złotoryja city. The hill is divided into two parts: a working quarry and a natural reserve established in 1959 for protection of exceptional geological forms ("basaltic rose" and columnar jointing, Fig. 2) and wildlife.

Wilcza The Góra basanite (Smulikowski, Kozłowska-Koch 1984) belongs to the Jawor-Złotoryja volcanic complex and is located on a tectonic contact between the Lower Palaeozoic Kaczawa Complex and Permian-Mesozoic North Sudetic Depression (Albrycht et al. 2006), underlain by Permian conglomerates and sandstones.

The Wilcza Góra basanite is a volcanic

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plug (Birkenmajer et al. 1970) dated with K-

The Wilcza Góra mafic/ultramafic xenoliths are bright green to blackish, oval to angular, up to 5 cm in diameter. The xenoliths have usually a composition of spinel harzburgite, but subordinate spinel lherzolite, dunite, websterite, clinopyroxenite, olivine clinopyroxenite and wehrlite occur. Half of the studied population of xenoliths contain minor amounts of amphibole, while phlogopite is present scarcely only. Texture of the peridotitic xenoliths is usually protogranular with transitions to porphyroclastic and equigranular one sensu Mercier and Nicolas (1975; Fig. 3a). Clinopyroxenite and websterite exhibit cumulative textures (Fig. 3b). In wehrlites oval to rounded clusters (6-8 mm in diameter) formed of amphibole, spinel, orthopyroxene, olivine and feldspar/devitrified glass occur (Fig. 3c). One of the xenoliths exhibits textural and modal variation: part A - coarse-grained amphibole and olivine, part B - pure dunite, and part C fine-grained amphibole-bearing websterite (Fig. 3d). Xenoliths of such complex modal composition has been never described from SW Poland.

Based on chemical composition of olivine four groups of Wilcza Góra xenoliths have been distinguished: group A which plots in olivine-spinel mantle array (OSMA, Arai, 1994), group A- plots outside, but very close to the OSMA field, and group B plotting outside the OSMA field and group C representing cumulates (Fig. 4).



orthopyroxene; (d) - composite xenolith.

Fig. 3. Textures of the Wilcza Góra xenoliths. (a) -protogranular texture of Wilcza Góra peridotite, (b) - cumulate texture, (c) - oval cluster formed of amphibole, clinopyroxene, spinel and



Fig. 4. Relationships between olivine and spinel composition in the olivine-spinel mantle array diagram (Arai, 1994).

The division into four groups is also visible in chemical composition of other silicates:

Groups A, A-. Olivine has forsterite content between 89.4 and 91.6 % for group A xenoliths and between 88.1 and 90.2 for group Axenoliths. NiO content exceeds 0.30 wt.%. Orthopyroxene has mg# varying from 0.89 to 0.92. Clinopyroxene is an Al, Crdiopside with mg# = 0.90 - 0.93. Clinopyroxene is LREE enriched with hump at Ce or Nd (Fig. 5a). Amphibole is a pargasite (mg# 0.91 in group A and 0.89 in group A-), LREE enriched with negative inflection at Pr (Fig. 5b). Spinel I is

characterized by mg# between 0.61 and 0.68 while cr# varies from 0.52 (gr A-) to 0.62 (gr A).

<u>Group B.</u> The Fo content in olivine varies from 84.1 to 88.7%, NiO concentration is usually above 0.3 wt.%. The mg# in orthopyroxene is 0.85-0.91. Clinopyroxene I has composition of Al, Cr,Ti diopside with mg# 0.86 - 0.91. Clinopyroxene shows LREE-enriched patterns similar to that in group A, but with lower REE contents (Fig. 5a). Amphibole has the composition of pargasite (mg# 0.88 - 0.85) and REE patterns similar to those in groups A and A-, but with lower trace elements concentrations (Fig. 5b). Composition of spinel varies in wide ranges (mg# 0.44-0.65, cr# 0.26-0.56).

<u>Group C.</u> The olivine forsterite content varies from 82.4 % to 77.0 % and NiO concentration is 0.20 - 0.30 wt.%. Composition of orthopyroxene vary between samples. It has mg# 0.84 in wehrlitic parts of composite xenolith or mg# 0.80-0.81 in websterite. Clinopyroxene I has composition of Al, Cr, Ti diopside/augite in websterite (mg# 0.79– 0.80) and in composite xenolith (mg# 0.85-0.86). Al, Ti augite occurs in hornblende clinopyroxenite (mg# 0.79-0.78). Clinopyroxene I is LREE enriched with hump at Sm (Fig. 5a) and REE concentrations lower than in groups A, A- and B. Amphibole I has a composition of pargasite with mg# 0.92-0.86 in composite xenolith and 0.73-0.74 in websterite. The REE pattern of amphibole I is concave downwards as in groups A, A- and B, but the primitive mantle- normalized content of LREE is lowest among all of the groups (Fig. 5b).



Fig. 5. Normalized a) clinopyroxene I REE patterns and b) amphibole I patterns (McDonough and Sun, 1995)

The <sup>143</sup>Nd/<sup>144</sup>Nd isotopic ratio is 0.512926 ( $\mathcal{E}_{Nd}$ =5.62) in group A- clinopyroxene, while the <sup>87</sup>Sr/<sup>86</sup>Sr is 0.703124. Two ranges of isotopic ratio occur in group B clinopyroxene: (1) <sup>143</sup>Nd/<sup>144</sup>Nd =0.512945-0.512955 ( $\mathcal{E}_{Nd}$ =5.99-6.18) and <sup>87</sup>Sr/<sup>86</sup>Sr =0.703118-0.703131, and (2) <sup>143</sup>Nd/<sup>144</sup>Nd =0.513009-0.513008 ( $\mathcal{E}_{Nd}$ =7.22-7.24) and <sup>87</sup>Sr/<sup>86</sup>Sr =0.703052-0.703063. Despite small variations in the isotopic composition, the Wilcza Góra peridotitic clinopyroxene locates in the field of "high-µ" on <sup>87</sup>Sr/<sup>86</sup>Sr vs. <sup>143</sup>Nd/<sup>144</sup>Nd diagram which is typical for upper mantle beneath northern margin of Bohemian Massif (Ackerman et al. 2007; Matusiak-Małek et al. 2014).

Temperatures of equilibration were estimated with use of the two-pyroxene geothermometer by Brey and Köhler (1990). Calculated temperatures are scattered from 920 to 980°C with no fixed relationship between groups.

The group A xenoliths from Wilcza Góra plot in the OSMA field (Arai 1994) and close to "Phanerozoic lherzolites" field (Griffin et al. 1999) therefore it represents standard mantle peridotites. The B xenoliths plot outside the OSMA field (Fig. 3) and contain Ti and Al-rich spinel. Such chemical composition may result from (1) cumulative origin of peridotites or from (2) their cryptic metasomatism. Group C peridotites have cumulative textures and is pyroxene rich which suggests its cumulative origin.

Harzburgitic composition of majority of Wilcza Góra peridotites points to restitic nature of the sampled subcontinental lithospheric mantle. However, lack of positive Na-Al clinopyroxene suggests this phase is not restitic but was rather introduced metasomatically. Also composition of spinel does not show the negative mg#-cr# correlation resulting from partial melting and therefore may also be secondary.

Shape of REE pattern in clinopyroxene is concave downward and LREE enriched. Such pattern is typically interpreted as a result of reaction of peridotite with alkaline melt (e.g. Downes 2001). This interpretation is confirmed by calculated composition of melt in equilibrium with Wilcza Góra clinopyroxene, which in general fits well to composition of host basanite. The fit between the hypothetic and natural melt is the best for cumulative xenoliths (Fig. 6a) suggesting that cumulates are precipitates from the host basanite. Melts in equilibrium with clinopyroxene from peridotites B, A- and A, and xenoliths are increasingly enriched in trace elements relative to the host basanite (Fig. 6b). The same relationships are true for hypothetical alkaline silicate melts in equilibrium with amphibole and the Wilcza Góra basanite. Therefore we suggest that clinopyroxene and amphibole (and possibly spinel) are the metasomatic phases, resulting from reaction of previously depleted peridotite and hydrous alkaline melt.



Fig. 6. Calculated composition of melt in equilibrium with (a) group B and group C clinopyroxene I and (b) group A, A- and B clinopyroxene I. Partition coefficients after Hart and Dunn (1993).

That melt has been reactively percolating through the mantle column causing precipitation of metasomatic phases. The melt was continuously depleted in trace elements and so was the trace element composition of clinopyroxene (Fig. 7), amphibole and spinel. The newly formed phases are always enriched in Fe. The composition of melt at the end of reactive percolation was identical to the Wilcza Góra basanite.



Fig. 7. REE sum vs. Sr content in clinopyroxene I.

Alkaline silicate melt percolating through the mantle column reacted also with olivine and orthopyroxene forming the protolithic peridotite causing its continuous enrichment in iron ("Fe-metasomatism"): group A xenoliths show Fe content typical for Phanerozoic mantle, whereas groups A-, B and show increasingly higher Fe contents (cf. e.g. Fig. 3, where this is visible as decreasing forsterite content in olivine). The order of trace and major elements depletion/enrichment follows the experimental models of o order of reaction in mantle column (i.e. Tursack, Liang 2012).

The Wilcza Góra xenolith suite represents depleted harzburgitic lithospheric mantle, affected by several concomitant metasomatic events: (I) "stealth" metasomatism (clinopyroxene and possibly spinel added); (II) modal metasomatism (amphibole added), and (III) cryptic metasomatism ("Fe-metasomatism"). Constant change in major and trace element contents demonstrate that the Wilcza Góra xenoliths records reactive percolation of a hydrous alkaline melt through depleted mantle column.

#### Stop 2: Krzeniów

The Krzeniów quarry is located about 75 km on E from Wrocław on the Łysanka Hill. Basalts are exploited since 1927 near Krzeniów, but the visited active quarry (three exploitation levels, 800 m in diameter) is operating since 1974. The Krzeniów basanite (Birkenmajer 2007) is a volcanic plug (Birkenmajer et al. 1970) emplaced into Cretaceous limestones and sandstones (Albrycht et al., 2006) of the North Sudetic Depression. The rock is dated at  $19.57 \pm 0.79$  to  $18.72 \pm 0.81$  Ma (K-Ar ages; Birkenmajer et al. 2007). Vertical columnar jointing is well developed on the lower level, it is inclined on upper levels (Birkenmajer 2007; Fig. 8a). Small xenoliths (typically 4 cm in diameter) of peridotites, pyroxenites and gabbros occur scarcely in the basanite. The Krzeniów xenoliths have been studied in detail by Matusiak-Małek et al. (2014) and the reader is referred to this paper for details.



Fig. 8. (a) View at Krzeniów quarry and well-developed columnar jointing in basalt. (b) Olivine I NiO vs Fo contents in peridotite xenoliths.

The peridotites have composition of spinel harzburgites and spinel dunites, are coarse grained, have protogranular to porphyroclastic texture. The peridotites have been subdivided into groups A and B based on the forsterite content in olivine I (Fig. 8b): group A has >89.8% Fo, whereas group B has <90.5% Fo. Both groups comprise harzburgites and dunites.

Group A orthopyroxene has high mg# 0.92 and contains 0.02 to 0.09 atoms of Al pfu. Clinopyroxene is not occurring in part of the group A harzburgites, called by us "A0" subgroup. Clinopyroxene has mg# 0.92-0.94 and contains 0.05 – 0.16 atoms of Al pfu. The REE patterns of clinopyroxene are LREE enriched shallow U-shaped (Fig. 9a). Negative Ti, Zr-Hf and Nb-Ta anomalies occur in their trace elements diagram (Fig. 9b).

Group B orthopyroxene has mg# 0.89 to 0.92, contains 0.03 - 0.07 atoms Al pfu. Clinopyroxene is rare or absent, has mg#=0.90-0.92 and contains 0.08 - 0.09 atoms Al pfu). Clinopyroxene is LREE enriched with hump Pr or Nd (Fig. 9a).

Clino- and orthopyroxene in the most of the studied rocks are not in chemical equilibrium. Isotopic <sup>143</sup>Nd/<sup>144</sup>Nd and <sup>87</sup>Sr/<sup>86</sup>Sr ratios of clinopyroxene plot the mantle sampled by Krzeniów basanite in the "high-µ" field.



Fig. 9. Primitive mantle-normalized (McDonough, Sun 1994) REE (a) and multi-trace elements patterns (b) of clinopyroxene I.

The Krzeniów A group peridotites were subjected to strong melt extraction, reaching from 20 to 35 % (based on MgO-Al<sub>2</sub>O<sub>3</sub> relationship in orthopyroxene, Upton et al., 2010). Clinopyroxene in those peridotites is a "stealth" metasomatic phase. The variation of its REE and trace element patterns were interpreted by Matusiak-Małek et al. (2014) to originate in a chromatographic metasomatic system(s) by precipitation from carbonatite-silicate melt. The silicate melt effects are strongest in proximal parts of the systems, whereas the carbonatitic imprint is strongest their distal parts. This is probably due to unmixing of carbonatitic melt from the carbonatite-silicate system which composition was changed by reactive percolation (Ionov et al. 2005).

The group B peridotites were strongly affected by reaction with alkaline silicate melt undersaturated first in both ortho- and clinopyroxene, and later undersaturated in clinopyroxene only (similarly to the model of Kelemen et al. (1990). This resulted in the decrease of forsterite content in olivine, and decrease of mg# of orthopyroxene ("Fe metasomatism"), dissolution of orthopyroxene and precipitation of olivine. Matusiak-Małek et al. (2014) speculate that this this kind of metasomatism was most intense above the asthenosphere, since short distance to source of melts and higher temperature allow for extensive melt percolation. Infiltrating melts have composition at least similar to Krzeniów basanite, because their calculated trace elements composition is similar to those of basanite.

#### Stop 3: The Grodziec castle

The Grodziec basanite is the last site during this filed trip which belongs to the Jawor-Złotoryja volcanic field (Fig. 1). The K-Ar datings indicate its Oligocene age (32.16±1.37 Ma; Badura et al., 2006). The basanite forms volcanic cone with poorly defined vertical columnar jointing. Rocks occurring on the top of the hill (389 m asl) were used in Medieval times for building of a castle. This resulted in the exceptional and characteristic appearance of the flat hill with castle on the top. Abundant xenoliths are visible in the castle walls (Fig.10), nevertheless our study is based on the samples collected mainly from basanite occurring in the middle part of the hill, beneath castle's outer tower.



Fig. 10. Basanite with xenoliths as a building material of the Grodziec castle. (Photo: M. Matusiak-Małek)

Oval to angular greenish to blackish xenoliths and black clinopyroxene, spinel and possibly olivine megacrysts occur in the Grodziec basanite. The xenoliths are from 1.7 to 14 cm in diameter, whereas megacrysts are from few mm up to 1.7 cm long. The xenoliths are usually fresh, but in some samples secondary phases (serpentine, iddingsite) occur abundantly along grain boundaries. The xenoliths form two suites: peridotitic (spinel lherzolites, subordinate spinel harzburgites and spinel dunites) of protogranular texture and cumulative/pyroxenitic (dunite, olivine clinopyroxenites, webrlites, websterite). Xenoliths from both the suites are characterized by spongy texture of clinopyroxene appearing in whole grain or in broad margins (Fig. 11). Voids in the spongy clinopyroxene are filled with alkali feldspar or glass, small crystals of olivine and spinel are scarcely present (Fig. 11). Scarce crystals of titanian richterite and rhönite occur in intergranular fine-grained aggregates in some of the peridotitic and cumulative xenoliths In some of the xenoliths hydrothermal phases (rhodohrosite, quartz, hyalophane, plagioclase) occur in interstitial clusters.

Phases forming the peridotite suite are Mg rich (olivine 90.5-91.3 % Fo, orthopyroxene mg# 0.91-0.92, clinopyroxene mg# 0.90-0.91; Fig. 12). Olivine, pyroxenes and spinel from three xenoliths have distinctly lower magnesium numbers (olivine Fo 89.2-89.9 %, orthopyroxene mg# 0.89-0.91, clinopyroxene mg# 0.89-0.90) and lower aluminium content in pyroxenes. The spongy parts of clinopyroxene are characterized by higher mg numbers and higher Ca and lower Al and Na contents than the homogeneous parts.



Fig. 11. Spongy texture of clinopyroxene in Grodziec peridotite. Square in (a) indicates area enlarged in (b). BSE images.

The cumulative xenolith suite is characterized by less magnesian silicate compositions. The spinel has mg# is similar to that in peridotites, but it contains significantly more alumina which results in chromium numbers close to zero.



0.92

Homogeneous parts of clinopyroxene forming both the peridotite as well as cumulative/pyroxenite suites show enrichment in LREE with convex downward patterns. Two kinds of the REE patterns occur in the peridotitic xenoliths: strongly LREE enriched (sLREEe in following) [(La/Lu)<sub>N</sub> = 10.0 - 17.0] and moderately LREE enriched (mLREEe in the following) [(La/Lu)<sub>N</sub> = 2.8 - 5.0](Fig.13). The sLREEe clinopyroxene is characterized by strong negative Sr, Zr, Hf and Ti anomalies, while in the mLREE clinopyroxene the anomalies are significantly less distinct. The (La/Lu)<sub>N</sub> ratio in clinopyroxene is 2.2-3.2, and only slight negative Zr anomaly is present in the clinopyroxene from clinopyroxenitic xenoliths from the cumulative/pyroxenite suite.

Temperatures calculated for the Grodziec peridotites on the clino-orthopyroxene pairs (Brey, Köhler 1990) vary from 960 to 1100°C. Similarly high temperatures have been noted in Lower Silesia only in the Księginki peridotites (Puziewicz et al. 2011), whereas in other localities the temperatures usually do not exceed 1000°C (Puziewicz et al. 2015).

Peridotites from the Grodziec basanite constitute a restite after ~17-23% of melt extraction (based on MgO-Al<sub>2</sub>O<sub>3</sub> ratio in orthopyroxene, Upton et al., 2010). Negative Al-Na correlation in clinopyroxene may suggest this phase also to results from partial melting, but it does not follow the MgO-Al<sub>2</sub>O<sub>3</sub> melting trend by Upton et al. (2010). This, as well as the REE patterns of the mineral, suggest that it is rather a metasomatic phase.



Fig. 13. Primitive mantle normalized (McDonough, Sun 1995) REE and multi-trace element patterns of clinopyroxene forming xenoliths from Grodziec.

Elevated contents of trace elements in peridotitic clinopyroxene demonstrate cryptic metasomatism of the upper mantle beneath Grodziec. The convex downward REE pattern points to reaction with alkaline silicate melt. The well pronounced negative HFSE anomalies show that the melt contained a carbonatitic component. Composition of metasomatic agent responsible for shaping the mLREEe clinopyroxene might have been only slightly LREE enriched, while the cumulative xenoliths are direct precipitates from the host basanite (Fig. 14).

Relation between melts shaping the trace element patterns in sLREEe and mLREEe clinopyroxene is not clear. The trace element composition of clinopyroxene from both the groups is clearly distinct and no transitional compositions have been found so far. But, the depth of negative Ti anomaly decreases constantly from the sLREEe through mLREEe to cumulative xenoliths. This observation may suggest that both the metasomatic melts were related or even had been related by fractionaction, e.g. by reactive melt percolation. Amphibole is present in small amounts in both peridotites and cumulates/pyroxenites suggesting the metasomatic melt(s) might have had hydrous nature.

The spongy clinopyroxene may originate either by its partial melting or reaction with infiltrating melt. As the spongy parts are depleted in Na and Al, melting (decompression?) seems to be the most possible cause of formation of spongy textures. The small crystals of olivine and pools of glass in the voids in spongy clinopyroxene also suggest its incongruent melting.



Fig. 14. Melts in equilibrium with sLREEe, mLREEe and cumulative clinopyroxene forming the Grodziec xenoliths compared to basanite form Wilcza Góra, which represent typical volcanic rocks from SW Poland. Partition coefficients after Hart and Dunn (1993).

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#### Stop 4: Księginki

The temporarily stopped nephelinite quarry in Księginki is located at the eastern margin of Lausitz Volcanic Field (Büchner et al.in press) and belongs to the Lubań-Frydlant Volcanic Complex. The latter is located at the NE prolongation of the Eger (Ohře) rift, as opposite to the other sites shown during this field trip, which belong to the Złotoryja-Jawor Volcanic Complex. The main part of the quarry is located close to the feeder of the former volcano. Three lava flows interbedded with tuffs occur in Księginki. The lava contains abundant xenocrystic material and numerous xenoliths, forming the pyroxenitic and peridotitic suites. The pyroxenitic xenoliths typically are up to 10 cm, whereas the peridotitic ones reach 30 cm; the larger xenoliths of both peridotites and pyroxenites (up to 50 cm in diameter) occur sporadically. The K-Ar dating of the nephelinite was not successful, but the age of the neighbouring lava flow fragments close to 30 My (Birkenmajer et al. 2011) is in our opinion good approximation. The Księginki xenoliths have been studied in detail by Puziewicz et al. (2011) and the reader is referred to this paper for details.



Fig. 15. Relationship between forsterite and Ni content in olivine in peridotites from the Księginki quarry.

The peridotites from Księginki are spinel harzburgites and spinel dunites (one lherzolite only was found in the set of 15 samples), are coarse- to medium-grained, have protogranular to porphyroclastic texture. The variation of forsterite content in olivine (from 86.0 to 91.0 %, see Fig. 15) is similar to that occurring in another sites visited during this trip. Orthopyroxene mg# corresponds to forsterite content of coexisting olivine (Fig. 16). The mineral is poor in aluminium (< 0.10 atoms pfu) in peridotites containing 89.2-91.9 % of forsterite. However, some rocks containing olivine Fo 90.0-91.5 contain more aluminous orthopyroxene (Al 0.10 – 0.16 a pfu). The orthopyroxene coexisting with olivine containing less than 89 % of forsterite is Al-enriched (Al 0.16-0.24 a pfu). Clinopyroxene (mg# 0.05-0.93) contains from ca. 0.10 atoms of Al pfu in most magnesian composition to 0.32 a pfu in the least magnesian ones. Spinel is scarce, it cr# varies from 0.35 to 0.62 and mg# from 0.61 to 0.71 (with one exception of harzburgite 2868, containing spinel of cr# 0.12-0.14 and mg# 0.70 – 0.75).



Fig. 16. Relationship between mg# and Al content in orthopyro-xene in peridotites from the Księginki quarry.

The clinopyroxenite suite consist mostly of olivine clinopyroxenites and scarce websterites, plus wehrlite. Some of them show cumulate texture with alkali basaltic intercumulus frozen during host eruption. The clinopyroxene occurring in the pyroxenite suite is LREE enriched with a hump at Pr-Nd (Fig. 17a). Puziewicz et al. (2011) showed that clinopyroxenite suite originated by crystal accumulation from the magma of composition identical to that of the host nephelinite.

The REE patterns of clinopyroxene occurring in the peridotitic suite are identical to those of the clinopyroxene from the pyroxenitic suite (Fig. 17 b). This led Puziewicz et al. (2011) to the conclusion that the clinopyroxene from peridotites was chemically reequilibrated concomitantly with the precipitation of pyroxenites. Significant negative Nb, Zr-Hf and Ti anomalies in trace element patterns of some samples suggest that carbonatitic component of the alkaline lava was locally active (unmixed?).



Fig. 17. Representative PM normalised (McDonough and Sun 1995) REE patterns of clinopyroxene from the Księginki pyroxenites and peridotites.

The Księginki metasomatic event was cryptic and is recorded mostly in the clinopyroxene trace element contents and proportions. The decrease of forsterite content in olivine from some of the peridotites, related with mg# decrease and Al content increase in pyroxenes, are the major element manifestation of this metasomatism, which was the Feone, as in other sites in the region. The metasomatic event was connected with resetting of

temperatures of ortho- and clinopyroxene equilibration, which is all studied samples fall in the range 1060 - 1120 °C.

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