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Petrozavodsk, Karelia, Russia
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ABSTRACT VOLUME
of the 13th IEC

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The abstracts of the Conference cover the following topics: the chronology of eclogite-facies metamorphic rocks; eclogites in orogenic belts: geodynamic consequences; Garnet peridotites and mantle eclogites; The microstructures and microchemistry of high-pressure and ultra-high-pressure minerals; the chemical geodynamics of subduction zones; modelling of subduction zone processes.

The Abstract Volume is of interest for geologists, petrologists and geochronologists, who study HP-UHP processes at different stages of Earth’s evolutions since Precambrian to nowadays.

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C-O-H metasomatism recorded in graphite-bearing garnet websterite from the Obnazhennaya kimberlite, Yakutia, Russia

Alifirova, T.A.[1], Mikhailenko, D.S.[1], Rezvukhin, D.I.[1], Aulbach, S.[2], Golovin, A.V.[1], Korsakov, A.V.[1], Oleinikov, O.B.[3]

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Metasomatism is ubiquitous in subcontinental lithospheric mantle (SCLM). A number of studies report a strong link between metasomatism and changes in oxygen fugacity (fO_2) in the SCLM (e.g. Stagno et. al., 2013). It is also known that fO_2 of Earth's interior controls speciation within the C–H–O–S system and stability of C-bearing phases (diamond, graphite, carbonates, carbides, volatile-bearing fluid and melt; e.g. Stagno et. al., 2013). Here we provide mineral chemical and isotopic data that suggest no less than one episode of mantle metasomatism related to the formation and preservation of elemental carbon minerals within Siberian SCLM.

We studied a graphite-bearing mantle xenolith from the diamond-free Obnazhennaya kimberlite pipe, Republic of Sakha (Yakutia), Russia, that represents a garnet websterite consisting of large garnet (Grt) and clinopyroxene (Cpx) crystals up to 12 and 20 mm in size, respectively. Orthopyroxene (Opx) forms smaller grains (up to 5 mm in size). Phlogopite is a minor component. Cpx hosts oriented lamellae of Opx and Grt up to 6 mm long and 0.5 mm wide. Grt grain cores contain homogeneously distributed, oriented mineral inclusions (silicates and Ti-oxides) that we interpret to be exsolved from a Si- and Ti-rich precursor. Melt inclusions in Grt are often linearly oriented and considered to postdate the exsolutions.

Graphite forms flattened hexagonal crystals (up to 3 mm in size) and is associated with Ti-oxides and Fe-Ni-sulfides. The carbon isotope composition for graphite, $\delta^{13}C$ of 8.5 ‰, is within the mantle range and denotes a mantle source for carbon.

Microstructural and mineral chemical data are consistent with the crystallization of the garnet websterite from high-T Mg-rich magmas similar to komatiite (Spengler & Alifirova, 2019), which forms in deep convecting mantle sources with low oxygen fugacity (Berry et. al., 2008). We suggest that the combined observations are best explained in a model whereby subsequent metasomatism of the reduced websterite by oxidising C-O-H fluids caused graphite (and phlogopite) precipitation through redox freezing (Rohrbach & Schmidt, 2011), and that such reactions constitute an important part of Earth's hidden carbon cycle.

The study was supported by the RFBR grant No. 18-35-20072.

Stagno, V., Ojwang, D.O., McCammon, C.A., Frost, D.J. (2013). The oxidation state of the mantle and the extraction of carbon from Earth's interior. Nature 493: 84ȣ88.

Spengler, D., Alifirova, T.A. (2019). Formation of Siberian cratonic mantle websterites from high-Mg magmas. Lithos 326: 384-396.

Berry, A.J., Danyushevsky, L.V., O'Neill, H.S.C., Newville, M., Sutton, S.R. (2008). Oxidation state of iron in komatiitic melt inclusions indicates hot Archaean mantle. Nature 455: 960.

Rohrbach, A., Schmidt, M.W. (2011). Redox freezing and melting in the Earth's deep mantle resulting from carbon–iron redox coupling. Nature 472: 209.

Rehydration of eclogites and garnet-replacement processes during exhumation in the amphibolite facies

Angiboust, S.[1], Hyppolito, T.[2], Cambeses, A.[1], Raimondo, T.[3], García-Casco, A.[4]

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EPMA and LA-ICP-MS trace-element maps have been acquired from amphibolitized eclogites from the Diego de Almagro Metamorphic Complex (Chile). Several garnet growth pulses and garnet resorption stages are revealed by major elements chemical zoning and by heterogeneous Y and rare earth element (REE) behavior associated subduction and exhumation of these rocks. Distribution of REE in prograde garnet is texturally and chemically coupled with the breakdown of REE-bearing minerals while formation of epidote and titanite generations during amphibolitization is recorded by complex textures involving new garnet generation and overprinting phases. The latest overprint stage is characterized by fine-grained intergrowth between garnet and epidote micro-veins, phengite, hornblende, albite and titanite. Garnet cracks have been gradually re-equilibrated during this event witnessing short-scale dissolution-transport-precipitation. Pseudosection modeling shows that local variability in water content during amphibolitization controls garnet stability at the expense of epidote. Overprinting microstructures are explained by the effect of locally-derived aqueous fluids that trigger the "unlocking" of elements from the reacting eclogite-facies paragenesis. These findings highlight the microscopic characteristics of amphibolitization processes documented in exhumed eclogite-facies terranes and shed light on the importance of thorough micro-chemical investigations while undertaking pressure-temperature estimates on rocks with strong textural disequilibrium.

Hyppolito, T., Cambeses, A., Angiboust, S., Raimondo, T., García-Casco, A., & Juliani, C. (2018). Rehydration of eclogites and garnet-replacement processes during exhumation in the amphibolite facies. Geological Society, London, Special Publications 478: 217-239.

Older and younger eclogites in the Belomorian province, Fennoscandian shield: an example from the Gridino area

Balagansky, V.V.[1], Maksimov, O.A.[2], Gorbunov, I.A.[1], Kartushinskaya, T.V.[1], Mudruk, S.V.[1], Sidorov, M.Yu.[1], Sibelev, O.S.[2], Slabunov, A.I.[2]

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Eclogites form in the lowermost part of thickened crust and subducted oceanic crust and are, thus, a critical indicator of geodynamic regime. They are rare in Paleoproterozoic (PR) terrains and are practically absent in Archean (AR) ones. Retrogressed eclogites have been recently reported from the Gridino area in the Belomorian province. The eclogites were best studied by previous researchers in a single boudin (9 × 16 m) occurring in AR grey gneisses exposed on the Stolbikha Island. Some researchers refer these rocks to the Archean and others to the Paleoproterozoic. Our field observations and structural constraints for both newly-dated and published eclogite samples can reconcile these contradicting points of view.

Central and southern parts of the boudin consist of banded, symplectitic and amphibolized eclogites. The banded eclogites were folded into recumbent tight to isoclinal folds whose hinge lines and axial surfaces gently plunge and dip to the south-southeast. They were refolded into open upright folds with the same orientation of their hinge lines. These rocks are sheared at boudin margins and are migmatized at the northern margin. Their TTG host is also sheared and is cut by 2.70 Ga old plagiogranite (Volodichev et. al., 2004). In the northern part of the boudin, the eclogites are also cut by a plagiogranite whose oscillatory-zoned zircons have yielded an age of 2.65 Ga (this study). The eclogitic mineral assemblage has survived in inclusions within garnet and consists of omphacite, garnet, rutile, quartz and zoisite (for more details see Maksimov et. al., this volume). Metamorphic zircons from these eclogites yielded ages of 2.72 to 2.65 Ga (Volodichev et. al., 2004; Li et. al., 2015). For zircons with a fir-tree zoning in these rocks we have obtained the same ages (2.71–2.68 Ga), but mineral inclusions in them correspond mainly to granulite- to amphibolite-facies conditions. In eclogites, most zircons formed shortly after the eclogite-facies metamorphism peak at granulite- to amphibolite-facies conditions, and inclusions of eclogite-facies minerals are rare in zircons (Kohn, Kelly, 2018). That is why we conclude that the banded eclogites formed shortly before 2.72 Ga.

In the eastern part of the boudin, the banded eclogites are replaced by green-grey massive eclogites that build up a body of complex shape (about 2 × 3 m). In a narrow transitional zone between these two types of eclogites, the compositional banding grows faint and disappears in the massive eclogites. However, several angular elongated fragments of the banded amphibolized eclogites occur within the massive eclogite body, with their orientation being consistent with that of the banding in the surrounding AR eclogites. Metamorphic zircons from the massive eclogites contain omphacite inclusions and are dated at ca. 1.90 Ga (Skublov et. al., 2011; Yu et. al., 2017). Thus, the AR banded eclogites underwent a PR eclogite-facies overprint.

Kohn, M.J., Kelly, N.M. (2018) Petrology and Geochronology of Metamorphic Zircon, Microstructural Geochronology: Planetary Records Down to Atom Scale. Geophysical Monograph 232: 35-61.

Li, X., Zhang, L., Wei, C., Slabunov, A.I. (2015) Metamorphic PT path and zircon U-Pb dating of Archean eclogite association in Gridino complex, Belomorian province, Russia. Precambrian Research 268: 74-96.

Skublov, S.G., Astaf'ev, B.Yu., Marin, Yu.B., Berezin, A.V., Mel'nik, A.E., Presnyakov, S.L. (2011) New data on the age of eclogites from the Belomorian mobile belt at Gridino settlement area. Doklady Earth Sciences 439: 1163-1170.

Volodichev, O.I., Slabunov, A.I., Bibikova, E.V., Konilov, A.N., Kuzenko, T.I. (2004) Archean eclogites in the Belomorian Mobile Belt, Baltic Shield. Petrology (Moscow) 12: 540-560.

Yu, H.L., Zhang, L.F., Wei, C.J., Li, X.L., Guo. J.H. (2017) Age and P-T conditions of the Gridino-type eclogite in the Belomorian Province. Russia. Journal of Metamorphic Geology 35: 855-869.

EBSD analysis of palisade quartz textures:
implications for coesite-quartz transformation, Tso Morari dome, Himalaya

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Evidence of mineral transformations at UHP conditions is often lacking in felsic rocks due to incomplete transformation and/or overprinting by later metamorphism and deformation. In the absence of coesite, the distinctive microstructures formed by coesite breakdown (e.g. 'palisade' quartz) provide the only robust evidence of burial to UHP depths. Whereas exhumation-related deformation accounts for the rarity of these microstructures in the felsic rocks of UHP terrains, low-strain rocks provide a potential window into their early history, preserving UHP metamorphic features and quartz microstructures after coesite (Schertl et. al., 1991). Understanding such microstructures therefore plays a crucial role in the determination of the burial depths and tectonic histories of rocks in these terrains.

Palisade texture in quartz occurs in the matrix of a specimen of metagranite from the Tso Morari dome, Ladakh, NW Indian Himalaya. The overall shape of quartz domains matches that of igneous single quartz grains in neighbouring (meta)granite specimens, which have apparently not undergone transformation to coesite. Electron Backscatter Diffraction (EBSD) and misorientation analysis have been used to demonstrate that these domains of palisade quartz are approximately bisected by a boundary separating systematic single-crystal crystallographic preferred orientations (CPOs). The subdomain CPOs correspond to quartz grains related by the dauphiné twin law. They are inferred to have inherited their crystallographic orientations from the pseudo-hexagonal arrangement in a coesite precursor phase. Furthermore, the differing CPOs between subdomains have a misorientation of c. 90°, consistent with twinning in the former coesite.

Schertl, H.-P., Schreyer, W. and Chopin, C. (1991) The pyrope-coesite rocks and their country rocks at Parigi, Dora Maira Massif, Western Alps: detailed petrography, mineral chemistry and PT-path, Contributions to Mineralogy and Petrology 108(1–2): 1-21

Prograde UHP metamorphism in felsic and mafic lithologies and clues to pre-Himalayan metamorphism in the Tso Morari dome, Ladakh, Himalaya

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Ultra-high pressure (UHP) metamorphism has long been associated with deep subduction. UHP minerals, such as coesite and microdiamond, are often found in discrete mafic units, hosted in larger scale continental terrains, such as in the mafic eclogites of the Tso Morari dome, Ladakh, Himalaya. Terrains such as these have commonly been overprinted by amphibolite facies, Barrovian metamorphism, so their early history is difficult to decipher. Samples of mafic eclogite dykes hosted in low-strain metagranite were collected from the centre of the Tso Morari dome in Ladakh, Himalaya, where the granite has been observed to transition into granite gneiss towards the high-strain mafic–felsic lithological boundary. All three of these lithologies are shown to preserve high pressure (HP) metamorphism indicating that the entire unit must also have been subducted to UHP conditions.

Low-strain metagranites provide a window into the early history of the rocks, where feldspar, white mica and pseudomorphs after cordierite preserve evidence of hydrothermal alteration prior to HP metamorphism. Kyanite inclusions within garnet also indicate that the high-Al bulk composition of the granite gneiss must have been achieved prior to garnet growth, also indicating that hydrothermal alteration prior to garnet growth may have been significant.

Elemental zonation within garnets from mafic eclogite and granite gneiss protoliths show a similar zoning pattern in rocks of different bulk compositions, indicating that both rock types share a similar prograde high-pressure metamorphic evolution, where highest pressure conditions are preserved in the garnet rims (cf. St-Onge et. al., 2013). Previous modelling of mafic eclogites has shown that there are two possible isopleth intersections for garnet core growth at ca. 20–23 kbar, 520–550 °C and 10–13 kbar, 575–625 °C (Palin, 2013). However, alteration of inclusion assemblages has made it difficult to determine the actual conditions of core growth. Combined modelling of mafic and felsic protoliths, shows that the lower pressure intercept of 10–14 kbar, 410–460 °C is common in both bulk compositions in water undersaturated conditions. Iterative modelling by fractionation of garnet and H_2O with respect to the observed garnet growth zones shows that successive garnet growth zones record higher pressure. Both protoliths record a discontinuity in garnets at their core-rim boundary, between abundant and few inclusions, which is also marked by an annulus of higher Mn attributable to garnet resorption and reincorporation of released Mn. Inclusions of pseudomorphed lawsonite are found at this boundary in mafic samples. All three features may reflect an influx of aqueous fluid at this stage.

Palin, R.M. (2013) Using Metamorphic Modelling Techniques to Investigate the Thermal and Structural Evolution of the Himalayan-Karakoram-Tibetan Orogen. PhD thesis, Oxford University, UK. https://ora.ox.ac.uk/objects/ora:7193

St-Onge, M.R. et. al. (2013) Integrated pressure – temperature – time constraints for the Tso Morari dome (Northwest India): implications for the burial and exhumation path of UHP units in the western Himalaya. Journal of Metamorphic Geology 31(5): 469-504. doi: 10.1111/jmg.12030

PTt-evolution and fluid-rock interaction in the Ordovician Corner Brook Complex (W-Newfoundland, Canada)

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The Corner Brook and Fleur de Lys metamorphic complexes in western and northwestern Newfoundland, Canada, comprise metasedimentary rocks of the partial subducted Humber margin of Laurentia metamorphosed at medium grade and intermediate to high pressure conditions during the collision with outboard arcs. Both complexes are interpreted as parts of an extruded wedge. The Corner Brook Complex (CBC) consists mainly of metapelitic and metapsammitic rocks. Its subdivision into metamorphic zones is supported by calculated PT pseudosections that display a continuous increase in metamorphic grade at intermediate pressure conditions. However, PT paths indicate an evolution of the complex at four stages: (I) Burial of Peri-Laurentian continental crust after closure of the intervening oceanic seaway initiated prograde growth of garnet at 500–550 °C, 6.2–9.3 kbar. (II) Maximum submergence of the CBC at 520–610 °C, 8.2–11.7 kbar was followed by extrusion and exhumation with simultaneous thermal relaxation. (III) Out-of-sequence imbrication within the complex was accompanied by extensive fluid flow and a final stage of thermal relaxation (56–650 °C, 6.9–9.2 kbar) forming a Barrovian-type zonation in the field. As a result the observed peak T mineral assemblages formed and only relics of the former high-pressure stage remained. Interrelated PT paths of opposing direction can be related to stacking in midcrustal levels. (IV) Late emplacement of the complex involved upper crustal folding and large-scale brittle thrusting.

We dated two samples with a predominating stage III assemblage by Rb-Sr mineral isochrones at 429 ± 6 and 440 ± 6 Ma. These ages confirm previous ages (U/Pb zircon 434 Ma, monazite 430 Ma, rutile 437 Ma; Ar/Ar white mica 413–430 Ma; Cawood et. al. 1994) and are related to the Salinic orogenic overprint (~440–420 Ma). Extensive fluid influx had a notable impact on the evolution of various segments of the complex and its extent varied strongly between metamorphic zones. Features produced by fluid-rock interaction are the partial resorption of garnet formed at high pressure and formation of megablasts where fluid flow was intense. By contrast in the Fleur de Lys Complex west of the town of Baie Verte the age of the maximum burial is known (e.g. in eclogite U/Pb metamorphic zircon 465 Ma, Castonguay et. al. 2014; Rb-Sr mineral isochron 461 Ma, Willner et. al. 2015). Nevertheless this complex was also overprinted by Salinic deformation during exhumation, but to minor extent compared to the CBC (Castonguay et. al. 2014).

Castonguay, S., van Staal, C.R., Joyce, N., Skulski, T., Hibbard, J.P. (2014). Geoscience Canada 41: 459-482.

Cawood, P.A., Dunning, G.R., Lux, D., van Gool, J.A.M. (1994) Geology 22: 399-402.

Willner, A.P., Glodny, J., Massonne, H.-J., van Staal, C., Zagorevski, A. (2015) International Eclogite Conference. Rio San Juan 2015, Program with Abstracts 104.

Preserved glass and crystallized melt inclusions in the coesite-bearing UHP eclogite of the Erzgebirge (Bohemian Massif)

Borghini, A.[1], Ferrero, S.[1,2], O'Brien, P.J.[1], Wunder, B.[3], Laurent, O.[4], Günter, C.[1] and Ziemann, M.A.[1]

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For the first time glassy inclusions have been identified along with nanogranitoids in UHP eclogite of the Erzgebirge, Bohemian Massif. The inclusions, 5–25 µm in diameter, range from glassy to polycrystalline and occur as clusters in the inner part of the garnet. The glassy inclusions are generally smaller than the nanogranitoids and they may contain a shrinkage bubble. The mineral assemblage in the nanogranitoids, investigated with Raman spectroscopy and EDS mapping, is biotite, quartz/rare cristobalite, white mica, kumdykolite or (more rarely) albite, and carbonate with variable amounts of kokchetavite and graphite. Kumdykolite is the orthorhombic polymorph of $NaAlSi_3O_8$ and kokchetavite is the hexagonal polymorph of $KAlSi_3O_8$ and they are typical metastable phases of preserved nanogranitoids regardless of protolith or pressure (Ferrero et. al., 2016). The presence of glass and nanogranitoids mineral assemblage suggests that these inclusions were former droplets of melt trapped in the garnet while it was growing. The melt composition is granitic, hydrous, high in alkalis and mildly peraluminous. The preliminary investigation of their trace element signature suggests that the melt was rich in LILE, Pb, Sr, Th, U and LREE.

The studied eclogites occur in lenses and blocks in diamond-bearing gneisses. They range from granoblastic to banded and their main peak assemblage is dominated by garnet and clinopyroxene, variable amount of quartz, ± white mica, ± dolomite and coarse grained rutile as accessory. The garnet, in the same microstructural position of the melt inclusions, contains also polycrystalline or palisade quartz inclusions surrounded by radial cracks, which are interpreted as quartz pseudomorphs after coesite. Thus the melt entrapment took place at UHP conditions in the coesite stability field.

Further investigations on the melt geochemistry will improve our understanding of the melting processes at mantle depths and, in general, provide new constraints for melt-rock interaction in the mantle in deep continental subduction-collisional settings.

Ferrero, S., Ziemann, M.A., Angel, R.J., O'Brien, P.J., Wunder, B. (2016) Kumdykolite, kokchetavite and cristobalite crystallized in nanogranites from felsic granulites, Orlica-Snieznik Dome (Bohemian Massif): Not evidence of ultrahigh-pressure conditions. Contributions to Mineralogy and Petrology 171: 3-12.

Halogens in metasomatic garnet websterite from the Western Gneiss Region, Norway: implications for subcontinental mantle metasomatism

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Exhumed, subducted crustal terranes record the most extreme metamorphic conditions that continental rocks are known to experience. Fluid flow and fluid-rock interaction under UHP eclogite facies conditions during subduction is evidenced by vein-associated garnet websterites in the Western Gneiss Region (WGR), Norway. Our study focuses on the metasomatism of ultra-high-pressure (UHP) rocks in the WGR; in particular, on determining the signature, source and recycling of halogens at the interface between crust and mantle. Samples analysed are from eclogite facies mafic-ultramafic bodies hosted within the WGR country rock. Anhydrous (garnet, quartz, olivine) minerals contain halogens at levels exceeding depleted MORB mantle concentrations, with the major fraction of halogens hosted in multi-phase inclusions. These results are consistent with a previous study of halogens in eclogite facies fluid inclusions in Norwegian eclogites (Svensen et. al., 2001). The halogen compositions show similarities to brine inclusions in diamonds (Johnson et. al., 2000) and mantle peridotite xenoliths from Siberia (Broadley et. al., 2018). Subcontinental mantle metasomatism may be associated with UHP, supercritical fluids derived from subducted, eclogite-facies, continental crust, rather than oceanic crust, as the continental crust is a greater source of halogens and water which characterise mantle metasomatism.

Svensen, H., Jamtveit, B., Banks, D.A., Austrheim, H. (2001) Halogen contents of eclogite facies fluid inclusions and minerals. J. Met. Geol. 19: 165-178.

Johnson, L.H., Burgess, R., Turner, G., Milledge, H.J., Harris, J.W. (2000) Noble gas and halogen geochemistry of mantle fluids: comparison of African and Canadian diamonds. Geochimica et Cosmochimica Acta 64: 717-732.

Broadley, M.W., Barry, P.H., Ballentine, C.J., Taylor, L.A., Burgess, R. (2018) End-Permian extinction amplified by plume-induced release of recycled lithospheric volatiles. Nature Geoscience 11: 682-687.

Application of the triple oxygen isotope system to mantle materials

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Oxygen isotope ratios ($^{18}O/^{16}O$) have been used in numerous studies of mantle lithologies to estimate 1) the protolith 2) the source of metasomatizing fluids, 3) temperature of formation, and 4) degree of equilibration between coexisting minerals. The $\delta^{18}O$ value of mantle olivine comprises a very restricted range (Mattey et. al., 1994), so that even subtle deviations from this 'canonical' value indicate some form of contamination. Eclogites span a range of 2–8‰ and suggest an altered oceanic crust or sediment protolith (MacGregor and Manton, 1986). However, the $^{18}O/^{16}O$ information alone provide limited information. The addition of the novel $^{17}O/^{16}O$ ratios provide additional constraints on mantle minerals, expanding the isotope data from a one-dimensional line to a two-dimensional field.

Our preliminary results demonstrate the utility of triple oxygen isotope analyses of mantle materials. OPX and olivine mineral separates from spinel peridotites are generally well-behaved for ^{17}O, with $\Delta'^{17}O$ values (see Sharp, 2013 for nomenclature) of -0.05 ± 0.01‰, the same as presumed mantle olivine. We see that CPX is out of $\delta^{18}O$ equilibrium in all cases. The $\Delta^{18}O$ values for olivine, garnet, OPX, CPX and phlogopite from a granular garnet peridotite (Kimberley, SA) suggest complete $^{18}O/^{16}O$ disequilibrium, but the $\Delta'^{17}O$ values of all samples are again typical of that of the average mantle. In contrast, a sheared peridotite from the same location has $\Delta^{18}O$ values in equilibrium at ~950 °C, but $\Delta'^{17}O$ values that suggest mixing between a low $\Delta'^{17}O$ – low $\delta^{18}O$ and a high $\Delta'^{17}O$ – high $\delta^{18}O$ component. One mantle eclogite sample, a grospydite from Smyth and Hatton (1977), has a wide range of $\Delta'^{17}O$ values but $\delta^{18}O$ values that appear in equilibrium. It has been suggested that the wide range in $\delta^{18}O$ values could suggest an origin for the eclogites from subducted altered oceanic crust (MacGregor and Manton, 1986). We are measuring the triple oxygen isotope values of altered oceanic crust in order to identify potential sources for the ^{17}O isotope disequilibrium seen. The $\Delta'^{17}O$ values of these samples can be used to support such an idea. In general, the $\Delta'^{17}O$ values of altered oceanic crust are higher than typical mantle. Low $\Delta'^{17}O$ values may be indicative of subducted sedimentary material.

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Geochronology and mineral geochemistry of titanite from retrograde eclogite, Southern Altyn Tagh HP/UHP belt, Western China

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Multiple growth zones of garnet and titanite grains were identified in retrograde eclogite from the Danshuiquan area in the southern Altyn Tagh HP/UHP belt. We conducted trace element microanalysis of garnet and titanite, and U–Th–Pb analyses of titanite. The garnet zonation is characterized by a core-to-rim increase in FeO and MgO contents and decrease in CaO and MnO contents, indicating a decompression and heating process. The garnet shows relatively flat heavy rare earth element (HREE) patterns and a slightly negative Eu anomaly with HREE decreasing from the core to rim. The titanite is homogeneous in major elements, but has different REE pattern from core to rim. The dark cores of titanite exhibit relatively low REE contents, no Eu anomaly and an obvious HREE deplection, suggesting that they grew contemporaneously with garnet and in absence of plagioclase, consistent with the growth features that occur during the transition from eclogite facies to granulite facies. The light rims of titanite have higher REE contents with a moderately negative Eu anomaly and also an obvious HREE deplection, suggesting that they grew at the granulite facies stage when garnet and plagioclase were present. U-Pb ages of 493 ± 21 Ma and 447 ± 34 Ma, respectively, were performed on titanite core and rim, representing the peak metamorphic age and the granulite facies overprint according to the characteristics of trace elements studied. The two ages of 493 ± 21 Ma and 447 ± 34 Ma are identical to the respective peak and retrograded granulite facies ages of HP/UHP rocks in the southern Altyn Tagh HP/UHP belt (Liu et. al., 2012; Cao et. al., 2019), indicating a similar and interrelated evolution. Therefore, the compositional zonation profiles of garnet and titanite developed in response to changing pressure and temperature conditions during subduction and exhumation, provide extensive records of the thermal, chronological and chemical histories of the host retrograde eclogite.

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Discovery of early-Paleozoic, retrograded eclogite at Nuomuhong area from the East Kunlun Orogenic belt, Qinghai Province, China: an evidence of exhumation from deeply-subducted oceanic crust

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In the last few years, several eclogite blocks have been reported in the East Kunlun Orogenic Belt (EKOB) located in the northwestern part of the China Centre Orogenic Belt (Meng et. al., 2013; Qi et. al., 2014; Song et. al., 2018). Recently, we have recognized another retrograded eclogite block in Nuomuhong area, eastern part of EKOB.

The eclogite sample mainly consists of garnet, clinopyroxene, orthopyroxene, amphibole, plagioclase, biotite, a little epidote, rutile, titanite, ilmenite, apatite and some Fe-oxides. Six stages were recognized: (1) Prograde amphibolite-eclogite facies: Grt I + Cpx I_a (Omp) + Amp I + Ep + Rt + [Lws (Lawsonite which has neither been found in the matrix nor is it included in garnet, there may exist reaction from lawsonite to epidote)]; (2) Peak eclogite facies: Grt II + Cpx I_b (Omp) + Rt; (3) Retrograde HP granulite facies: Cpx II_a (low-sodic) + Pl I + ilm; (4) Retrograde granulite facies: Cpx IIb (low-sodic) + Opx + Pl II + ilm; (5) Retrograde granulite-amphibolite facies: Amp IIa + Pl III + ilm; (6) Retrograde amphibole facies: Amp IIb + Pl IV + Bt + ilm. P–T conditions have been calculated with THERMOCALC. The calculation showed that eclogite experienced peak stage at T = 570 °C, P = 25.5 kbar, then went through a retrograde path of decompression and heating in the course of exhumation.

The eclogite samples all plot in the basalt field of the TAS diagram. The REE distribution pattern is flat, with a slight enrichment in LREE. The $(La/Yb)_N$ is 1.17–2.12 and δEu is 0.92–1.05, showing geochemical characteristics that are similar to MORB. Two different groups of metamorphic ages (zircon U-Pb ages by SHRIMP) have been obtained from the eclogite samples: 459.1 ± 7.6 Ma (MSWD = 0.33) and 416.9 ± 4.0 Ma (MSWD = 1.2). The first 459.1 ± 7.6 Ma age is earlier than other continental subduction eclogite samples discovered in EKOB (recording a peak, eclogite-facies, metamorphic age of 425–428 Ma) and associated with Center East Kunlun Ocean northward deep subduction. The second 416.9 ± 4.0 Ma age may represent the amphibolite-facies retrogression of the eclogite samples during the exhumation, when intracontinental environment replaced the ocean crust subduction environment in the Nuomuhong area, eastern part of EKOB.

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Epidote spherulites and radial euhedral epidote aggregates in a metavolcanic breccia in the Dabie UHP metamorphic belt (China): implication for dynamic metamorphism

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Epidote spherulites are identified in a greenschist facies metavolcanic breccia enclosing a body of coesite-bearing eclogite at Ganghe in the Dabie ultrahigh-pressure metamorphic belt, east-central China. The epidote spherulites are formed by fibrous, radially arranged, and rare earth element (REE)-rich epidote crystals (REE = 0.13–0.36 (or slightly higher) cations per formula unit, cpfu) and interfibrillar REE-poor epidote (REE ≤0.10 cpfu). Some of the epidote spherulites are overgrown by radially arranged euhedral epidote crystals, which also form aggregates around preexisting quartz, plagioclase, and/or epidote. The epidote grains in such aggregates display oscillatory zoning, with REE content varying from a negligible amount to about 0.44 cpfu. Epidote also occurs as REE-poor individual euhedral crystals about the radial epidote aggregates or form loose clusters of randomly oriented crystals. Thermodynamic modeling of the mineral assemblages in the plagioclase pseudomorphs and in the matrix shows that they formed at greenschist facies metamorphic conditions (435–515 °C and 5–7 kbar). The spherulites and radial euhedral crystal aggregates, however, do not belong to these assemblages and are non-equilibrium textures. They imply crystal growth under large degrees of supersaturation, with relatively low ratios of the diffusion rate (D) to the crystal growth rate (G). At low D/G ratios, spiky interfaces are favourable for diffusion-controlled growth and the resultant texture is a collection of spikes around a growth center, forming a spherulite. The change of epidote texture from spherulite to radial euhedral crystal aggregates implies a decrease of supersaturation and an increase of D/G, such that the crystal morphology was controlled by its crystallographic structure. The crystallization of the individual epidote grains corresponds to a further drop of supersaturation and a further increase of the D/G ratio, approaching to the equilibrium conditions. Transiently higher P-T conditions are inferred from the spherulite-forming reactions, relative to the P-T estimates for the equilibrium assemblages. The fibrous crystals in the spherulites having relatively large interfacial energies would inevitably adjust their shapes to equilibrium ones with low interfacial energies if the P-T-H_2O conditions were maintained for a sufficiently long period of time. The non-equilibrium epidote aggregates likely formed in response to P-T and fluid pulses, possibly related to seismicity.

UHP eclogite-facies feldspathic rock from Yuka terrane in North Qaidam orogenic belt, NW China

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The North Qaidam orogenic belt (NQOB) is known as an Early Paleozoic UHP metamorphic belt in northwest China. It consists of predominantly gneisses, schists and marbles with minor lensoid eclogite and garnet peridotite. The detailed metamorphic P–T evolution of eclogites has been well defined. However, the evolution history of their host rock is not well constrained yet.

In this contribution, we present detailed petrographic study on a feldspathic rock in Yuka terrane, the western fragment of NQOB, and defined a clockwise P–T path for it. This rock is interbedded with an UHP coarse-grained phengite eclogite and they form a large composite lens hosted by regional granitic gneiss. The feldspathic rock mainly consists of Na-rich Pl, Phn, Grt, Amp, Qz and minor Rt, Zo, Bt and Cpx. The amount and grain size of Grt porphyroblasts increase toward the contact boundary with eclogite. In order to study whether the feldspathic rock underwent UHP metamorphism and its P-T path, as well as its relationship with eclogite, two samples were collected: Sample A is from the core of the rock, far away from the eclogite, whereas sample B is adjacent to the eclogite. Compare to sample A, sample B contains less amount of Qz, Bt, Phn and Pl, more amount of Amp and Grt, and larger grain size of Grt. Grt in sample A clearly shows core-rim structure with core-rim decreasing X_{Grs} and X_{Sps} and increasing X_{Prp}. The optically dark-colored core contains abundant inclusions of Bt, Phn (3.32–3.34), Qz, Ab, Rt, Ap, Ep and Sph, whereas the light-colored rim contains a few inclusions of Phn (3.40–3.48), Qz and Rt. Grt in sample B is obviously larger (2–5 mm in diameter) and show core-mantle-rim structure, in which, the core and the mantle part are almost the same as the core and rim of Grt from sample A in chemical composition and mineral inclusions, but overgrows an extra darker and wider rim with abundant inclusions of Amp, Bi, Phn (3.34–3.38), Rt and Qz and an increase in X_{Grs} and X_{Sps} as well as a slight decrease in X_{Prp}.

By phase equilibrium modelling method, we obtained P = 1.21–1.24 GPa, T = 595–622 °C and P = 1.21–1.25 GPa, T = 592–644 °C for prograde stages, and P = 2.88–2.97 Gpa, T = 680–686 °C and P = 2.82–3.32 GPa, T = 612–634 °C for peak stages of sample A and B respectively; And P = 1.32–1.37 GPa, T = 656–685 °C for retrograde stage of sample B.

Zircons from the feldspathic rock show core-rim micro-structure. The cores display sector and fir-tree zoning, contain Grt, Omp, Phn and Rt inclusions and exihibit flat HREE patterns without negative Eu anomalies; The rims are narrow, have lighter color and contain inclusions of Phn, Ap, Qz and Rt. LA–ICP–MS dating yielded two metamorphic ages of 435 ± 5 Ma and 400 ± 3 Ma on core and rim respectively, almost the same as the results of the adjacent elogite. All these data suggest that the feldspathic rock are *in situ* with the eclogite and they underwent UHP metamorphism together, and the fliud activity in the contact zone during the exhumation results in the retrograde metamorphism of the feldspathic rock.

The existence of carbonate and silicate melts in UHP eclogite from Erzgebirge in central Europe

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Carbonate and carbonate-silicate melts can transport different types of elements than aqueous solutions and hydrous silicate melts, providing a different means for mass transfer and crust-mantle interaction in subduction zones. Although previous studies have demonstrated the existence of carbonate melts in subduction zones, little is known about their behaviors in subduction zones. We carried out a combined study of zircon U-Pb ages, trace elements, Hf isotopes and inclusion analyses as well as whole-rock geochemistry, rock-forming mineral chemistry and inclusion analyses for carbonate-bearing UHP eclogites from Erzgebirge in central Europe. The results not only provide evidence for the existence of carbonate and silicate melts, but also place constraints on the timing, mechanism and effect of crustal anatexis in the deep continental subduction zone.

Coesite was found in garnet and zircon of our eclogite samples, confirming that the eclogites underwent UHP metamorphism. Garnet and omphacite exhibit different extents of chemical zoning, indicating their formation by multiple episodes of metamorphism. Melt structures occur in the eclogites, indicating the existence of anatexis. Multiphase crystal inclusions occur in garnet and omphacite, and they often display euhedral to subhedral shapes and occasionally approaching a negative morphology of the host mineral. A few of them are surrounded by radical cracks, textures characteristic of decrepitation. They can be classified into two types: (1) different proportions of silicate minerals such as quartz, mica, plagioclase, biotite, amphibole and chlorite; (2) carbonates and different proportions of silicate minerals. The occurrence of these multiphase carbonate and silicate inclusions indicates both carbonate and silicate melting during mineral growth under UHP conditions.

Two episodes of zircon growth were identified: (1) dark-CL zircon cores, exhibiting high Th and U contents and high Th/U ratios of 0.32–1.69, steep HREE patterns and variable negative Eu anomalies, containing inclusions of coesite/quartz, garnet, omphacite, calcite, magnesite, apatite, rutile, kyanite and phengite as well as multiphase crystal inclusions; (2) bright-CL rims, low Th contents and low Th/U ratios of 0.06–0.75, relatively flat HREE patterns and relatively lack of negative Eu anomalies, and containing single-crystal mineral inclusions of coesite/quartz, clinopyroxene, plagioclase, K-feldspar, calcite and apatite as well as multiphase crystal inclusions. High Th/U ratios and the presence of multiphase crystal inclusions indicate zircon growth during the anatexis under UHP conditions. They gave consistent U-Pb ages of ca. 340 Ma, consistent with their formation during the UHP metamorphism. The occurrence of coesite and magnesite in zircon and aragonite in garnet indicates that the UHP metamorphism took place at a depth of $>$ 16–175 km. The Ti-in-zircon and Zr-in-rutile thermometers as well as the Fe-Mg exchange thermometer of Grt-Cpx pair yield consistent temperatures of ca. 1000 °C. Thus, the carbonate and silicate melts were produced at ca. 4.5 GPa and 1000 °C during the peak UHP metamorphism or the initial exhumation of deeply subducted continental crust. The silicate melts were produced by dehydration melting of hydrous minerals, whereas the occurrence of carbonate melts indicates the involvement of carbonate during the crustal anatexis and thus has bearing on the recycling of crustal carbonate into the mantle. The coexistence of carbonate and silicate melts in the UHP eclogites provide an excellent window for studying the fluid action in the continental deep subduction zone.

Garnet Lu–Hf and Sm–Nd geochronology: a time capsule of the metamorphic evolution of eclogites

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Garnet is one of the indispensable candidates in investigating the history of geological processes that are encapsulated in rocks. Compositional zoning in metamorphic garnet can be used to elucidate quantitative *P–T* paths and provide direct estimates of mineral growth rates that can be linked directly to tectonic processes. Linking *P–T* information from garnet-bearing assemblages with garnet Lu–Hf and Sm–Nd geochronology is becoming increasingly powerful (Cheng, et. al., 2008, 2018a, 2018b; Lapen et. al., 2003). Technological advances in chemical procedures and mass spectrometry have allowed for the precise determination of the Nd–Hf isotope composition of small sample amounts, which has boosted the growth of Lu–Hf and Sm–Nd geochronology over the last two decades (Baxter et. al., 2017). When combined with petrographic and chemical observations, Lu–Hf and Sm–Nd ages of garnet hold the promise of providing unprecedented resolution in the timing and rate of metamorphism (Cheng, et. al., 2018a, 2018b; Baxter et. al., 2017), although there are many potential pitfalls in the acquisition and interpretation of these data. This presentation provides a brief review of the basic science and development of the garnet Lu–Hf and Sm–Nd systems, highlights the potential of garnet Lu–Hf and Sm–Nd geochronology, and reviews several crucial issues related to the complexities of interpretation of the radiometric ages. Several case study using combined garnet Lu–Hf and Sm–Nd dates for eclogites bearing diverse metamorphic histories from various orogenic belts are presented

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Exploratory modelling of common crustal rock densities at ambient eclogite facies P-T conditions and some natural examples in a giant UHP terrain: Implications for buoyancy and collision tectonics

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HP and UHP terranes in collision belts are often dominated by felsic rocks (granitoid gneisses) whose physical properties must be a major factor in the tectonic evolution of the orogeny, yet their HP and UHP mineralogy is usually poorly preserved. This study focusses on rock density, which influences buoyancy and hence the tendency to subduct or educt. Bulk compositions of common granitoid gneisses and metabasic eclogites in the Western Gneiss Region (WGR) giant HP-UHP terrane, Norway, were used to generate pseudosections over a wide range of P-T conditions. These were used to generate rock densities over the same P-T ranges. For rare field examples where HP/UHP mineral parageneses have survived retrogression, or where experimental results are available, the mineral assemblages are well reproduced by the model calculations. The density pattern for all modelled compositions shows a strong gradient across the transition from medium- and low-T facies to eclogite facies, while under eclogite facies conditions a wide P-T realm has densities that vary little, except for a sharp step at the quartz-coesite transition. Hence if metamorphic transformations are efficient during subduction most lithologies will undergo a significant, rapid increase in density above about 17 kbars. Mafic rocks quickly become negatively buoyant with respect to mantle rocks (densities >3.5 $g.cm^{-3}$), while common granitoid lithologies achieve densities of 3.05–3.12 $g.cm^{-3}$ under quartz-stable conditions and values slightly less than mantle peridotites (~3.35 $g.cm^{-3}$) under the coesite-stable P-T conditions pertaining in the northernmost WGR. Hence felsic compositions would have tended to remain positively buoyant with respect to the mantle, unless the latter was substantially serpentinised. Evidence from orogenic peridotites in the northern WGR mitigates against a serpentinised mantle above the subduction zone, but this does not rule out a low-density serpentinite mantle wedge close to the lower-P, low-T southern WGR. However, kilometre-size eclogite massifs are common in the WGR and these may have contributed to a higher average crustal density.

The pseudosections give insights into the evolution of mineral assemblages and density during retrogression. More mafic compositions favour low phengite, omphacite-rich parageneses that require ingress of aqueous fluid to retrogress to lower density parageneses, while more K-rich, Ca-poor compositions tend to have more phengite at high pressure, which would decompose spontaneously (and dehydrate) upon decompression. If eduction was driven by forces other than simple buoyancy, such rocks would have undergone rapid reduction in density, enhancing uprise through increased buoyant upthrust. However, where lack of water retarded retrogression in mica-poor lithologies, higher densities may have persisted. Water plays a key role in density and buoyancy evolution of granitoid-dominated, subducting crust. Evidence from the southern WGR indicates that transformation of dry, Proterozoic granulite facies metagranitoids to dense, eclogite-facies parageneses required a substantial ingress of water to enhance reactivity. Limits to water availability resulted in survival of unreacted, low-density rock volumes. On balance, it seems that the metamorphic transformations predicted by this modelling would, if efficient, have substantially increased the density of the predominant mass of felsic rocks in the WGR, but not to the extent that it could become negatively buoyant. During eduction, the sharp density gradient in P-T space associated with feldspar formation and reduction in garnet would have enhanced buoyancy and perhaps acted to accelerate exhumation. Partial melting at this stage would have further enhanced the buoyant upthrust.

Partial melting of Variscan eclogites: petrological and geochronological constraints from the French Massif Central

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Partial melting of mafic eclogites, although rarely described (e.g. Wang et. al., 2014), is expected to have important implications for their exhumation and for the rheology of deeply subducted lithosphere (cf. Labrousse et. al., 2011).

Mafic eclogites from the French Massif Central (Haut-Allier) display garnet-rich layers that have intriguing similarities and differences with respect to the surrounding eclogites. Both are dominated by garnet, omphacite and rutile, but the host eclogite also contains significant proportions of kyanite and muscovite and quartz. Garnet from the host rock are centimetre sized and are strongly chemically and optically zoned with an epidote-rich core. Garnet in the garnet-rich layer is millimetre sized with a slight zoning similar to that of the epidote-free rim of the large garnets. Kyanite is common in the matrix of the host eclogite but is never observed in the garnet-rich layers. The latter are distinctively enriched in Ti-bearing minerals (rutile and ilmenite).

Phase diagram modelling shows that these layers can be attributed to localized melting of the eclogite, and a subsequent melt-loss, due to focussed influx of H_2O-fluids probably associated with localized deformation. This occurred at P–T conditions above 27 kbar and 850 °C. Partial melting involved muscovite, kyanite and quartz to produce a silica-rich melt and a mafic residue enriched in titanium. Muscovite dehydration melting alone cannot explain the total consumption of kyanite in the garnet-rich layer and external input of water is therefore required.

This discovery, so far unique in the Massif Central, may be put in relation with the existence of high-pressure trondhjemitic melts, described since 1978 by Nicollet, Leyreloup and Dupuy in another part of the Massif. Consequently, Variscan partial melting of mafic eclogites could be widespread in the French Massif Central, having consequences for the initiation of the exhumation processes. These results will be discussed in the light of new U-Pb zircon and apatite geochronological data.

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Ultrahigh Pressure Metamorphism: Insights from Natural Mineralogical Assemblages and Experiments

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Discoveries of first coesite (Chopin, 1984) and microdiamond (Sobolev and Shatsky, 1990) in metamorphic rocks of continental affinities led to the formulation of the UHP metamorphism concepts which provide better understanding of Earth dynamics. The major fraction of the UHP minerals is hidden inside of the deep Earth, and therefore, we know only about those which are incorporated in mantle xenoliths, or occur as inclusions in deep-seated kimberlitic diamonds. Diamond due to its chemical inertness and stability to decompression can be undoubtedly considered as a perfect “container” for other UHP minerals.

Most UHP minerals lose their unique structural characteristics during different geological events accompanied by decompression, melting, metamorphic reactions and geochemical processes. Though these processes can be easily observed in larger scales of the rock outcrops, the understanding of minerals microstructure in atomic scale plays the most important role. This is because it reflects their growth and destruction as matter changes from one state to another at certain pressures and temperatures conditions. One of the most exciting earth materials indicating deep subduction and exhumation through phase transformation and fluids assistance – are carbon, hydrocarbon and their polymorphs. Many UHPM terranes were recognized due to finding of diamond within metamorphic rocks. Furthermore, detailed studies of these diamonds revealed their formation from carbon-hydrocarbon-rich fluids and provided a new insight into fluid-rocks and crust-mantle interactions (Sumino et. al., 2011).

Diamond, coesite/stishovite (?), TiO_2 with alfa-PbO structure, majoritic garnet, pyroxenes and olivine (with exsolution lamella formed due to decompression) remain the most indisputable minerals which directly reveal their ultrahigh pressure genealogy. This is because these minerals were studied experimentally and their phase transformations at verified PT-conditions can be projected from experimental setups to the larger scale of metamorphic terranes. Last decade diamond, moissanite, native metals, silicides and many other unusual minerals were found in ophiolitic chromitites and in some mafic magmatic rocks and crustal metamorphic rocks. Similar minerals were found in Precambrian metamorphic rocks, where they are considered as geologically recycled fragments of meteorites and products of the meteoritic bombardments. Reports of possible laboratory and industrial materials contamination are still under consideration.

How can we find a best possible way to avoid artifacts in studying these extremely interesting and complicated mineralogical assemblages? My presentation will consider different approaches in studying of ultra-high pressure minerals in metamorphic rocks and their experimental analogs through observations under optic microscope, electron scanning and transmission microscopy, focused ion beam, spectroscopy and synchrotron assisted techniques.

Ultra-deep subduction and fluid behaviour of felsic and mafic granulites from the South Altun orogen, W China

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The South Altyn orogen in West China contains UHP terranes formed by ultra-deep (> 150–300 km) subduction of continental crust. Felsic granulites with mafic granulites and ultramafic interlayers occur as tectonic blocks in the HP–UHP belt. Felsic granulites mostly consist of Grt, Ky, Per, Pl, Qz, Rt, Bt and minor Spl + Crn. Four generations of mineral assemblages (I–IV) were distinguished. The first generation (I) represented by the remarkable zoning in garnet core (I-a) and mantle (I-b) is interpreted to record an early prograde evolution to the peak UHP eclogite facies stage with *P–T* conditions of 3–7 GPa/700–1100 °C, where the fluid-phase is modelled to be absent. The second generation characterized by the formation of coronate/atoll-like garnet around kyanite or perthite (II-a), and by the formation of ternary feldspar and plagioclase coronas (II-b). The former is recovered to witness the decompression in the suprasolidus eclogite facies conditions from 2.8 to 2.4 GPa at 1000 °C, and the latter is suggested to reflect the decompression in HP–UHT granulite facies conditions (e.g. 2.4–1.75 GPa/970–1040 °C). The third generation marked by the formation of micro-grained aggregates of Spl + Crn + Pl (III) between Grt and Ky reflects a further rapid decompression to LP granulite facies conditions at ~0.3–0.4 GPa/900–1000 °C. And the fourth generation characteristic of the later growth of Bt together with very fine grains of Qz + Kfs (IV), is interpreted to indicate an isobaric cooling evolution with residual melt crystallization. Mafic granulites studied are composed of Grt, Cpx, Pl, Amp, Rt, Qz, Ky and Spr, which have experienced similar decompression evolution to felsic granulites from eclogite facies conditions to HP–UHT granulite facies conditions and further to LP–UHT granulite facies conditions. The HP–UHT conditions are constrained to be 2.3–1.6 GPa/1000–1070 °C based on the mineral assemblages of Grt + Cpx + Rt + Pl + Amp ± Qz and mineral compositions including anorthite in plagioclase (XAn = 0.52–0.58), jadeite in clinopyroxene (XJd = 0.20–0.15) and TiO_2 in amphibole (Ti^{M2} = 0.14–0.18). The LP–UHT conditions are identified from the symplectites of Spr + Pl + Spl, formed by the metastable reaction between garnet and kyanite at <0.6–0.7 GPa/940–1030 °C. Geodynamically, it is possible that a continental slab represented by the felsic granulites enclosing mafic granulites may have subducted to depths of >120–200 km, and driven by the buoyancy force, the detached continental rocks would exhumed rapidly.

Precursors and PT evolution of garnet peridotites and mantle eclogites from orogenic zones

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Serpentinized garnet/spinel peridotite with lenses of eclogite and garnet/spinel pyroxenite are commonly present in amphibolite-granulite facies felsic rocks along ancient orogenic zones. They are exhumed due to their involvement into buoyant (felsic) crustal material buried into mantle depths at the end of subduction orogeny or as results of peridotite hydration that severed as a medium to transport and exhume the dens bodies of HP(UHP) rocks. Studies from many orogenic zones showed that the HP(UHP) bodies of mafic and ultramafic rocks can derive both from subducted slab and orogenic mantle. To distinguish geotectonic position of their source area, geochemical criteria, mainly their composition with cratonic mantle or oceanic lithosphere is commonly compared. It is also accepted that both oceanic peridotite and orogenic mantle peridotite above subduction zone are subject of permanent metasomatism and fluid infiltration that change their original composition. In addition, only small portion of these mafic and ultramafic rocks are exhumed, which make it difficult to recognize their source area exclusively based their geochemistry.

This contribution focuses on minerals and their textures that are preserved in HP(UHP) mafic and ultramafic rocks and allow to decipher their PT trajectory and possible source area from which the rocks were sampled and exhumed. Diversity of the exhumed mantle bodies are controlled by the typical long-leaving, low-temperature geothermal gradient in subduction zone, where mantle rocks at the interface of subducted slabs are isobarically cooled down. Depending on their sampling by down or upgoing crustal materials in the subduction channel, they can undergo prograde HP(UHP) metamorphism or simply exhume from their source area. As the orogenic mantle above the subduction slab is subject of permanent infiltration by fluids, derived from subducted crustal material, the host peridotite contains layers of various compositions that are crystallized or recrystallized into garnet pyroxenite, eclogite, garnetite etc.

Metamorphic evolution of mafic and ultramafic bodies that are usually part of a coherent crustal slices or occur within a dismembered complex might be further complicated by heating during their exhumation. In most cases, this process occurs when subduction of oceanic slab is over and starts continental collision. Slowing down or stopping subduction of slab during continental collision can leads to slab breakoff with subsequent mantle wedge corner flow and mantle upwelling that results heating of partially exhumed HP(UHP) rocks. The degrees of thermal overprint of HP(UHP) rocks, both of crustal and mantle lithologies, depend on the depth to which they were exhumed and their position and distance from the heat source (ultramafic intrusions). As the mantle derived magma emplaces and interacts with crustal rocks still in the mantle depth, it can undergo granulite-amphibolite facies metamorphism during its crystallization and possible exhumation. If age or field relations of such rocks are not clear, they could be easily misinterpreted and considered as part of old basement units.

Multi-stage metamorphic events of HP rocks in Danshuiquan, south Altyn Tagh, implications for differential exhumation

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The South Altyn Tagh is one of the typical HP-UHP metamorphic belts in China. HP-UHP rocks in south Altyn Tagh mainly located in Jianggalesayi, Keqike Jianggalesayi, Younusisayi areas to the west and Yinggelisayi, Danshuiuqan areas to the east. UHPM evidences including coesite, Ru + Cpx exsolutions in garnet, Amp+Pl exsolutions in sphene and former stishovite have been reported (Zhang et. al., 2002; Gai et. al., 2017; Liu et. al., 2002, 2004, 2005, 2007, 2018). In Jianggalesayi and Keqike Jianggalesayi areas, Zircon U-Pb dating from the eclogites yielded eclogite facies age of ~500 Ma and granulite facies retrograde age of ~450–460 Ma, which indicated a clock wise P-T-t path (Liu et. al., 2012). While in the eastern part of south Altyn Tagh, only one peak stage range from 487–509 Ma were obtained, the retrograde age is still elusive.

In this study, we focus on the retrograde eclogite and its country rock granitic gneiss in Danshuiquan area. The internal structure of zircon from retrograde eclogite revealed by CL imaging displays a distinct zonation, which comprises peak (HP) and retrograde domains. Peak domain with eclogite-facies inclusion assemblage of Grt+Omp+Q+Ru was yielded 502.1 ± 2.2 Ma, and retrograde domain with granulite-facies inclusion assemblage of Grt+Cpx+Amp+Pl+Q+Ru was yielded 484.1 ± 1.6 Ma. For the granitic gneiss, two metamorphic domains with age of 502 ± 3.4 Ma and 485 ± 2.5 Ma were obtained, which is accordant with the retrograde eclogite. In combination with geothermobarometer and pseudosection calculations, the results indicate that the retrograde eclogite were subjected a HP graniulite-facies metamorphism at 1.43–1.64 GPa, 857–916 °C and an amphibolite-facies metamorphism at 0.8~0.9 GPa, 704~756 °C, meanwhile the granitic gneiss yield a clockwise P-T path with a prograde P-T condition of 1.57~1.75G Pa, 770~810 °C, an eclogite-facies condition of 2.2~ 2.5 GPa, 950~1000 °C and a retrograde condition of 1.07~1.33 GPa, 737~831 °C. Thus, two consistent clockwise P-T paths were established.

Contrast the P-T-t path of the eclogite and granitic gneiss in Danshuiquan with the UHP rocks in the west segment of south Altyn Tagh (Jiangalesayi and Keqike Jianggalesayi), all the HP-UHP rocks experienced peak stage metamorphism at ~500 Ma, while the UHP rocks in the Danshuiquan area experienced HP granulite-facies metamorphism at ~483–488 Ma, which is ~30 Ma earlier than the UHP rocks in the west segment. This result implies that the HP-UHP rocks in south Altyn Tagh with character of differential exhumation.

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Mg-O isotopes in jadeite quartzite record large-scale action of metamorphic fluids during continental deep subduction

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Fluids derived from dehydration of subducting crust rocks are critical to mass and energy transports at the slab-mantle interface in subduction zones. Previous studies of UHP metamorphic rocks from the Dabie-Sulu orogenic belt indicate that the continental crust underwent metamorphic dehydration and partial melting during its subduction and exhumation in the Triassic (Zheng, 2009, 2012). In particular, premetamorphic protoliths are dominated by the igneous rocks of Neoproterozoic age and show low to negative $\delta^{18}O$ values relative to normal mantle values. This gave rise to metamorphic fluids with abnormally depleted ^{18}O signatures. In contrast, less is known about the nature of metamorphic fluids derived from metamorphism of metasedimentary rocks. Jadeite quartzites from the Dabie orogen also record deep subduction of the continental crust, and provide sound targets to decipher the source and composition of metamorphic fluids in the continental subduction zone.

We carried out an integrated study of petrography and whole-rock geochemistry, including Mg-O isotopes and zirconology, for coesite-bearing jadeite quartzites from the Dabie orogen. All of zircon U-Pb data for the jadeite quartzties from different outcrops gave consistent discordia lines with upper intercept ages of ~1.9–2.0 Ga and lower intercept ages of 224–235 Ma. Minerals and whole-rocks from the jadeite quartzites show variable $\delta^{18}O$ values from 4.38 to 9.40 ‰. Whole-rock $\delta^{26}Mg$ values vary from -0.43 to 0.61‰, most of them being greatly higher than the normal mantle values. In combination with zircon geochemistry and Mg-O isotope results, we demonstrate that the jadeite quartzites would probably have the same protolith of Paleoproterozoic granites, and underwent physical weathering and large-scale metasomatism by subducting crust-derived fluids with high $\delta^{26}Mg$ values during the continental collision in the Triassic. Specifically, the whole-rock Mg isotopes show significant positive correlations with not only Mg contents but also Rb/La, Rb/Gd and Rb/Nb ratios, but a negative correlation with Na contents. These observations indicate that the metasomatic fluids would probably derive from breakdown of biotite in felsic country rocks (such as paragneiss and/or orthogneiss) during the continental collision. Considering the spatial occurrences of the target samples (~500 km^2), the metasomatic fluids would be produced on a large scale during the continental subduction to subarc depths. Such large-scale of fluid action is for the first time revealed in the continental subduction zone, indicating that fluid flow was significant for continental subduction zones.

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The discovery of glaucophane in Groix island (France) in 1883: an example of interference between science, nationalism and politics

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The discovery of glaucophanites at Groix, an island on the west coast of Brittany (Armorican Massif, France), is generally attributed to Charles Barrois, the great geologist who was the first to describe them scientifically in 1883 and 1884 (Barrois, 1883b). However, the original correspondence of Ferdinand Fouqué with François de Limur, a notable of the city of Vannes, in Brittany, amateur archaeologist and mineralogist, shows that the reality was different. An unpublished letter from De Limur, dated October 8, 1883, designates him as discoverer of the glaucophane-bearing rocks of Groix. The letter, accompanied by samples, was addressed to Ferdinand Fouqué, the president of the *Société minéralogique de France*. François de Limur submitted a note to be inserted in the *Bulletin de la Société minéralogique de France*, but Fouqué did not publish it. At the same time, De Limur had submitted his discovery to the German petrographers Ferdinand Zirkel of Leipzig and Arnold von Lasaulx in Bonn, with whom he had continuous exchanges. In 1879, Zirkel entrusted the study of rocks from Brittany to an American student, Charles Withman Cross, who became famous after 1903 as one of the designers of the CIPW norm; François de Limur provided the samples and guided him in the field (Cross, 1881). At the end of 1883, Zirkel and von Lasaulx identified glaucophane under the polarizing microscope in De Limur's specimens. Arnold von Lasaulx wrote a brief note on the subject, in which he explicitly attributes the discovery of the rocks to De Limur (Lasaulx, 1883). De Limur's collection, stored today at the Rennes University, contains samples of glaucophanites, some with pseudomorphs after prismatic lawsonite, a mineral discovered 12 years later (Ransome, 1895), and which De Limur apparently interpreted as pseudomorphs after andalusite.

Meanwhile, Charles Barrois undertook the survey of the geological map of Lorient at the scale of 1:80 000, to which the island of Groix belongs. After having neglected the note submitted by De Limur, Fouqué favoured the study of the glaucophanites by Charles Barrois (Barrois, 1883b), who claimed to have observed them during his survey and then minimized, if not dissimulated, the contributions of François de Limur and Arnold von Lasaulx.

To understand the attitude of Ferdinand Fouqué, it should be known that he was a convinced republican, and thus hated the personalities, like François de Limur, who had supported the regime of Napoléon III. Fouqué personally suffered from hunger during the siege of Paris by the Germans in 1870–1871 – to the point of having to eat his cat –, and he considered the peace treaty with Bismarck's Germany as a betrayal. For Fouqué, the scientific cooperation between François de Limur and Arnold von Lasaulx, a Frenchman and a German, was probably an unbearable humiliation. This story must remind us today, at the time of the rise of nationalisms, that such feelings are not really compatible with scientific ethics.

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Quartz with traces of amorphization: A diffusion-limited form of coesite retrogression?

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Some samples of pyrope-bearing whiteschists from Dora-Maira (Italian Alps), which have reached the diamond P-T stability domain, contain an anomalous form of α-quartz. Frezzotti et. al. (2015) have shown that fifteen α-quartz crystals included in a pyrope and two of the matrix, studied under a Raman spectrometer, show abnormal features, with bands at 485–490 cm^{-1} and 604 cm^{-1}. These anomalies seem typical of incipient amorphization of quartz under pressure, a phenomenon observed experimentally or in impactites, when quartz undergoes pressures much higher than its stability domain, while it remains metastable because of a very unfavourable kinetics, either during a shock (impact) or at low temperature (experiments). For this reason, it has been envisaged that the anomalous quartz of Dora-Maira could result from some sort of shock, or from a low-*T* overpressure at the inclusion scale (Godard et. al., 2011).

New investigations by microgoniometry and electron-backscattered diffraction (EBSD) have led us to the following observations: Inclusions have regular shapes that are not those of garnet negative crystals but correspond to subhedral tabular crystals of coesite. Each inclusion contains a few, typically 1 to 5, crystals of α-quartz, sometimes with the traces of amorphization described above and whose crystallographic orientations, measured with EBSD, are very different from each other within one inclusion. These quartz inclusions developed numerous radial fractures in the host pyrope, as usually seen around coesite. Finally, two inclusions show the palisade-like microstructure that is typical of coesite replacement.

The new data clearly show that the inclusions are quartz pseudomorphs after coesite. Indeed, a low-*P* phase (e.g., α-quartz) that has become metastable at ultrahigh pressure can be partially amorphized, but it is also known that an ultrahigh-*P* phase (e.g., stishovite) can also give an amorphous phase (e.g., amorphous SiO_2) at low pressure, with or without a stable phase (e.g., α-quartz), again for kinetic reasons. The phenomenon has been observed experimentally at low temperature for stishovite. We suggest that it may take place under certain conditions for coesite, which would thus turn into quartz (stable phase) accompanied by minor amorphous silica (metastable) under kinetically unfavourable conditions (low temperature and/or rapid decompression). This hypothesis might explain the recent observation of amorphous silica among the transformation products of coesite in an eclogite of Su-Lu (Taguchi et. al., 2018). Transformation into this type of anomalous quartz, in some cases with relict bands of coesite as what was observed in the Lanterman eclogites (Antarctica) (Palmeri et. al., 2009), is likely to be considered as a particular type of diffusion-limited low-*T* retrogression of coesite.

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Late Neoproterozoic (Ediacaran) metamorphism at the transition from eclogite to amphibolite facies in the Beloretzk Complex, SW-Urals, Russia

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The Beloretzk Metamorphic Complex (BMC) in the Southern Urals was accreted to the former eastern margin of the Baltica protocontinent during the Neoproterozoic Timanide orogeny. Three major units with lenses of metabasite with MORB affinity occur: In the structurally lowermost unit eclogite lenses are intercalated within marble and micaschist and also the Mesoproterozoic Achmerovo granite gneiss. This is overlain by an intermediate unit with garnet amphibolite and garnet micaschist, whereas the uppermost unit is composed of amphibolite, greenschist and metapelite. PT-paths of rocks of the two lowermost units were determined using calculations of PT pseudosections and multivariant reactions showing similar clockwise loops, but significantly different peak metamorphic conditions.

For the phengite-bearing eclogite from the lowermost unit peak PT conditions of 17–19.5 kbar, 520–570 °C (stage I) are followed by a symplectite stage II at 11–12 kbar/570–600 °C. For the Achmerovo granite gneiss in the same unit similar maximum pressures at 16–18 kbar were derived for supposed 500–600 °C. Lower peak pressures occur in the intermediate unit: a garnet amphibolite yields peak conditions of 10.5–15.5 kbar, 490–560 °C (stage I) followed by stage II around 6.6 kbar, 710 °C. A garnet micaschist from the same unit shows almost isobaric heating from stage I at 9–12 kbar, 570–600 °C towards stage II at 10.4–11 kbar, 620–640 °C followed by stage III at 7–9 kbar, 580–620 °C.

We dated the eclogite by a 7-point Rb-Sr mineral isochron (phengite grain size fractions, omphacite, apatite) at 532.2 ± 9.1 Ma. Absence of a correlation between phengite grain sizes and apparent ages indicates that the age dates the crystallisation of the eclogitic peak PT assemblage. The age is youngest compared to a range of white mica Ar-Ar plateau ages at 541–597 Ma in metapelitic rocks of the BMC (Glasmacher et. al. 2001). Ar-Ar spot ages of detrital phengite in Upper Vendian sedimentary rocks derived from the BMC yielded 571–609 Ma (Willner et. al. 2004). Hence there is a trend of increasing ages from bottom to top of the BMC. An identical age of a blueschist at 535 ± 6 Ma in the Kvarkush Complex 600 km further north (Beckholmen & Glodny 2004) proves comparable conditions along strike of the ancient convergent margin. We interpret the lowermost units of the BMC as rocks from different depths of the subduction channel. During return flow and exhumation both units were amalgamated and accreted against the upper unit which likely represents a basal accretionary prism.

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Palaeoproterozoic deformation events in an eclogite-bearing amphibolite-gneiss complex, northern Belomorian Province, Fennoscandian shield

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In the northern Belomorian Province (BP), TTG gneisses and subordinate amphibolites have shared a complex deformational and metamorphic history. Eclogites of disputable Archaean (Volodichev et. al., 2004; Li et. al., 2015) or Palaeoroterozoic (Skublov et. al., 2011; Yu et. al., 2017) age are established in the Kuru-Vaara, Salma and Gridino areas. Based on isotopic ages, this study aims to correlate Palaeoproterozoic deformational events with Palaeoproterozoic eclogite metamorphism proved by omphacite inclusions in 1.9 Ga zircons (Yu et. al., 2017; Imayama et. al., 2017).

In the Gridino area, the most prominent deformation event resulted in a vertical shear zone with gentle stretching lineation that is exposed in the eastern part of the Izbnaya Luda Island. Folds formed during this shearing. Some of them display an axial leucosome crystallized at amphibolites-facies conditions. Magmatic zircon from the leucosome yielded a U-Pb SIMS age of 1941 ± 17 Ma.

Open recumbent folds characteristic of the entire BP occur in the Kuru-Vaara area and reflect a vertical contraction event described by many researchers. They have axial leucosome. Zircons from the leucosome and TTG mesosome have inherited Archaean cores and yield a U-Pb SIMS age of 1950 ± 36 Ma. Pegmatoid, amphibolite-facies leucosome in amphibolites is subparallel to gentle axial surfaces of open to isoclinal folds, and yield a U-Pb SIMS age of ca. 1.89 Ga. A similar age was obtained from leucogranitic leucosome which formed at amphibolite-facies conditions and truncates retrogressed eclogites strongly amphibolized by 2.83 Ga leucosome (for more details see Kartushinskaya et. al., this volume). Zircons from this leucogranitic leucosome yield a U-Pb SIMS age of 1888 ± 8 Ma.

In the Salma area, the Shirokaya Salma shear zone contains a boudin of retrogressed eclogites. Necks of the bouding are filled with pegmatoid microcline leucosome. The latest high-U euhedral zircon from the leucosome yields a U-Pb SIMS age of 1880 ± 6 Ma. This latest zircon surrounds an earlier, low-U zircon that in turn contains Archaean zircons inherited from the TTG host. The low-U zircon has a U-Pb SIMS age of 1919 ± 28 Ma

So, the 1.94–1.95 Ga deformation events correspond to the main frontal collision of the Lapland-Kola collisional orogeny (Daly et. al., 2006) and predate the Paleoproterozoic eclogite metamorphism. The 1.89–1.88 Ga deformational events occurred after the second, transpressional stage of the Lapland-Kola collisional orogeny (Daly et. al., 2006) and postdate the Paleoproterozoic eclogite metamorphism. We suggest that this eclogite metamorphism occurred very close to the transpressional stage or coincides with it.

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Tales from the neighborhood: new insights from the HP units adjacent to the UHP Brossasco-Isasca Unit, Western Alps

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The Brossasco-Isasca Unit (BIU) of the southern Dora-Maira Massif (DMM) in Western Alps of Italy is one of the most studied ultra-high pressure (UHP) units worldwide. In spite of the large amount of papers published in the last 35 years on the BIU, the geodynamic processes responsible for the formation and exhumation of continental UHP units are still debated. Conceptual and numerical models trying to explain how a continental unit can reach, and can be exhumed from, UHP conditions are calibrated with existing geological and petrological data from the tectonic nappe stack which includes the UHP unit itself. To test the validity of any model, a precise knowledge of peak P-T conditions experienced by the UHP unit, as well as by its adjacent units, is therefore required.

In the southern DMM, the UHP BIU is sandwiched between two quartz-eclogite facies units, the lower San Chiaffredo Unit (SCU) and the upper Rocca Solei Unit (RSU). These units are lithologically similar, being the outcome of the Alpine metamorphic reworking of the same Variscan amphibolite-facies basement intruded by Permian granitoids (e.g. Compagnoni et. al., 2012).

In contrast to the well constrained P-T evolution of the BIU (e.g. Ferrando et. al., 2017 and references therein), peak P-T conditions for its adjacent units are poorly constrained, most studies dating back to over 15 years ago and largely relying on conventional thermobarometric methods. We provide, for the first time, a precise estimate of the peak and prograde P-T conditions registered by the units bounding the BIU, using the same (internally consistent and therefore comparable) modern thermobarometric approaches. Four metapelites from the three units (SCU: sample DM1667; BIU: sample DM1281; RSU: samples DM1504 and DM1707) are studied in detail. Thermobarometric estimates are obtained combining multi-equilibrium thermobarometry (Average PT) and the pseudosection approach.
The obtained results can be summarized as follows:

- The prograde P-T paths inferred from the SCU sample (DM1667) and from one RSU sample (DM1504) are similar and point to peak P-T conditions of 500–520 °C, 20–24 kbar.
- Peak P-T conditions constrained for the BIU sample (DM1281) are in agreement with those already known from the literature (730 °C, 40 kbar), but its prograde evolution is not. The early prograde evolution occurred along a moderately steep P/T gradient, similar to that followed by the adjacent HP units; this stage was followed by an intermediate steep, almost isothermal, pressure increase, and by a late temperature increase along a moderately steep P/T gradient, still at increasing pressure.
- The most surprising result comes from the second RSU sample (DM1707), for which UHP peak
  P-T conditions (540 °C, 29 kbar) have been inferred. The prograde evolution constrained for this sample is intermediate between that registered by samples DM1667 (SCU) and DM1504 (RSU) and that registered by sample DM1281 (BIU). Although relict coesite was not identified in this sample, evidence of the former occurrence of coesite (i.e. inclusions consisting of palisade quartz surrounded by radial cracks) are widespread in the rim of Grt porphyroblasts. Moreover, palisade quartz has been also observed in the matrix of undeformed metagranitoids closely associated to this sample.

The results obtained from sample DM1707 strongly suggest that a portion of the RSU experienced UHP conditions at P-T conditions significantly different from those of the BIU, but located along the same prograde path. Although further geochronological studies are needed in order to test if the UHP BIU shared a synchronous prograde evolution with the adjacent eclogitic units, this discovery opens new exciting possibilities to explain the attainment of UHP metamorphic conditions in the BIU.

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Time scales of Palaeoproterozoic eclogite metamorphism

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Although subject to some controversy, eclogites forming part of coherent orogenic belts first appear in the geological record at around 2000 Ma, with a number of examples falling in the age range 2100–1700 Ma, followed by a comparatively sparse record until the late Neoproterozoic. This emergence of eclogitic metamorphism has been argued to signify establishment of modern-style subduction regimes by about 2000 Ma, although geochemical and geological arguments suggests that "plate tectonic style" regimes are likely to have been established before this time.

The geochronological records of Palaeoproterozoic eclogite metamorphism for the most part provide little fidelity regarding time scales of high-pressure metamorphism. Nonetheless in several instances, isotopic derived age data appears to support short durations (< ca. 10 Ma) of high-pressure conditions. An alternative way to investigate the durations of high-P conditions in ancient eclogites is to use compositional patterns in garnet as a means to evaluate potential temperature-time histories, coupling those to P-T models to derive rates of pressure change. Compositional gradients in garnet will begin to diffusionally relax at temperatures above about 650 °C. For the majority of documented Palaeoproterozoic eclogites, peak temperatures are estimated to have been between 700–750 °C at pressures between c. 1.8 and 2.5 GPa, and therefore garnet compositional gradients generated during prograde growth would have been exposed to temperatures that induced significant diffusional relaxation. In several documented examples of Palaeoproterozoic eclogite, partially relaxed prograde zoning is still preserved in garnets of less than ca. 2 mm diameter, suggesting the garnets were exposed to temperatures in excess of 700 °C for no more than several million years at most. In these examples, post peak paths are interpreted to record in excess of ca. 1 GPa of near isothermal pressure drop. Assuming no reaction overstepping, for a range of bulk compositions applicable to documented Palaeoproterozoic eclogites, prograde garnet should have begun forming at around 1 GPa (or even less), and started to compositionally relax on the prograde path. Therefore, the preservation of relic zoning in small garnets implies that some Palaeoproterozoic eclogites traversed upwards of 2GPa of pressure change in several million years at most, comparable with the upper end of rates of pressure change recorded in Phanerozoic eclogites.

As with eclogites of any age, the extent that these apparent rates of pressure change map to rates of depth change is unclear, and requires evaluation of the geologic context. Nonetheless, diffusional modification of garnet as a recorder of time scales, particularly in ancient eclogites where the fidelity of geochronological methods is comprised, is a cost effective and potentially efficient tool to understand the geodynamic significance of their emergence in the geologic record.

A revised petrological model for subducted oceanic crust:
Insights from phase equilibrium modeling

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Many geological and geodynamical studies of metamorphism in subduction zones have relied upon worldwide compilations of modeled slab-top pressure–temperature *(P–T*) conditions, although recent evaluation of such datasets has shown that these predictions are often ~100–300 °C colder than the conditions recorded by exhumed metamorphic rocks. As such, different interpretations formulated using such "cold" assumptions may be subject to uncertainty. Here, we apply phase equilibrium modelling to forward-model how phase assemblages, the *P–T* conditions of key devolatilization reactions, and the effect of densification with depth vary for typical MORB along newly defined "hotter" subduction zone geotherms for cold, warm, and average environments. The depth and extent of devolatilization of typical MORB is strongly dependent on the geotherm under which the oceanic crust subducts. At the onset of subduction along a warm geotherm, metabasites contain ~3 wt% of H_2O, and release ~45% of the bulk-rock H_2O in a fluid pulse at ~20 km. Below these depths, metabasites will dehydrate gradually liberating 45% of the bulk-rock H_2O and complete dehydration will be achieved at ~70 km. Oceanic crust subducting along an average geotherm will contain ~3.5 wt% of H_2O at the onset of subduction, and will release ~40% of the bulk-rock H_2O in two fluid pluses occurring at ~30 and 50 km. Below these depths, the metabasite will dehydrate gradually liberating ~50% of the bulk-rock H_2O and complete dehydration will be achieved at ~80 km. By contrast, at the onset of cold subduction, metabasites will typically be H_2O undersaturated, and will dehydrate gradually at different depths, subducting ~0.6 wt% of H_2O to sub-arc depths. Metabasites subducting along a warm and average geotherm will liberate most of the fluids at shallower depths, suggesting that these lithologies might preferentially exhume, yet MORB subducting along cold geotherms will not dehydrate until greater depths, inhibiting buoyancy-driven exhumation. While we show that metabasites formed along warmer geotherms are denser than metabasites from colder geotherms, buoyancy-driven exhumation provoked by fluids play a most important role than the overall metabasite bulk-rock density.

The eclogite xenoliths from Obnajennaya kimberlite pipe as evidence of subduction processes in the lithospheric mantle under northern Siberian Craton

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The geochemical properties of eclogite xenoliths from kimberlite pipes suggest two main points of view for eclogite genesis: implication of subduction processes or cumulates of high-pressure melting in lithosphere mantle. Many authors (Taylor et. al., 2005; Jacob et. al., 1994 and others) showed that the eclogite protolith was an ancient oceanic crust, which later underwent recycling melting to form TTG melts and carbonatite. The oxygen and carbon isotopes values confirm the hypothesis that many eclogite mantle come from mafic part of ophiolite complexes. Taylor L.W. (2003, 2005) noted high $\delta^{18}O$ values and +Eu anomalies for eclogite xenoliths from north of Siberian craton and suggested the reaction of depleted peridotite with TTG and carbonatite melts during subduction. In addition, there were suggestions that the origin of enriched peridotite xenoliths also be associated with the refertilization of depleted restite harzburgites by melts formed in the subduction wedge (Pernet-Fisher et. al., 2015).

The mantle xenoliths from upper-Jurassic Obnajennaya kimberlite pipe (Kuoika field, Yakutia) were studied. Based on petrographic features, three types of mantle xenoliths were identified. Eclogites and clinopyroxenites occupy about 10–15% population among xenoliths. They are characterized by two-mineral (garnet and clinopyroxene) composition and show medium-to -coarse-grained porphyroblastic structure. Garnet in the eclogites differs from that in the clinopyroxenites by a higher content of CaO and FeO ($Prp_{55–62}$ $Alm_{22–30}Grs_{8–18}$ in clinopyroxenites and $Prp_{40–45}Alm_{13–29}Grs_{15–30}$ in eclogites). Clinopyroxenes are distinguished by reduced magnesia content (Mg# 91–84), as well as low calcium content (16–18 wt.%). The high contents of jadeite components in the clinopyroxene ($NaAl[Si_2O_6]$ – 25–32%) classify this group of rocks as eclogites.

The $\delta^{18}O$ varies in Cpx from 5.7 to 6.4 and in Grt from 5.8 to 6.3 that is higher compared to that in the mantle (Mattey, 1994). It is assumed that the formation of the protolith of the xenolith group occurred in an island-arc environment, as melts in the subduction zone during accretion of the Birekte block to the Siberian craton ~ 1.8 MA (Rosen, 2003).

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Archaean deformation events in an eclogite-bearing, amphibolite-gneiss complex, northern Belomorian Province, Fennoscandian shield

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TTG gneisses and subordinate amphibolite bodies underwent a complex deformational and metamorphic history in the northern Belomorian Province. Retrogressed eclogites have been recently established in the Kuru-Vaara, Salma and Gridino areas. Some of researchers consider eclogites as Archaean (Volodichev et. al., 2004; Mints et. al., 2010; Shchipansky et. al., 2012; Li et. al., 2015) and others as Palaeoproterozoic (Skublov et. al., 2011; Liu et. al., 2017; Yu et. al., 2017). This study focusses on relationship between principal Archaean deformation and migmatisation events and their age that throw light on an age of the eclogites thought to have formed in the Archaean.

In the Kuru-Vaara study area, the earliest deformational and metamorphic event resulted in boudinage, foliation and migmatisation of eclogites. Tonalitic leucosome surrounds and outlines an amphibolite lens-shaped boudin whose central part contains relics of banded symplectitic eclogites, with the migmatisation having obliterated eclogites (Balagansky et. al., 2015). This tonalitic leucosome has not been established in the TTG host. Zircons from the leucosome display a fine oscillatory zoning typical for magmatic zircon from TTG rocks. The zircons yielded a U-Pb SIMS age of 2829 ± 11 Ma and are referred to the leucosome crystallization. This event postdates an Archaean eclogite-facies metamorphism which occurred at 2.87 Ga (Shchipansky et. al., 2012).

In the Gridino study area, Archaean deformational events are clearly recorded in the Western Domain of the Izbnaya Luda Island, where microcline granites cut the earliest isoclinal folds deforming TTG gneisses. Furthermore, the granites are folded into later tight to isoclinal folds. Oscillatory-zoned zircons from the granites yielded a U-Pb SIMS age of 2657 ± 23 Ma. Isoclinal folds of a similar orientation are observed on the Stolbikha Island where they deform Archean banded symplectitic eclogites (for more details see Balagansky et. al., this volume).

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Elastic and trace element geothermobarometry – quartz inclusions in garnet on the trail of the P-T path for the Lower Seve Nappe rocks, Scandinavian Caledonides

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Metamorphic rocks forming during subduction-exhumation processes preserve textural and structural information about prograde and retrograde paths of their evolution. In turn, precise pressure (P) and temperature (T) estimations provide a base for tectonic interpretations. Traditionally, a quantification of the P-T conditions for a specific part of the P-T path is based on an equilibrium of a mineral assemblage used for conventional geothermobarometry calculations or an equilibrium of such a mineral assemblage and a bulk rock composition used in phase equilibrium modeling approach. In many cases, however, the recovery of the full P-T path using the equilibrium-based methods is very challenging. The P-T estimates are often associated with significant uncertainties, or they are impossible to obtain due to several factors, e.g., listing just a few – a lack of the suitable mineral assemblage preserved a chemical heterogeneity of a sample, and a high-T homogenization of zoned minerals. The new opportunity for extracting detailed P-T information from the metamorphic rocks is given by recent development of elastic (e.g. Kohn, 2014; Murri et. al., 2018) and trace element (e.g. Thomas et. al., 2010) geothermobarometers.

In this study, we have applied the Titanium-in-Quartz trace element geothermometer and Quartz-in-Garnet elastic, Raman-based geobarometer to mica-schists and gneisses collected along the 2.4 km deep borehole penetrating the LSN (COSC-1 drilling project, see e.g. Lorenz et. al., 2015). For both methods, the quartz inclusions in two chemically distinct garnet zones, cores and rims, have been targeted. The new approach combined with the phase equilibrium modeling resulted in a successful determination of the prograde and retrograde P-T path for the LSN. Quartz inclusions in garnet cores preserved information about the initial growth of the garnet in the greenschist/amphibolite facies conditions. The inclusions occurring close to the garnet rim determined the peak-P conditions and provided the first evidence for the lower eclogite facies metamorphism of the LSN in the studied area. In turn, the P-T conditions calculated by the thermodynamic modeling confirmed the amphibolite facies regional overprint of the LNC rocks.

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Natural Graphite Cuboids: Implication to UHPM complex

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Graphite cuboids are abundant in ultrahigh-pressure metamorphic rocks and are generally interpreted as products of partial or complete graphitization of pre-existing diamonds(Frezzotti et. al., 2011; Janák et. al., 2013, 2015; Majka et. al., 2014). The understanding of the graphite cuboid structure and its formation mechanisms is still very limited compared to nanotubes, cones, and other carbon morphologies (Jaszczak et. al., 2003; Rakovan and Jaszczak, 2002). This paper is devoted to the natural occurrences of graphite cuboids in several metamorphic and magmatic rocks, including diamondiferous metamorphic assemblages from the Kokchetav massif. The studied cuboids are polycrystalline aggregates composed either of numerous smaller graphite cuboids with smooth surfaces or graphite flakes radiating from a common center. Silicates, oxides, and sulphides are abundant in all the samples studied, testifying that the presence of oxygen, sulfur, or sulphides in natural systems does not prevent the spherulitic growth of graphite. The surface topography and internal morphology of graphite cuboids combined with petrological data suggest that graphite cuboids originated from a magmatic or metamorphic fluid/melt and do not represent products of diamond-graphite transformation processes, even in diamond-bearing rocks.

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U-Pb and Lu-Hf geochronology of blueschist and eclogite from the Vestgötabreen Complex, Svalbard

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The Vestgötabreen Complex is a type locality for high pressure – low temperature (HP-LT) metamorphism on Svalbard in the High Arctic. The Complex is divided into a Lower and an Upper tectonic unit on the basis of lithology and P-T conditions. The Lower unit consists of HP-LT metasedimentary rocks, phyllite and calc-schist, whereas the Upper unit is composed of mica rich schist with isolated lenses of blueschist and eclogite (e.g. Hirajima et. al., 1988, Agard et. al., 2005). Previous dating yielded an Early Ordovician age (~ 470 Ma K-Ar mica – Horsfield, 1972; ~ 470–475 Ma ^{40}Ar-^{39}Ar mica – Dallmeyer et. al., 1990; 476 ± 30 Ma U-Pb zircon single grain – Bernard-Griffiths et. al., 1993). Samples of eclogite and blueschist from the Vestgötabreen Complex were chosen for *in-situ* U-Pb zircon, monazite and allanite dating by SIMS (secondary ionization mass spectrometry) and Lu–Hf garnet-whole rock dating. Zircon in eclogite forms small (<50 μm) grains containing distinctive core and rim domains. The ^{206}Pb/^{238}U dates range from 363 to 1655 Ma and the youngest zircon population yields the concordia age of 478 ± 17 Ma (MSWD = 1.1). Monazite from the same sample occurs as rare small (<30 μm) inclusions in garnet rims and in the matrix as cores of allanite-epidote aggregates. Monazite yields a ^{206}Pb/^{238}U age of 470 ± 7 Ma (MSWD = 1.6). Allanite surrounding monazite gives a younger age, although with large uncertainty (393 ± 51 Ma, MSWD = 1.6). Two garnet generations interpreted to record the transition from blueschist to eclogite facies were distinguished in eclogite. A Lu-Hf 3-point isochron age of 458 ± 3 Ma (MSWD = 0.6) is interpreted to represent Grt-II growth. Monazite found as inclusions in garnet within blueschist define a weighted mean ^{206}Pb/^{238}U age of 487 ± 6 (MSWD = 0.3). Garnet in the blueschist shows prograde zonation and Lu concentration in the cores. The Lu–Hf dating yields 459 ± 5 Ma (MSWD = 1.7). The U-Pb zircon and monazite ages as well as Lu-Hf garnet dating agree with former workers thus, providing the further evidence of the Early Ordovician subduction.

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Phlogopite eclogite of the Marun-Keu Complex (Polar Urals) –
PT conditions and absolute age data

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In the Polar Urals, the eclogite-amphibolite-gneiss Marun-Keu Complex is developed in the outer zone of the Ural folded belt. The "Mica Hill" area is the most studied to date. Materials can be found in numerous publications (e.g. Liu et. al., 2019, with refs.). This Complex is represented by a large number of blocks of massive garnet peridotites, metagabbro and eclogites located in a matrix of banded amphibolite-eclogite-gneiss rocks. To the north of the Mica Hills along the Nyakhar-Neo-Shor creek, there are found outcrops of the banded matrix rocks, with alternating gneisses, *Phen-Ky* eclogites, and amphibolites. During field work in 2017, we discovered phlogopite eclogite boudins among the *Phen-Ky* eclogites. This type of rocks for the Marun-Keu Complex was previously unknown. Alkaline basalt was the protolith of the phlogopite eclogite (wt.%, SiO_2 45.62; TiO_2 0.39; MgO 13.98; K_2O 3.71), now consisting of garnet (up to 2 mm in size), prismatic omphacite (up to 3 mm), and phlogopite flakes (up to 2–3 mm). The garnet core composition is $Gros_{18}Alm_{25}Pyr_{44}$, rim composition is $Gros_{24}Alm_{29}Pyr_{35}$; newly formed grains are Alm-richer ($Gros_{19}Alm_{37}Pyr_{29}$). Omphacite has an almost homogeneous composition (Jd component 33–38%, X_{Mg} 82-84). Phlogopite is also uniform in composition (X_{Mg} 81–83). The garnet cores contain numerous inclusions of kyanite, phengite, phlogopite and SiO_2, less often omphacite and amphibole developed after phlogopite, rims do not contain inclusions. Omphacite contains syngenetic garnet, phlogopite and phengite, and later clinozoisite, amphibole and albite. Phengite has Si = 3.23–3.25 apfu, Ti = 0.03 apfu. To estimate the PT conditions for the formation of these metamorphic parageneses, the TPF (Konilov et. al., 1995) program was used, as well as various geothermometers and geobarometers (Auzanneau et. al., 2010; Perchuk A., 1992). Peak metamorphism conditions for the phlogopite eclogite (cores of garnets and omphacites with syngenetic inclusions) correspond to the *Zo* subfacies of the eclogite facies at P = 28 kbar, T = 680 °C. Retrograde conditions documented by the formation of garnet and omphacite rims correspond to the *Amp-Zo* subfacies of the eclogite facies (P = 14 kbar, T = 652 °C); the small, newly-formed garnets and amphiboles reflect a later epidote-amphibolite facies stage (P = 11 kbar, T = 512 °C). The absolute, Ar-Ar age of phlogopite is 442.2 ± 5 Ma and records, in our opinion, the time of subduction; the known ages of 360 Ma reflect accretionary processes during the formation of the Ural orogen.

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Evidence for partial melting in eclogite from the Western Gneiss Region, Norwegian Caledonides, and comparison with partial melting experiments

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Evidence for partial melting in eclogites commonly does not survive because of later recrystallization. We describe an example that displays well-preserved features indicative of partial melting. The observed textures and compositions correspond well with results from experimental modelling of eclogite melting. Anatectic meta-eclogites are found in the northern part of the Western Gneiss Region in the Norwegian Caledonides, where the highest temperatures and pressures (~800–850 °C, 3.6 GPa) are recorded in this giant HP-UHP terrain (Cuthbert et. al., 2000). P-T conditions for the retrogressive symplectite stage were ~10–12 kbar at ~850 °C. A lens of meta-eclogite at Lyngstad displays trondhjemite seggregations having diffuse contacts towards their host. Marginal trondhjemite contains coarse Cpx+Cl symplectites and poikiloblasts of Hbl, along with large Grt‘s and often small Ap grains. Primary Zo, Ph and Rt are now only found as inclusions in Grt. Ph is partially decomposed to biotite and Pl. Pl ($An_{16–20}$) in the trondhjemite at the border with eclogite contains small grains of Ab, Ksp, Mu and Chl along grain boundaries (melt?). Further from the trondhjemite, Grt‘s are almost unzoned (although Prp decreases slightly rimwards) and show partial replacement by Pl, Cpx and Hbl, and are always surrounded by a moat of Pl ($An_{28–35}$). All primary Omp has been replaced by coarse symplectites of Cpx ($Jd_{6–8}$) + Pl ($An_{20–24}$) or Hbl + Pl ($An_{30–35}$). In one Grt an inclusion was found near the rim formed from an intergrowth of Qtz + Pl + Kfs with minor Chl and Hbl. A “channel” connecting it with matrix Pl contains fluid inclusions. The bulk inclusion composition is very similar to the trondhjemite. It is interpreted as a relict melt. Its close association with symplectites shows that symplectite growth and melting of the eclogites (at 10–12 kbar and ~850 °C) were coeval.

In melting experiments on a MORB eclogite (Larikova et. al., 2011) at 700 °C, 9–13 kbar with a NaCl-H_2O fluid, Grt’s remained stable but became more Ca-rich and Mg-poor near their rims. Omp recrystallised to Cpx + Pl ± Hbl symplectite. Melt (glass) occurred within the symplectite and as a rim around Grt. Trace elements in melt showed enrichment in Eu and Sr but an unusual, general depletion of REE and other elements compared to the initial MORB eclogite. The Lyngstad eclogite shows remarkable similarities with these experimental results, reinforcing the interpretation of anatexis during decompression. The association of coarse Cpx + Pl symplectite with trondhjemitic melt suggests that symplectite can form as a direct result of partial melting at conditions close to the wet basalt solidus minimum. The whole rock trace element analyses of the Lyngstad trondhjemite seggregations show an unusual, but strikingly similar pattern to those observed in the experiments, which differs from typical tonalite-trondhjemite. The causes of the depletions are not yet well understood, but may have implications for models of TTG formation involving eclogite melting (e.g. Rapp et. al., 2003).

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New perspectives on the metamorphic ages and *P-T* path of Belomorian eclogites, Russia

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The Belomorian eclogite from the eastern Baltic shield was earlier reported to be of Archean age(s) (c. 2.8–2.7 Ga) with possible peak condition(s) at 13–18 kbar, 700–750 °C and oceanic subduction was accounted for; the subsequent retrogression under granulite- and amphibolite-facies might last till late-Paleoproterozoic during exhumation (Mints et. al., 2014). However, our recent studies on the well-preserved eclogite and its retrograde equivalent and several TTG wall rocks have revealed some new perspectives (Li et. al., 2017a, b; Liu et. al., 2017; Yu et. al., 2018, 2019): (1) well-preserved 1.9 Ga mafic eclogite and coeval eclogite-facies metamorphism have been confirmed by both zircon U-Pb dating and garnet Lu-Hf geochronology. The peak eclogitic condition is defined at > 18–19 kbar, 750–800 °C; during the retrogression, higher temperature > 850–900 °C is attained at 10–12 kbar that answers to the HP granulite-facies, and further cooling to < 650 °C at < 10 kbar is confined at 1.86 Ga by titanite U-Pb dating. (2) the Neoarchean (c. 2.7 Ga) event is documented only by zircons that answers to a HP-HT (granulite-facies) metamorphism, which may not achieve eclogitic conditions though. This event is also recorded by the TTG wall rocks, having experienced anatexis at 2.69 Ga. (3) the protolith of the Belomorian eclogite exhibits a N-MORB affinity with possible ages of 2.87–2.92 Ga, while the country rock gneiss seems to be formed at 2.73–2.74 Ga due to migmatization. In a summary, the 2.7 Ga event(s) mainly derived from zircons is featured by HP-HT metamorphism but with undefined yet *PT* parameters, and whether it had reached eclogitic condition is still arguable that requires further investigation. The defined 1.9 Ga (HT) eclogite-facies metamorphism is probably related to crust thickening during the Lapland-Kola and/or Svecofennian collisional orogeny, that the obtained *P-T* path by pseudosection method refers only to this event. Furthermost, the upcoming challenges will concern: (1) what is the tectonic significance for the 2.7 Ga event and (2) how the 2.7 Ga (anhydrous?) HP-HT rock (granulite) transformed into the 1.9 Ga hydrous eclogite.

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The garnet amphibolites from the Xigaze ophiolite, southern Tibet and their metamorphic evolution: Do they represent retrogressed eclogite?

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The garnet amphibolites were found within the Xigaze ophiolitic mélange of the central Yalung Zangpo Suture Zone. There are two types of garnet amphibolites, which record different P-T path and occurred in the ophiolite mélange of different localities. Type A is a massive garnet amphibolite, which experienced five metamorphic stages. Their mineral assemblages are distinguished as Amp1 + Pl1 + Cpx1 + Ttn (M1); Grt-c + Cpx2 + Amp2 + Pl2 + Rt + Ttn (M2); Grt-r + Cpx3 + Amp3 + Pl3 + Rt + Ttn (M3), Cpx4 + Amp4 + Ep + Pl4 + Ttn4 (M4) and final subgreenschist-facies Prh + Ab + Act + Chl + Cal, respectively. Type B, foliated garnet amphibolite occurs in shear zone, associated with metarodingite in a serpentinite matrix, and only recorded three metamorphic stages. These are: Grt3 + Cpx3 + Amp3 + Pl3 + Ilm (M3), Amp4 + Pl4 + Ilm + Ttn (M4) and final, subgreenschist-facies Prh + Ab + Act + Chl + Cal, respectively. Pseudosection and compositional contours of type A garnet amphibolite show that: the first metamorphic stage (M1) is defined at ~775–825 °C/ 15–17.5 kbar; the second metamorphic stage (M2) at ~810–845 °C/ 14.2–15.3 kbar; the third metamorphic stage (M3) at ~835–860 °C/ 13.8–14.8 kbar; the fourth metamorphic stage (M4) at ~550–690 °C/ 5.4–10.5 kbar and final, subgreenschist, metamorphic stage at low P-T conditions. T-max metamorphic stage (M3) of Type B garnet amphibolite was figured out at ~840–890 °C/ 9.4 – 10 kbar; cooling metamorphic stage (M4) was at ~ 690–770 °C / 6.5–8.3 kbar and final, sub-greenschist, metamorphic stage was at low P-T conditions. Type A massive amphibolite records a geothermal gradient of ~10.5°/km, whilst Type B foliated amphibolite documents a geothermal gradient of ~18°/km. The calculated P-T path of garnet amphibolite documents earlier, eclogite-facies, HP conditions, followed by a granulite-facies, HT overprinting during the exhumation of the Xigaze ophiolite.

Improved Small-Volume U-Pb Zircon geochronology by LA-MC-ICPMS and application for metamorphic zircons

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Accurate measurement of small volume (<0.5ng) U-Pb geochronology is significant for zircon grains with complex inner structure. We provide and evaluate a higher spatial resolution LA-MC-ICP-MS dating method using GeoLas HD laser ablation and Nu Plasma 2 mass spectrometer with spot diameter of 5μm (0.117μm per pulse) and 10μm (0.077μm per pulse). Overcoming the difficulty of downhole fractionation, this method is verified by investigating four zircon standards (91500, GJ-1, TEM, and PLE) with the precision for the weighted mean $^{206}Pb/^{238}U$ age within 1%. Using this technique, we have exactly applications in three UHT/UHP metamorphic samples with age range widely from 14Ma to 2000Ma. The zircons from these samples have tiny shapes, plentiful inclusions or complicated structures. The concordant age results demonstrate our zircon U-Pb dating method is credible and repeatable.

TEM observations of diamond-bearing vugs in melt inclusions of zircons from stromatic migmatites of Sulu UHP terrain

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Diamond-bearing vugs are identified in a few multiphase solid inclusions (MSI) of zircon grains from a stromatic migmatite in the Sulu ultrahigh-pressure (UHP) terrane. The vugs with offshoots, which is characteristic of decrepitation (fracturing), consists of large holes with stalagmite-like surface, growth banding, and porous aggregate. The transmission electron microscope (TEM) and laser Raman observations on a foil sample show that (1) the growth banding is manifested by zircon-rich layer and carbon-bearing silicic layer which is made up of nano-size diamond, amorphous carbon, cristobalite, and silicic glass; and (2) the porous aggregate consists of cavities, carbon-bearing silicic glass and nano-size diamond fragments. Other inclusions contemporarily trapped by zircon grains include melt inclusions (MI), low-pressure MSI and monophase mineral inclusions (MMI), and CO_2-rich fluid inclusions (FI). The MI consist of relict H_2O-bearing glass and daughter minerals including kokchetavite, kumdykolite, K-feldspar, albite, quartz, muscovite, biotite and calcite. The low-pressure MSI and MMI are typical amphibolite-facies minerals, including biotite, oligoclase–andesine, epidote/allanite, amphibole, kyanite, garnet, diopside, rutile, ilmenite, paragonite, apatite, calcite and ankerite. The CO_2-rich FI contain the daughter minerals of quartz, albite, calcite and muscovite. The observations suggest that (1) partial melting of the rocks occurred in the stability field of diamond, and was non-equilibrium melting at the expense of low-pressure amphibolite-facies assemblage; (2) diamond-bearing vugs represent former silicate-carbon-rich fluids coexisting with carbon-bearing granitic melts which may play a role of oxygen buffer in crystallization of the early diamond (Dia I) from the fluids; (3) nano-size diamond fragments in the porous aggregate record the decrepitation of the inclusions, and the silicic glass and amorphous Fe-Co-Si-C material were instantaneously precipitated from the fluid during the decrepitation. The carbon-bearing silicic glass probably suggests organic Si-C-metal complexe in the fluid, which may be responsible for the formation of the later diamond (Dia II) due to *pH* decrease. The Raman carbonaceous-material geothermometer gives a temperature of 269 ± 56 °C recorded by the amorphous carbon in the vugs, which is interpreted as the temperature of decrepitation of the inclusions.

New evidence of ultra-deep continental subduction to mantle depths in the stishovite stability field and its possible mechanism of exhumation

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The long prism/needle-shaped, polycrystalline quartz aggregates and square/ parallelogram-shaped, single-phase quartz inclusions in omphacite and garnet of ultrahigh pressure eclogite were first discovered from the Jiangalesayi area, South Altyn UHP belt. Based on their morphology, these quartz inclusions are quartz paramorphs after stishovite (Liu et. al., 2018). The minimum peak pressure of the eclogite is estimated to be > 8–9 GPa at 800–1000 °C based on the stability field of stishovite. This new evidence, together with previous stishovite exsolution texture microstructure in the gneiss from the same region (Liu et. al., 2007), suggests a ultra-deep subduction and exhumation of the South Altyn continental rocks to/from mantle depths in stishovite stability field. Evidence of ultra-deep subduction of continental materials might be more common and diverse than previous thought.

Exhumation of subducted continental rocks from ≥ 300km has been considered impossible because they are denser than mantle at these depths (Irifune et. al., 1994; Wu et. al., 2009). How did the stishovite-bearing continental rocks of the South Altyn Tagh exhumated?

As we all know, the densities of stishovite (4.3g/cm^3) are much higher than coesite (2.9 g/cm^3), and stishovite transforms into coesite with temperature increases. Density calculations were performed for subducted continental rocks along phase transition of stishovite to coesite, using the third-order Birch-Murnaghan equation of state based on mineral fractions obtained from experiments (Irifune et. al., 1994; Wu et. al., 2009) and Perple_X. The results show that the density of siliceous rocks decrease remarkably, lower than the sourrounding mantle in coesite stability field, whereas the density of oligosiliceous and silicon unsaturated rocks is higher than surrounding mantle.

Thus, we propose that the thermal induced transformation could provide an initial driven force for the exhumation of ultra-deep subducted silica-enriched felsic continental rocks. Temperature increase could be derived from an increased geothermal gradient from convective mantle or mantle plume. Mafic to ultramafic rocks and silica-deficient rocks may be captured by the upwelling subducted continental rocks and exhumated together.

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Multiple metamorphic events from Paleoproterozoic to early Paleozoic in Oulongbuluke block, NW China and their geological implications

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The Oulongbuluke block is previously considered as a small Precambrian continental block between the Qilian orogenic belt and the North Qaidam ultrahigh-pressure (UHP) metamorphic belt in northern Tibet, northwestern China. Our new data show the Oulongbuluke block underwent multiple metamorphic events from Paleoproterozoic to early Paleozoic. Paleoproterozoic mafic granulites have been recognized from the eastern and western part of the block. Zircon U-Pb datings yield a common metamorphic age of about 1930 Ma. It indicates that the whole Oulongbuluke block underwent the Paleoproterozoic granulite facies metamorphism, and was interpreted as product during the formation of Columbia supercontinent. In the northern part of the Oulongbuluke block (northern Wulan area), small amounts of late Mesoproterozoic (1.2–1.1 Ga) magmatic and high grade metamorphic rocks have been newly reported. Our preliminary works show that the late Mesoproterozoic metamorphic rocks experienced a medium-low pressure amphibolite-granulite facies metamorphism. The newly recognized Mg-Al granulite has mineral assemblages of garnet + sillimanite + orthopyroxene + cordierite ± spinel ± kornerupine + rutile + quartz. Its decompression texture is characterized by orthopyroxene + cordierite corona around garnet. Monazite U-Pb dating of the Mg-Al granulite yields a metamorphic age of 1142 ± 34 Ma. Phase equilibria modeling show that the Mg-Al granulite underwent a clockwise P-T path with a decompression heating process (up to 850–950 °C). The late Mesoproterozoic metamorphic event is associated with Grenvillian orogeny related to the amalgamation of Rodinia Supercontinent. Early Paleozoic metamorphic event is also commonly identified in north Wulan area. This event records a peak temperatures of 800–900 °C at 6–7 kbar, followed by high – temperature decompression. Zircon and monazite petrochronology reveals a protracted high temperature metamorphism from 500 to 450 Ma, nearly contemporaneous or slightly older than UHP metamorphism recorded in the North Qadiam UHP metamorphic belt, to the south of the Oulongbuluke block. It is explained as a continental arc metamorphic event related to the northward oceanic subduction prior to the continental deep subduction along the North Qaidam Mountains during early Paleozoic.

Metamorphic evolution of high-pressure rocks in the Younusisayi area, South Altyn Tagh

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In this study, high pressure (HP) metamorphic eclogite and granitic gneiss (Ma et. al., 2018) were first discovered in the Younusisayi area of the South Altyn Tagh, where eclogite occur as lenses in granitic gneiss. The peak stage mineral assemblage of the eclogite is Grt + Omp + Ru + Qz, with P-T condition of T > 750 °C, P > 18 kbar, and the granitic gneiss with peak stage mineral assemblage of Grt ± Omp + Ky + Per(Ksp) + Ru + Qz and peak P-T condition of T = 970~1010 °C, P = 23.2~25.3 kbar, which indicate both the eclogite and granitic gneiss experienced eclogite-facies peak stage metamorphism. Further more, the eclogite also experienced HP granulite-facies (Grt + Cpx + Pl + Ru + Qz) and amphibolite-facies (Grt + Cpx + Amp + Pl + Ru + Ilm + Qz) retrograde metamorphism with P-T conditons of P = 13~15 kbar, T = 790~830 °C and P = 4~5 kbar, T = 600~650 °C respectively. And the granitic gneiss underwent HP granulite-facies (Grt + Ky + Ksp + Pl + Ru + Qz), granulite to high amphibolite-facies (Grt + Ky + Ksp + Pl + Bi + Ru + Ilm + Qz) and low amphibolite-facies (Ky + Ksp + Pl + QZ + Bi + Mu + Ru + Ilm) three stages of retrograde metamorphism, with P-T conditions of P = 16~17 kbar, T = 850~890 °C, P = 10.5~11.5 kbar, T = 770~790 °C and P = 5–6 kbar, T = 600–650°C, respectively. Thus, two consistent clockwise P-T paths were obtained.

Zircon LA-ICP MS U-Pb dating reveal the protolith age of the eclogite was 600~950 Ma, with eclogite-facies age of 498.0 ± 1.7 Ma and HP graniulite facies age of 451.3 ± 1.7 Ma. Meanwhile, the protolith age of the granite gneiss was estimated as 900.2 ± 4.1 Ma, with the peak metamorphic age of 497.8 ± 2.7 Ma.

In conclusion, the eclogite and granitic gneiss in Younusisayi are with similar P-T-t path, and also consistent with the HP-UHP metamorphic rocks in Jianggalesayi and Keqike Jianggalesayi area, south Altyn Tagh (Liu et. al., 2002, 2004, 2005, 2007, 2018; Cao et. al., 2013; Gai et. al., 2017). Which indicate that both the eclogite and granitic gneiss experienced continental deep subduction and metamorphism as the HP-UHP rocks in the south Altyn Tagh. On the other hand, the confirmation of HP metamorphic rocks in Younusisayi provide new restrictions to the spatial and temporal distributions of early Paleozoic HP – UHP rocks in the South Altyn Tagh.

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Preliminary data on UHP fluid preserved in impure marbles from the Dora-Maira Massif

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The investigation of the tectono-metamorphic evolution of subducted marbles at mantle depth is fundamental for our understanding of the deep processes responsible for the deep carbon cycle. Moreover, the recent discovery of micro-diamond at Lago di Cignana (Frezzotti et. al., 2011) demonstrates, for the first time, the possibility to mobilize carbon through UHP carbonate dissolution, without the need of decarbonation reactions. In this contest, the evolution of the fluid phase during subduction and exhumation of impure marbles is promising to follow the fate of carbonates during deep subduction.

In the UHP Brossasco-Isasca Unit (BIU) of the Dora-Maira Massif, some dam- to hm-scale lenses of impure marbles are scattered in the paragneiss of the Polymetamorphic Complex. Previous studies on the Costa Monforte lens indicate that these marbles underwent Alpine metamorphic peak at ~4.0 GPa and ~730 °C (Castelli et. al., 2007) and that multiple events of dissolution-precipitation of dolomite occurred during UHP prograde to early-retrograde evolution in presence of a complex, solute-rich aqueous fluid (Ferrando et. al., 2017).

In order to more precisely asses the composition and nature of this fluid, a sample of impure marble with a very-simple mineral assemblage has been selected for fluid inclusion study. The selected sample is a banded marble mainly composed by different proportions of Mg-calcite, porphyroblasts of dolomite, porphyroclastic and neoblastic diopside and olivine, with minor retrograde antigorite, tremolite and Mg-chlorite (Ferrando et. al., 2017). The UHP peak mineral assemblage consisted of aragonite (now converted to calcite), dolomite, diopside and olivine. Micro-Raman analyses on primary multiphase aqueous inclusions, occurring within the core of peak diopside, allowed the recognition of the assemblage Mg-calcite + talc ± tremolite ± dolomite ± H_2O_{liq} ± a non-Raman active phase that in optical microscopy results to be a cubic daughter mineral (i.e. a chloride). SEM-EDS analysis on open inclusions, revealed appreciable Cl content in tremolite and talc (Ferrando et. al., 2017). This finding point to a dominantly aqueous, saline COH fluid, containing Ca, Mg, and Si as dissolved cations. This solute-rich fluid is likely responsible for the dissolution-precipitation of carbonates at UHP conditions.

Castelli, D., Rolfo, F., Groppo, C., Compagnoni, R. (2007) Impure marbles from the UHP Brossasco-Isasca Unit (Dora-Maira Massif, western Alps): evidence for Alpine equilibration in the diamond stability field and evaluation of the $X(CO_2)$ fluid evolution. Journal of Metamorphic Geology 25(6): 587-603.

Ferrando, S., Groppo, C., Frezzotti, M.L., Castelli, D., Proyer, A. (2017) Dissolving dolomite in a stable UHP mineral assemblage: Evidence from Cal-Dol marbles of the Dora-Maira Massif (Italian Western Alps). American Mineralogist 102(1): 42-60.

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Possible evidence for incipient decompression melting in the Dora-Maira Massif

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One of the most intriguing aspects of UHP metamorphism regards petrologic and dynamic processes acting during deep subduction and subsequent exhumation. The increasing evidence for partial melting of suitable UHP lithologies during decompression (e.g. Greenland Caledonides; Cao et. al., 2019) made this process relevant for both petrology and geodynamics, because it can be responsible for the recycling of crustal material in the mantle wedge and for the exhumation of the UHP terranes.

Deformed quartz-feldspathic layers occur within dam- to hm-scale impure marble lenses scattered in the paragneiss of the Polymetamorphic Complex of the UHP (~4.0 GPa and ~730 °C: Castelli et. al., 2007) Brossasco-Isasca Unit (BIU; Dora-Maira Massif).

Under the microscope, the quartz-feldspathic layers are paragneisses mainly made by variable modal amounts of Qtz + Wm + Zo + Kfs + Grt + Plg. Peak mineral assemblage consisted of Coe (now Qtz) + Phg + Zo, whereas Kfs + Grt + Plg formed during decompression. The quartz-feldspathic layers preserve peculiar microstructures such as: i) tiny, optically continuous, Qtz and/or Plg films enveloping Zo + Qtz aggregates; ii) poikilitic Kfs and Grt including Qtz, Zo and Phg. Such microstructures, never reported in the Dora-Maira Massif, are commonly interpreted as evidence for incipient partial melting (e.g. Vernon, 2011). They suggest that, during exhumation of the BIU, an incipient melting of the quartz-feldspathic layers produced small volumes of melt, subsequently crystallized into melt pseudomorphs. The inferred P-T path of the BIU (Castelli et. al., 2007) confirms that, during nearly-isothermal decompression in the Qtz stability field, the Unit reached P-T conditions compatible with the “wet solidus” curves experimentally determined for granitic and pelitic systems (e.g. Huang and Wyllie, 1973; Hermann and Spandler, 2007).

Cao, W., Gilotti, J.A., Massonne, H.J., Ferrando, S., Foster, J.C.T. (2019) Partial melting due to breakdown of an epidote-group mineral during exhumation of ultrahigh-pressure eclogite: An example from the North-East Greenland Caledonides. Journal of Metamorphic Geology 37(1): 15-39.

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Archean eclogites from the Belomorian Province (examples from the Gridino area)

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Archean (Volodichev et. al., 2004; Li et. al., 2015) and Paleoproterozoic (Volodichev et. al., 2012; Skublov et. al., 2011; Yu et. al., 2017) eclogites have been reported from the Gridino area, Belomorian Province, Fennoscandian Shield. The biggest eclogite boudin, found on Stolbikha Island, Gridino area, occurs among mylonitized gneissose granites cut by a 2701.3 ± 8.1 Ma massive plagiogranite vein (Volodichev et. al., 2004). The boudin and hosting gneissose granites are cut by a 1875 ± 30 Ma pegmatite vein (Skublov et. al., 2011). The boudin hosts earlier banded symplectitic eclogites and later massive less reworked eclogites that developed after the earlier ones (for more details see Balagansky et. al., this volume).

The earlier eclogites consist of Grt, Cpx-Pl symplectites, Amp, Bt, Zo, and Qz. These rocks contain relics of a Grt-Omp paragenesis that occurs as Omp inclusions (28% Jd) in garnet (16–23% Prp, 27–35% Grs, 43–51% Alm). The symplectites occur as aggregates of Di-Pl composition (2–12% Jd, up to 6% Ae and 26–52% An) transformed to a varying degree. Their integrated composition is consistent with Omp (20–28% Jd). Zonal garnets contain abundant Rt, Qz and Zo inclusions. The primary mineral association Grt-Cpx-Pl-Qz of symplectitic eclogites was derived at T = 750–850 °C and P = 11–14 kbar, which is consistent with the transitional field of eclogite/high pressure granulite-facies metamorphism. Zircons from the earlier eclogites occur as rounded almost isometric crystals, 50–150 µm in size, with the low (0.22–0.42) Th/U ratio; they are depleted in HREE. These characteristics are typical of metamorphic zircons from rocks metamorphosed under eclogite/high pressure granulite-facies conditions. The zircons contain Zo, Grt and Rt, but Crb, Cpx (Jd up to 6%), Pl and Qz are common, too. A U-Pb age of the zircons (n = 27) varies from 2.71 to 2.68 Ga. Rare 5–10 µm thick rims seems to be Paleoproterozoic. Thus, the earlier symplectitic eclogites were formed in the Archean (not later than 2.72 Ga), and they display no intense Paleoproterozoic metamorphic overprint.

The later massive eclogites make up a morphologically complex body at the eastern boudin margin and bear a better preserved Grt-Omp paragenesis. Garnet contains 45–52% Alm, 21–29% Prp and 18–29% Grs, while garnets from the earlier eclogites are enriched in Grs and are depleted in Prp. Cpx contains up to 35% Jd and up to 10% Ae. Secondary Pl contains 18–27% An. This Grt-Omp assemblage was formed at T = 700–800 °C and P = 14–7 kbar, which corresponds to eclogite facies. The age of this later eclogite-facies metamorphism was determined from prismatic zircons with Omp inclusions and is 1.9 Ga (Skublov et. al., 2011; Yu et. al., 2017).

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Is there sufficient proof of diamond in crustal rocks formed by regional metamorphism?

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The recently reported occurrences of micro- and nano-diamonds in gneisses and related rocks from Phanerozoic orogens (e.g., Collings et. al., 2016; Janák et. al., 2015; Majka et. al., 2014; Ruiz Cruz & Sanz de Galdeano, 2013; Thiéry et. al., 2015) strongly support the idea of continental subduction, which could be the most important geological process to recycle continental crust into the mantle. Thus, researchers should exercise due care to prove the existence of diamonds in crustal rocks formed by regional metamorphism.

The diamonds of the aforementioned publications are usually enclosed in garnet. However, another common indicator mineral of ultrahigh-pressure (UHP), coesite, and even Na-rich clinopyroxene are lacking in the studied metamorphic rocks. Therefore, the question arises if the reported occurrences of diamondiferous crustal rocks reflect true UHP rocks. Studies of so-called diamondiferous gneisses from the Betic Cordillera, S Spain, and the Western Gneiss Region, Norway, yielded peak pressure conditions of only 13 kbar (Massonne, 2014) and 14 kbar (Liu & Massonne, 2019), respectively. Both studies disprove the previously reported diamond occurrences. Li and Massonne at China University of Geosciences at Wuhan are currently working on so-called diamondiferous rocks from Bulgaria (Rhodope), Slovenia (Pohorje), and Sweden (Seve Nappe) and come to the conclusion that the studied rocks are characterized by garnet showing a chemical dichotomy. A core, being rich in mineral inclusions such as quartz, biotite, and ilmenite, is surrounded by a garnet mantle that experienced peak pressures around 15 kbar. These conditions were reached during a second metamorphism, whereas the early garnet core was formed at pressures below 10 kbar. The garnet core also contains voids being prone of trapping diamonds from the slurry used for abrading and polishing rock thin-sections. Thus, it is important to verify diamonds **below** the surface of an enclosing mineral, for instance, by Raman spectroscopy (see Nasdala & Massonne, 2000). Such a proof was never presented in the recently published articles on diamondiferous metamorphic rocks. Therefore, it is suggested here that at least an independent research group should check a rock for diamonds before it can be acknowledged as diamondiferous by the scientific community. Furthermore, in-situ studies are required to prove diamond in a rock. Mineral separates are not suitable for such a proof. Accepting this, only two occurrences of diamonds in crustal rocks, excepting impact metamorphism, are verified: those in the Kokchetav Massif in Kazakhstan (e.g., Shatsky et. al., 1995) and the Erzgebirg in Saxony (e.g., Massonne, 2003). Diamond is included in such rocks not only in garnet but also in zircon, clinopyroxene, and kyanite. In addition, diamond can be part of crystallized fluid inclusions (e.g. Stöckhert et. al., 2009). This and other evidences point to crystallization of diamond from silicate melts that later penetrated orogenic crust. Thus, true diamonds formed by regional metamorphism of crustal rocks were not verified yet.

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Contrasting zircon-garnet relationships in UHP eclogite and HP granulite, North Qaidam terrane, western China

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The North Qaidam terrane near Dulan exposes UHP eclogite across >100 km^2 as well as a smaller exposure of HP granulite west of the eclogite outcrops. Zircon U-Pb ages are ca. 463–422 Ma from eclogites and 449–410 Ma from HP granulites, but the connection between these ages and the samples' P-T paths is unclear. LAICPMS trace element analyses from garnet and zircon illustrate contrasting relationships in UHP eclogite and HP granulite. A UHP phengite eclogite records peak P-T conditions of 675 °C, 32 kbar, near the stability limit of lawsonite in this rock composition (Hernández-Uribe et. al., 2018). Zircon yields a weighted mean age of 429 ± 2 Ma, flat HREE slopes (Yb/Gd = 0.52–4.2), and small to absent negative Eu anomalies (Eu/Eu* = 0.65–2.1). Garnet shows little zoning in major or trace elements, and REE patterns show flat HREE slopes (Yb/Gd = 0.3–1.5) without negative Eu anomalies (Eu/Eu* = 1.2–1.7). HREE patterns and concentrations (10–30x chondrite) are similar in both zircon and garnet, suggesting equilibration between zircon and garnet. We therefore interpret the zircon age to record near-peak P-T conditions; fluid release from lawsonite breakdown likely promoted zircon growth as well as equilibration of the major minerals that record the peak P-T conditions. An intermediate HP granulite records peak P-T conditions of 775–875 °C, 14–17 kbar, and field evidence suggests significant partial melting (Christensen, 2011). Zircon yields a weighted mean age of 418 ± 2 Ma, flat HREE slopes (Yb/Gd = 1.4–5.6) without negative Eu anomalies (Eu/Eu* = 0.98–1.2). Garnet is zoned, with inclusion-rich cores, an inclusion poorer mantle, and Mg-rich rims (~Prp_{40}). Garnet REE patterns show increasing HREE slope and curvature from cores (Yb/Gd ~ 5) to mantles and rims (Yb/Gd ~ 30–40) without negative Eu anomalies (Eu/Eu* ~ 1.5–1.8). All garnet zones contain much lower HREE concentrations (Yb = 10–40x chondrite) than zircon (Yb = 100–1000x chondrite), and zircon lacks the curved HREE pattern shown by garnet, suggesting zircon did not equilibrate with any of the analyzed garnet zones. We therefore interpret that the zircon post-dates the P-T conditions recorded by garnet, and likely records the presence of melt. REE analysis of garnet therefore provides a useful tool to relate zircon to garnet, especially in melt-present samples where zircon growth may occur during garnet dissolution.

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Kuru-Vaara eclogites of the Belomorian Province, Fennoscandian Shield: ages of protolith and metamorphism

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The Belomorian Province (BP) of the Fennoscandian Shield is a key location in case of study early tectonic processes since it contains a significant Precambrian eclogites. Gridino-type and Salma-type eclogites are the most studied eclogite-facies rocks within the BP (e.g., Yu et. al., 2019). Kuru-Vaara eclogites are related to the Salma-type and regarded as either Archean (Balagansky et. al., 2015) or Proterozoic (Liu et. al., 2017) in age. We have identified two types of Kuru-Vaara eclogites: eclogitic boudins and a partially eclogitized coronitic gabbronorite dike. The whole-rock, omphacite and garnet fractions from the boudin-like eclogites yield approximately equal Lu-Hf and Sm-Nd isochron ages of ca. 1.9 Ga. Both Kuru-Vaara eclogite types have zircon cores with a magmatic geochemical signature, such as HREE enrichment, pronounced negative Eu and positive Ce anomalies, moderate or high Th/U ratio. U-Pb dating of the cores yields magmatic protolith ages of ca. 2.9 Ga for boudin-like eclogites and ca. 2.44 Ga for coronitic metagabbronorite. Ca. 1.9 Ga zircon rims and grains from all Kuru-Vaara eclogites show low Th/U ratios and HREE depletion, reflecting growth of metamorphic zircon in equilibrium with garnet; their Proterozoic age constrains eclogites-facies metamorphism. Oxygen isotope composition for boudin-like eclogites confirms equilibrium between garnet and Proterozoic zircon domains. Values of $\delta^{18}O$ in the high-Mg portion of growth-zoned garnet coincide with those in zircon domains dated at ca. 1.9 Ga ($\delta^{18}O_{grt}$ = 4.6–5.0‰; $\delta^{18}O_{zrn}$ = 4.7–5.1‰). $\delta^{18}O$ in Archean magmatic zircon cores is distinguished by higher values up to 5.9‰.

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The continental origin of the eclogite at Mica Hill and implications for evolution of the Polar Urals, Russia

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The protolith recovery of eclogite is important to understand the nature and process of orogeny. It has been debated whether the eclogites of the Marun-Keu complex, Russian Polar Urals represent a fragment of metamorphosed oceanic crust or continental crust (Udovkina,1985; Dobretsov,1991; Shatsky et. al., 2000; Molina et. al., 2002,2004 ; Glodny et. al., 2003, 2004 ; Liu et. al., 2018). Here, we report the petrography, major and trace elements, Sm-Nd isotopic compositions and U-Pb geochronology of zircons found in eclogites from the garnet- peridotite-eclogite unit in the complex. The remnants of spinel and pyroxene and pseudomorphs of plagioclase can be found in some eclogites in addition to high MgO contents (most greater than 8 wt%) and $Mg^{\#}$ index ($Mg/[Mg + Fe^{2+}]$ = 0.7–0.8), high Al_2O_3 and CaO contents (16–26 wt%, 10–15 wt%, respectively), and lower TiO_2 (less than 0.5 wt%). Higher chromium concentrations (greater than 1000 ppm) exist for the eclogitic spinels. The light rare earth elements (LREE) are enriched, with a La_N/Sm_N ratios of 1.5 ~ 4.6, a positive Eu anomaly (δEu = 1.0 ~ 2.3), and εNd (t) = –3 ~ +2. These features indicate that the protoliths of eclogites are troctolite and gabbro, which may be formed in the rift environment of a continental margin. Using the SHRIMP method to date the zircons we obtained two groups of ages which are 500–490 Ma and 370–360 Ma, respectively. The older population constrains the formation time of the protoliths while the later population represents peak metamorphic age of the eclogite facies.

Therefore, the eclogite is the product of metamorphism of the newly formed Eastern European continental margin, which was subducted under the Syum-Keu intra-oceanic arc, and not the metamorphosed ophiolite (Paleo-Urals oceanic crust). This result is significant for understanding the tectonic evolution of the Polar Urals.

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High-ferrous olivine in coesite-bearing diamondiferous eclogite from kimberlite pipe Udachnaya (Siberia, Russia)

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Diamond-bearing eclogites are metamorphic rocks with typical Ultra High Pressure minerals – diamond and coesite – probing the deepest lithospheric mantle. Mixed paragenesis mineral inclusions in diamond, such as SiO_2-phase and harzburgitic garnet or olivine, were described in some kimberlite pipes (Wang, 1998; Ragozin et. al., 2006) and could indicate multistages of diamond growth, connected with a strong change in chemical environment (Stachel et. al., 1998). Here, we show results of our ongoing investigation of diamondiferous eclogite containing the rare paragenesis of coesite and olivine from the Udachnaya kimberlite pipe.

Eclogite Uv-09-537 is a coarse-grained rock consisting of ~40% garnet, 50% clinopyroxene and 10% coesite. Accessory minerals include diamond, phlogopite, plagioclase, olivine and potassium feldspar. Garnet has a chemically homogeneous core which is surrounded by a rim with significantly different composition. MgO content increases from 13.3 wt% to 19.2 wt%, and FeO decreases from core to rim from 16.1 wt% to 10.5 wt%. Whereas the garnet core has a normal rare-earth element (REE) distribution pattern, with an increase from light to medium REE, the rim REE shows progressive increase from light to heavy REE, with lower medium REE abundances than in the core. According to Jerde et. al. (1993), these REE patterns can be explained by a partial melting of eclogite. Clinopyroxene is omphacite with an admixture of K_2O up to 0.3 wt%. Olivine occurs as grains up to 60 μm located along grain boundaries between garnet and omphacite, but never in direct contact with coesite. The olivine chemistry in the studied sample differs from that of peridotite paragenesis, as forsterite content is low (#69–76), NiO content is below electron microprobe detection limit, and low contents of MnO (0.7 wt%), CaO (0.3 wt%) and P_2O_5 (0.7 wt%) were detected. Thus, we here report the first findings of high ferrous olivine in diamondiferous coesite-bearing eclogite from Udachanaya.

According to the experimental study of Safonov and Butvina (2006), formation of mixed paragenesis is the result of the reactions (1–2) of eclogite with K-Na-enriched fluid:

$$\text{Coe} + 1/6\text{K2O} + 1/12\text{Prp} + 1/12\text{Grs} = 1/3\text{Kfs} + 1/4\text{Di} \quad (1)$$

$$\text{Coe} + 2/9\text{K2O} + 2/9\text{Prp} = 4/9\text{Kfs} + 1/3\text{Fo} \quad (2)$$

whereby Coe is coesite, Prp is pyrope, Grs is grossular, Kfs is kalifeldspar, Di is diopside and Fo is forsterite.

The preservation of distinct garnet rims and mixed paragenesis suggests a relatively young metasomatic event, which induced strong chemical gradients but was not diamond-destructive.

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Eclogite, garnet peridotite, and amphibolite complexes in the Precambrian basement of Vestranden (northernmost Western Gneiss Region), western Norway

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Vestranden is a large basement window composed mainly of Precambrian granitic gneisses, analogous to the Western Gneiss Region (WGR) in Norway. Both windows are exposed west of the thick south-central Caledonian nappe pile, and both contain eclogite and garnet peridotite. Some of these HP rocks were metamorphosed *in-situ* (Mørk 1985), and others originated elsewhere and were tectonically inserted (Medaris , 2018). Distinguishing between these radically different origins is critical, with consequences for large-scale models of the tectonic evolution and the crustal architecture.

We have undertaken detailed investigation of the metamorphic petrology, zircon geochronology, and geochemistry of HP mafic, ultramafic and associated rocks in Vestranden, building on our previous data (Johansson & Möller, 1986; Johansson, 1987; Möller, 1988, 1990; Dallmeyer, 1992). Metagabbro and metadolerite that belong *sensu strictu* to the Precambrian orthogneiss complex record high-pressure granulite-facies Caledonian metamorphism. However, other types of mafic rocks occur interfolded with the Precambrian rocks: thick complexes of layered amphibolite with variable amounts of Grt–Bt–Ky paragneiss and subordinate marble and calc-silicate. The origin of these rocks has been unknown, but they also record high-pressure granulite- and amphibolite-facies conditions (*in-situ* micro-diamond previously proposed for Roan Grt–Ky-gneiss has not been verified). Moreover, two km-sized eclogite-facies complexes occur in Roan. One of them, the Kråkfjord complex, is a one km^2 layered intrusion with a basaltic carapace. The core consists of MgAl-rich kyanite eclogite with layers of garnet peridotite and Grt–Opx–Cpx pyroxenite. The carapace is FeTi-rich retroeclogite with minor Grt–Ky paragneiss.

U–Pb spot dating of composite zircon grains from FeTi-rich eclogite, Grt-Ky paragneiss, and a leucocratic meta-tonalite layer in the Kråkfjord complex (SIMS), and 0.1–0.5 m thick meta-tonalite layers and dykes in banded amphibolite elsewhere in Vestranden (LA–ICP–MS), reveals an Ordovician igneous origin of the tonalitic rocks, and Siluro-Devonian metamorphism of the complexes. Tonalite dykes are absent in the host orthogneiss complex, implying that the amphibolitic and eclogite–peridotite complexes were derived west of this Precambrian continental basement, from the Iapetus ocean, and have been tectonically emplaced into their present positions.

Trace element data (particularly the REEs) from the Kråkfjord FeTi eclogites indicate a MORB affinity. The peridotites, pyroxenites, and kyanite eclogites have significantly lower trace element contents, especially the LREEs. The tholeiitic AFM trend suggests that the rocks are related by fractional crystallization, with the core being cumulate layers (cp. the Eiksundal Complex in the WGR (Jamtveit, 1987). Enrichments in the alkalis, Pb, Sr, U, Th, and Ba suggest interaction with crustal fluids.

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Eclogite-to-granulite transition in the Ufipa Complex (Tanzania): A window to decipher the timescale of collision-induced crustal thickening

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The Ufipa Complex of Southwestern Tanzania is an eclogite-bearing Neoproterozoic metamorphic complex that is equivalent to the Mozambique Belt (e.g., Boniface & Schenk, 2012). The complex contains eclogites and granulitized eclogites in quartzofeldspathic gneiss. The less-retrogressed eclogite is massive, medium-grained, and bimineralic, consisting mainly of omphacite, garnet, rutile, and minor clinoamphibole. Metagabbroic eclogite is coarse-grained, kyanite-bearing, and partially granulitized. Garnet porphyroblasts contain inclusions of omphacite and kyanite, whereas the matrix omphacite is completely replaced by intergrowth of jadeite-poor omphacite and plagioclase with clinoamphibole. Kyanite nematoblasts (up to 1.2 cm in length) in the matrix contain inclusions of primary omphacite and clinozoisite; they are replaced partially by coronitic garnet and/or very fine-grained symplectitic aggregates of corundum and spinel. At least three metamorphic stages, an eclogite stage (M1), a granulite stage (M2), and a retrograde amphibolite stage (M3) can be distinguished. Garnet–clinopyroxene–kyanite–quartz geothermobarometry yielded a pressure of 1.9–2.1 GPa and T of 920–960 °C for the M1 eclogite stage and P of 1.3–1.6 GPa and T of 900–940 °C for the M2 granulite stage. Compositions of secondary clinoamphibole suggest ~~a~~ moderate temperature and pressure for the M3 stage. LA-ICP-QMS U–Pb dating of zircons from bimineralic eclogite yielded a concordia age of 588 ± 3 Ma. Sector-zoned or uniform, low Th/U zircons with inclusions of kyanite, rutile, omphacite and garnet suggest that these zircon grains are metamorphic origin; REE patterns support the growth of zircons during the M1 eclogite stage. On the other hand, metamorphic zircons, overgrowing around oscillatory-zoned magmatic cores (upper intercept age at 1,916 ± 20 Ma), from metagabbroic eclogite yielded a concordia age of 562 ± 3 Ma. Although the metamorphic rims do not contain eclogite-facies mineral inclusions, REE patterns and Eu anomalies suggest ~~a~~ growth during the M2 granulite stage. In-situ dating using a petrographic thin-section also confirmed that a zircon associated with coronitic garnet of M2 grew at ~ 560 Ma. New zircon geochronology revealed that time interval Δt between the M1 eclogite facies metamorphism and the M2 granulite-facies recrystallization was ~ 26 m.y. (Tsujimori et al., 2019)

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Carpholite- to coesite- to kyanite- to cordierite-stage: indicator minerals as proxies for the tectonometamorphic evolution of the Himalayan orogen

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The Himalaya is the result of a spectacular, still on-going, subduction-collision process. Within this 2500 km wide orogen, high pressure rocks are found in three environments: in the suture zone; close to the suture zone; and (mostly) far (>100 km) from the suture zone. During closure of the Tethys ocean, oceanic subduction produced an Andean-type magmatic arc along the Asian margin whilst low temperature–high pressure metamorphism prevailed in the accretionary wedge. Remnants of this stage are recorded in the Cretaceous-age blueschists (glaucophane-, lawsonite- or ***carpholite***-bearing schists) preserved in the NW Himalaya and South Tibet. Ophiolites in this fossil suture zone (e.g., Luobusa and Nidar) locally contain microdiamond and associated phases typical for ultra-high presssures but these are relict deep mantle phases unrelated to Himalayan subduction–collision processes. With closure of Tethys, the Indian margin continental crust, including its sedimentary cover, was dragged down quickly to extreme depths before partly exhuming at the same rapid rate. Such deeply subducted and rapidly exhumed Indian Plate basement and cover rocks occur directly adjacent to the suture zone and enclose eclogites of Eocene age, some ***coesite***-bearing (Kaghan/Neelum and Tso Morari), formed from Permian Panjal Trap, continental-type, basaltic magmatic rocks. Continued movement of the Indian plate northwards led to crustal stacking and a thickening and widening of the orogen. Crustal metamorphic sequences developed ***kyanite*** at this stage. After a roughly 10–20 Ma insulation period the stack of mostly middle- to upper-continental crust, with its high radiogenic heat production, started to melt. This resulted in the production of leucogranites and migmatites as well as the transformation of kyanite-bearing sequences into ***cordierite+/-***sillimanite-bearing rocks during ductile flow of deeper units up to shallower structural levels. Where eclogites occurred in the thickened stack, these were overprinted by granulite-facies assemblages during this much younger (Oligocene–Miocene) stage. Such granulitised eclogites residing in anatectic cordierite±sillimanite-grade Indian Plate are documented significantly south of the suture zone in Kharta/Ama Drime/Arun, north Sikkim and NW Bhutan). An exception is noted in the granulitised eclogites directly at the suture zone close to Namche Barwa in the eastern syntaxis. In summary, chronological sequence of carpholite-, coesite-, kyanite- and cordierite-bearing rocks demonstrates the transition from oceanic subduction to continental collision via continental subduction. The granulitized eclogites extruded in anatectic gneisses preserve evidence of former thick crust as possibly also in other wide hot orogens such as the European Variscides.

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Panafrican eclogite relicts in metaophiolites from Shackleton Range (Antarctica)

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Antarctica is a key region for the reconstruction of past supercontinents such as Rodinia (1.3–0.9 Ma) and Gondwana (600–500 Ma). HP/UHP metamorphic rocks are useful for reconstructing the evolution of these continents, because they evidence palaeo-subduction zones and/or suture zones due to continental collision. In Antarctica, remnants of HP/UHP metamorphism are barely documented (Godard & Palmeri, 2013). Apart from the well-preserved HP/UHP rocks of the Lanterman Range (Di Vincenzo, 2016 and ref. therein), HP relicts have been obliterated by late HT metamorphism or are hidden by the ice cap.

The Shackleton Range (SR) is a key area for the study of the Grenvillian belt (1.3–0.9 Ga) and the Early Palaeozoic fold belts related to the amalgamation of Gondwana (i.e., Panafrican orogeny). The SR forms an elongated E-W trending belt located at the NW margin of the East Antarctic Craton. It mainly consists of two terranes. The northern one has been divided into 3 units: the Pioneers Group (mainly Middle-Late Proterozoic metasediments), the Stratton Group (mainly Archaean-Middle Proterozoic gneisses) and an ophiolite complex interleaved with the previous groups (e.g., Talarico et. al., 1999). The ophiolite complex consists of medium-grade mafic and ultramafic rocks (garnet-epidote amphibolites, metagabbros, serpentinites) and less abundant metasedimentary cover rocks (garnet-staurolite-kyanite micaschists, garnet-bearing quartzites and grey marbles) (Talarico et. al. 1999). The petrological study of a garnet amphibolite from the ophiolite complex revealed cryptic evidence of an earlier HP assemblage. The amphibolite shows porphyroclasts of pyrope-rich almandine with low grossularite and spessartine contents ($prp_{33}alm_{58}grs_{7}sps_{2}$), and amphibole+plagioclase symplectites. The presence of kyanite relicts surrounded by spinel + anorthite + staurolite symplectites suggests that the rock derived from some kyanite eclogite by retrogression. The host rocks, garnet-staurolite-kyanite-bearing micaschists, show zoned almandine porphyroblasts with a typical bell-shaped spessartine pattern and low to very low pyrope and grossularite contents ($alm_{72\text{-}88}prp_{5\text{-}8}grs_{9\text{-}1}sps_{14\text{-}3}$, from core to rim), with Fe-rich staurolite (X_{Mg} = 0.12) and Al-rich muscovite (Si^{4+} = 3.0–3.1 for 11 equivalent O).

The petrological data suggest a different P-T evolution between the amphibolites, considered to be retrogressed eclogites, and the medium-P host micaschists, which have either been completely retrogressed or have never undergone an HP stage. In any case, the retrogressed eclogite is the first evidence of HP metamorphism in the ophiolite sequence of the Shackleton Range. ^{39}Ar-^{40}Ar ages of 510–485 Ma obtained on muscovite and biotite from the host micaschists indicate that the amphibolite-facies event corresponds to the final stage of the Panafrican orogeny, whereas the earlier eclogite-facies stage is likely to be related to the closure of the Mozambican Ocean between Africa and Antarctica.

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Were subduction styles, magmatism and *P–T–t* paths different at elevated mantle temperatures? Results of 2-D petrologic thermal-mechanical modeling

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Geochemical studies suggest that early Archean continental crust was predominantly mafic and gradually became more silicic from 3.0 to 2.0 Ga during and after a proposed transition to a global plate tectonics regime (e.g., Hawkesworth & Brown, 2018). The change to more silicic continental crust is attributed to (i) recycling of mafic crust into the mantle in continent–continent convergence zones and/or (ii) gradual addition of felsic crust in subduction zones. The first hypothesis has been supported by numerical modelling at conditional appropriate to the late Archean to early Proterozoic, which showed that extensive recycling via peeling-off (delamination) of mafic lower crust was near ubiquitous in continent–continent convergence zones (Chowdhury et. al., 2017; Perchuk et. al., 2018) and also occurs in a stagnant-deformable lid tectono-magmatic geodynamic regime (Sizova et. al., 2015). Here, we present the results of a systematic numerical modeling study of intra-oceanic subduction and associated magmatic processes, which are related to the second hypothesis (Perchuk, 2019). The numerical modeling suggests that a hotter mantle in the Precambrian led to retreating subduction and the generation of voluminous plateau-like basaltic crust due to decompression melting of hot asthenospheric mantle rising against the motion of the slab rather than the arc magmatism that is typical of contemporary subduction. This process continued as long as the retreating style of subduction was maintained. With increasing maturity of the system subduction retreat ceased and the role of decompression melting strongly decreased, whereas fluid-fluxed melting of the mantle coupled with melting of the hydrated slab started to produce basaltic and felsic arc volcanic rocks similar to those associated with contemporary subduction. Retreating subduction at higher mantle temperatures caused faster descent of the downgoing slab, leading to colder thermal gradients, similar to those associated with active subduction in the western Pacific today. The results of our experimental study demonstrate that a hotter mantle in the Precambrian changes dramatically both the slab dynamics and the processes of magma generation and crustal growth associated with intra-oceanic subduction zones.

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First find of phengite eclogites and garnet-glaucophane schists associated with jadeitites in the Kenterlau-Itmurundy serpentinite mélange (North Balkhash ophiolite zone; Central Kazakhstan)

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The east-west trending North-Balkhash ophiolite zone (NBOZ) is attributed to the Late Palaeozoic Dzhungar-Balkhash domain of Kazakhstan and extends over ~ 250 km for a width of 5–15 km. The NBOZ is mainly composed of a serpentinite mélange and tectonic slices of siliceous, basaltic and volcanogenic formations belonging to a Middle-to-Upper Ordovician accretionary wedge. The NBOZ serpentinite mélange contains a number of blocks, consisting in well-preserved residual and cumulative ultramafic complexes, along with layered gabbro and deformed plagiogranites. Dobretsov & Ponomareva (1965) also described numerous outcrops of jadeitites, including semi-precious varieties, associated with albitites and Ab-Act schists with minor relics of glaucophane, similarly included within the serpentinite mélange. Yermolov & Kotelnikov (1991) also reported garnet amphibolites and provided the U-Pb age of 450 Ma for zircons from the Ab-Act schists, reportedly formed after the jadeitites.

During recent fieldwork, phengite eclogites associated with garnet-phengite-glaucophane schists were observed for the first time, forming sparse pods or blocks of 4×5 m^2 in size in the NBOZ serpentinite mélange. In addition, different types of jadeitites and associated chlorite-zoisite, omphacite-jadeite, jadeite-richterite-fuchsite rocks have also been identified. The eclogites possess mineral assemblages of the metamorphic peak preserved, including large euhedral grains of garnet up to 3 mm in size, with prograde chemical zoning from core ($Sps_9Prp_7Grs_{32}Alm_{51}$) to rims ($Sps_6Prp_8Grs_{28}Alm_{57}$), as well as $Jd_{40–45}$ omphacite, high-silica phengite with $Si_{3.35–3.40}$ (a.p.f.u.), Rt and Qz. The peak mineral parageneses of the eclogites are replaced by clinozoisite, glaucophane with albite and later by barroisite with magnesiokataphorite. The garnet-phengite-glaucophane schists similarly contain euhedral garnet grains with an outstanding prograde zoning from Mn-rich core ($Prp_3Grs_{22}Sps_{32}Alm_{41}$) to Fe-rich rims ($Prp_6Grs_{24}Sps_6Alm_{64}$); glaucophane replaced by magnesioriebeckite, later by winchite and lastly by actinolite; phengite with $Si_{3.35–3.45}$ (a.p.f.u.); clinozoisite with various Al/Fe ratios; Rt, Ab and Qz. Lawsonite has not been recognized yet. Thus, it can be inferred that the Ab-Act schists described and dated by Yermolov & Kotelnikov (1991) likely represent strongly retrogressed blueschists rather than jadeitites, so that the obtained age estimate must be reassessed.

Preliminary P-T estimates for the eclogites indicate HP/LT peak conditions of ~ 15 kbar and 600 °C. The garnet-phengite-glaucophane schists were formed at a metamorphic peak of ~ 11 kbar and 530 °C. These primary results indicate the involvement of accretionary oceanic wedge complexes into the subduction process, whereas the presence of jadeitites and associated rock types, in turn, characterizes the processes in a mantle wedge, related to the precipitation from a fluid (P-type formations). Given the excellent preservation of the rock types, the Kenterlau-Itmurundy serpentinite mélange of the NBOZ represents a key locality for studying the processes in a subduction channel and mantle wedge.

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Deceiving zircon REE patterns and U-Pb dates from migmatite-hosted eclogites (Montagne Noire, France)

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Zircon REE patterns are widely used to attribute specific U-Pb dates to eclogite-facies metamorphism. Eclogites hosted in sillimanite-bearing migmatites in the Montagne Noire dome (French Massif Central) reached c. 750 °C, 21 kbar (pseudosection modelling and Ti-in-zircon thermometry) before significant decompression at high temperatures. Zircon crystals in the eclogite yield three distinct clusters of dates at c. 360 Ma, 340 Ma and 315 Ma. Whatever their apparent ages, however, all crystals display identical REE patterns (no Eu anomaly, flat HREE), usually ascribed to eclogite-facies equilibration. In the absence of other criteria, none of these dates can be unequivocally attributed to the HP event. Using the results of a previously published Sm-Nd dating of garnet, and regional considerations, we interpret the 360 Ma date as the age of the eclogite-facies event. The 315 Ma zircon dates obtained from the embedding sillimanite-bearing migmatitic rocks are interpreted as the age of the low-pressure high-temperature (LP-HT) metamorphism (~6 kbar, 730 °C). This strongly suggests that this date of 315 Ma obtained on some of the zircon grains from the eclogite has to be related to the LP-HT overprint and cannot therefore be attributed to the eclogite-facies metamorphism as previously suggested. We argue that zircon could have grown in distinct pulses at different stages of the P-T evolution of these mafic rocks, characterised by the presence of significant proportions of stable or metastable garnet. We caution against the use of REE patterns to determine the age of HP metamorphism in eclogites occurring in migmatitic domes. Misinterpreted young ages may lead to inferring erroneous fast exhumation rates and consequently questionable geodynamic models.

Volatiles in diamonds from eclogite UV2440: evidence of different growth conditions

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An unusually large range of volatile components was determined by Gas chromatography-mass spectrometry for twelve analyzed diamonds found in xenolith of eclogite UV2440 from the Udachnaya kimberlite pipe. The extracted diamonds were divided into three groups: 1) brownish crystal with sculptures on the faces; 2) brownish crystal with many black inclusions inside; 3) small colorless octahedron sharp-rib flat-faced.

The main volatile components in diamonds are hydrocarbons and their derivatives: aliphatic (paraffins and olefins), cyclic (naphthenes and arenas), oxygen-containing (alcohols, ethers and esters, aldehydes, ketones and carboxylic acids), heterocyclic compounds (dioxanes and furans), nitrogen, halogen and sulfonated compounds, as well as carbon dioxide and water. The proportions of these components for the studied groups of diamonds differ. The total content of hydrocarbons and their derivatives in diamonds is 1, 2, and 3: 69.3 rel.%, 77.7 rel.% and 72.5 rel.%, respectively. In addition, diamonds have significantly different total content of aliphatic (CH_4-$C_{17}H_{36}$) and cyclic hydrocarbons (C_6H_6-$C_{16}H_{26}$). The highest relative content of these hydrocarbons (29.1%) was found for colorless diamond 3. The contents of light saturated hydrocarbons (methane CH_4-n-isobutane C_4H_{10}) in diamonds 1, 2 and 3 were: 1.38, 0.22 and 1.67, respectively. Methane was detected in all diamonds, but its amount is insignificant, especially in diamond 2 - 0.001 rel. %. The content of medium-saturated hydrocarbons (n-pentane C_5H_{12}-n-dodecane $C_{12}H_{26}$) in diamonds 1, 2 and 3 is 5.19, 2.19 and 2.03%, respectively. The proportions of heavy saturated hydrocarbons (n-tridecan $C_{13}H_{28}$ – n-heptadecane $C_{17}H_{36}$) for diamonds were significantly different: 3.14, 2.40 and 7.79 %, respectively. Comparison of the content of oxygenated hydrocarbons in different diamonds showed that it is the highest (58.6 rel.%) in dark diamond 3 and the lowest in diamond 2 (41.6%). For dark diamond 2, the main components are carboxylic acids (32.8% $C_2H_4O_2$ – $C_{14}H_{28}O_2$), while for diamonds 1 and 3 these are aldehydes (C_5H_8O – $C_{18}H_{26}O_4$), respectively 15.7 and 15.1%. According to the calculated H/(O+H) ratios (from 0.82 to 0.88), diamonds 2 and 3 crystallized under more reducing conditions than diamond 1. Chlorinated saturated hydrocarbons (paraffins) (1-chlorobutane C_4H_9Cl – 1-chlordecane $C_{10}H_{21}Cl$) and chlorinated and brominated unsaturated hydrocarbons (olefins) (3-methyl-3-chloro-1-butene C_5H_9Cl, 2-chlorophenol $C_6H_5ClO_3$ chloro-2-butanone C_4H_7ClO and 1-bromo-2-chloroethane C_2H_4BrCl), as well as saturated and cyclic fluorinated hydrocarbons (1-fluorobutene C_4H_9F and p-fluoroethylbenzene C_8H_9F). Twenty-nine nitrogen-containing compounds (from acetonitrile C_2H_3N to tridecannitrile $C_{15}H_{29}N$) were identified in diamond 2 and 16 in diamond 1. From 19 to 25 sulfonated compounds were present in all groups of diamonds. Among the sulfonated compounds, along with sulfur dioxide (SO_2), carbon disulfide (CS_2) and dimethyl disulfide ($C_2H_6S_2$), a large amount of thiophenes from C_4H_4S (thiophene) to $C_{13}H_{25}S$ (2-undecylthiophene) was found. The highest content of carbon dioxide (more than 9.0%) is characteristic of diamond 1. For diamonds 2 and 3 of the amount of CO_2 close – 3.5 and 3.2 %, respectively. The water content in diamond 3 (12.6 rel.%) is significantly higher than that in diamonds 1 and 2: 8.9 and 7.0 rel.%, respectively.

Diamonds from a single mantle rock exhibit a wide range of crystallization conditions during their formation. This include not only change in the redox conditions ((H/(O+H) that varies from 0.82 to 0.88), but also variation in the activity of sulfur and halogens. Our data clearly indicate the possibility of the formation of all described volatiles, including halogenated hydrocarbons, in a limited volume and their stability under the conditions of the upper mantle.

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Carbonatite and silicate metasomatism of peridotites of the cratonic lithosphere roots in relation with intensity and types of kimberlite magmatism

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Over 1200 kimberlite bodies, emplaced during Middle Paleozoic (MP) and two Mesozoic cycles, form 29 kimberlite fields inside the Siberian Platform (SP). All the economically important kimberlites are of MP age. An absolute majority of Mesozoic kimberlites have very low diamond grade ($T_{2–3}$) or even practically barren in diamonds (J_3), and this feature was related with very significant changes in thickness, composition and red-ox condition in the SP Lithospheric Mantle (LM) produced by influence of melts/fluids of Permian-Triassic Siberian Super Plume. Very significant differences in the amounts of kimberlite bodies and their average diamond grade are known for different SP kimberlite fields of MP age. A complex study of MP kimberlites, their LM xenoliths and diamonds (mineral and fluid inclusions) shows that these differences can be related with intensity of carbonatite and silicate types of metasomatic treatment of SP LM depleted peridotites of the LM roots and Lithosphere-Asthenosphere (LA) interaction zone.

Results of geochemical and isotopic studies of the LM extremely depleted peridotites presented in kimberlites by xenoliths of megacrystalline peridotites allowed us to conclude that: 1) U-type lithospheric diamond formation was related to initial stage of carbonatite metasomatism (CM) of minor intensity; 2) the increase of CM initially resulted in high concentration of CaO in Cr-pyrope to amounts characteristic to pyropes of lherzolite, then transformation of opx into cpx (wehrlitization) and subsequently carbonation of the initial Cr-pyrope harzburgites and dunites; 3) the final stage of opx-cpx transformation, wehrlitization and carbonation were not related to diamond formation; 4) the increase of the CM intensity resulted in a) enrichment of initially sub-calcic Cr-pyropes by Ca-component without any significant changes in their Cr-content and b) increase of total LREE content combined with shifting of peaks from Ce to Pr and then to Nd.

Minor scale of silicate metasomatism (SM) of these LM peridotites modified by CM of varying intensity produced conditions for generation of insignificant amount of kimberlite melts which form kimberlite fields with few bodies, but significant part of them are presented by high-grade kimberlite. Mirninsky and Nakynsky kimberlite fields can be the examples of this situation: the first includes 7 kimberlite bodies and five of them are highly diamondiferous, and the second includes 3 highly diamondiferous bodies. The increase of SM was related to increase of garnet and pyroxenes in the depleted peridotites and a decrease of Cr/(Cr + Al) ratio in the system. These changes are reflected in the pyrope composition that shows: 1) decrease of Cr/(Cr + Al) ratio leds to decrease of Cr-content in pyropes; 2) increase of Si and Al in the system combined with increase of opx and cpx contents shifts Ca-component content in pyropes (both low-Ca for harzburgites and high-Ca for wehrlites) to amounts characteristic for pyropes of lherzolite paragenesis. This situation is well presented in the LM xenoliths and minerals of LM origin in SP kimberlites of both Mesozoic (Triassic and Upper Jurassic) cycles of emplacement: 1) pyropes from these kimberlites have narrow range of Cr-content (usually 0.2–8.0 wt.%, or even less; 2) both low-Ca pyropes of harzburgite-dunite paragenesis and high-Ca ones of wehrlite paragenesis are extremely rare in these kimberlites.

In case of high intensity of both CM and SM in the LM peridotites, large volume of kimberlite melt can be produced that result in emplacement of hundreds of bodies in the kimberlite fields but with minor amounts. Daldynsky and Alakitsky kimberlite fields with over 250 kimberlite pipes and with only 7 of high-grade among them can be an example of this situation, and Upper Muna field with 29 pipes and with 7 of high-grade among them present intermediate situation between Mirninsky/Nakynsky and Daldynsky/Alakitsky kimberlite fields.

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Two orogenic cycles recorded by eclogite and host gneiss in North Qaidam orogenic belt, NW China

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Eclogites and host gneiss documenting two orogenic cycles not only contain essential information on subduction and exhumation processes during the last orogenic cycle, but can also expand our knowledge of the fossil orogeny of the earlier orogenic cycle. The North Qaidam orogenic belt (NQOB), consisting predominantly of gneiss and marbles with minor eclogite and garnet peridotite, is known as an Early Paleozoic UHP metamorphic belt in northwestern China. Recent studies have shown that some paragneisses in NQOB have recorded a Grenvillian (ca. 1000–900 Ma) metamorphic event in addition to the Early Paleozoic metamorphic event, indicating that the NQOB probably records the amalgamation of Rodinia. However, no eclogite with evidence of both Neoproterozoic and Early Paleozoic events have yet been reported.

We present here a new eclogite and its host paragneiss that have preserved the imprints of these two metamorphic events. The eclogite is composed of garnet, omphacite, phengite, epidote, amphibole, quartz and rutile. Garnet shows a pronounced core-mantle-rim zoning, with X_{Prp} slightly decreasing and X_{Grs} increasing from core to mantle, and X_{Prp} rapidly increasing and X_{Grs} decreasing from mantle to rim. Phengite has Si content up to 3.52 p.f.u. Geochemical data show that the eclogite has slight LREE-depleted REE distribution patterns, similar to present-day N-MORB. The eclogite zircon shows a magmatic core, a metamorphic mantle and a metamorphic rim. The mantle contains amphibole, epidote, titanite and quartz inclusions, whereas the rim contains garnet, omphacite and rutile. A protolith age of 1087 ± 23 Ma, and two metamorphic ages of 929 ± 14 Ma and 453–424 Ma were yielded on core, mantle and rim, respectively, by the U-Pb method. P–T conditions of 616–669 °C and 5–7 kbar have been obtained for the Neoproterozoic metamorphic event by considering the stability field in a P-T pseudosection of the mineral inclusions in zircon mantle. The combined results of the phase equilibrium modelling and Grt-Omp-Ph thermobarometers indicate a clockwise P–T path with peak conditions of 663 °C and 32.7 kbar was obtained for the Early Paleozoic metamorphic event.

The host paragneiss consists mainly of garnet, phengite, biotite, plagioclase, quartz and titanite, with minor omphacite and rutile. Garnet usually consists of an orange core with lower X_{Grs} but higher X_{Alm} and a pale pink rim with higher X_{Grs} but lower X_{Alm}. The foliated phengite in matrix has a Si content of 3.36 p.f.u. The phase equilibrium modelling and Grt-Omp-Ph thermobarometer calculation yielded a clockwise P–T path with peak conditions of 643 °C and 26.5 kbar. Zircon from the paragneiss is composed of a detrital core (994–1334 Ma), a metamorphic mantle and a metamorphic rim. The mantle displays flat HREE patterns with obvious Eu anomalies. The rims enclose garnet, omphacite and phengite inclusions. Two metamorphic ages of 912 ± 7 Ma and 447 ± 13 Ma were obtained on the zircon mantle and rim, respectively. These data suggest that the eclogite protolith probably belonged to a pre-Rodinia Mesoproterozoic oceanic crust, was emplaced in the active continental margin during the ocean subduction and, together with the host paragneiss, experienced the Neoproterozoic metamorphic event related to the Rodinia amalgamation and an Early Paleozoic continental subduction.

A re-evaluation of the mantle and crustal evolution of garnet peridotites from the northern UHP domain of the western Gneiss Region, SW Norway

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The Scandinavian Caledonides form a complex of nappes derived from both Baltica margin and more outboard terranes, some of Laurentian affinity. The nappes, thrusted from W/NW to E/SE (during Caledonian times) over the Baltic basement, are sub-divided, from bottom to top, into the Lower, Middle, Upper and Uppermost Allochthons. The Lower and Middle Allochthons are derived from the overridden continent Baltica, whereas the Uppermost Allochthon contains exotic continental segments and arc complexes interpreted to represent either fragments of Laurentia or nearby arc terranes. The intermediate Upper Allochthon is actually a variety of thrust-bounded terranes derived either from the thinned outermost edge of Baltica or from more outboard, oceanic terranes (Gee et. al., 2013).

Within the central part of the Scandinavian Caledonides orogenic garnet peridotites occur at two distinct structural levels: 1) within Proterozoic basement gneisses of the western Gneiss Region (WGR), SW Norway (Brueckner et. al., 2010) and 2) within the Seve Nappe Complex in northern Jämtland, Sweden (top part of the Middle Allochthon; Gilio et. al., 2015). This presentation is concerned however only with the garnet peridotites located within the northern part of the WGR, SW Norway (Van Roermund, 2009).

About 20 years ago relict majoritic garnet microstructures were discovered (for the first time) within relatively coarse-grained garnetites and/or porphyroclasts dispersed within well-layered garnet-free/garnet-bearing peridotites and associated pyroxenites (Otrøy island, northern part WGR), SW Norway (Van Roermund and Drury, 1998). The microstructural evidence consisted of 3 basic elements: 1) Crystallographically-oriented two-pyroxene exsolution lamellae/needles inside cores of garnet. 2) Precipitation-free rims around these garnet cores and 3) Interstitial pyroxene crystals that decorate straight triple-point junctions (between garnets boundaries) and/or between two adjacent garnet grain boundaries. This exsolution microstructure formed the onset of a lot of (re)new(ed) research concerning the petrogenesis of orogenic garnet peridotites located within the northern UHP domain of the WGR.

In this presentation I will focus/summarize/review the “consequences” of the discovery of this “complex” exsolution microstructure (including “associated and new” mineralogical, geochemical- and geochronological work) for the petrogenesis/tectonometamorphic evolution of the orogenic garnet peridotites in (the northern part of) the WGR, SW Norway.

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The lithosphere beneath an active orogen: petrologic constraints from high-pressure xenoliths in western Tibet

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Xenoliths hosted in post-collisional volcanic and subvolcanic rocks are firsthand samples of the lower crust and the upper mantle. They thus give direct information on the structure and composition of the roots of the orogens, providing insights on the deep crustal dynamics and on the interaction between lower crust and mantle.

The Tibetan Plateau (TP), together with the Pamir-Karakorum Range (PK), is the highest and largest topographic plateau on Earth. Post-collisional ultrapotassic dykes hosting lower crustal and/or mantle xenoliths have been reported from both the PK (e.g. Kooijman et al., 2017) and the central-eastern segment of the TP (e.g. Cheng & Guo, 2017). Post-collisional ultrapotassic dykes have been also found in the western part of the TP (Pognante, 1990), but no crustal xenoliths have been reported so far from this area.

Here we present preliminary petrologic data on xenoliths hosted by lamprophyric dykes from the Shaksgam Sedimentary Belt (Xinjiang, China), a sedimentary unit correlated to South Pamir (Groppo et al., 2019) and located at the junction between the PK and the TP in western Tibet.

The lamprophyric dykes are mostly porphyritic minettes. The abundant Grt xenocrysts, characterized by kelyphites, could be mantle derived.

Most of the analysed xenoliths are of deep crustal or mantle origin and include:

(a) Ap-bearing clinopyroxenite (Cpx, Ap, <Kfs, <Phl,): mineral assemblage and microstructures suggest that these xenoliths might derive from a metasomatized mantle;

(b) basic granulite (Cpx, Grt, <Pl): it reflects thermobaric conditions typical of the deep crust;

(c) acid granulite (Qz, Kfs, Grt, Pl, <Ky): the almost anhydrous assemblage and the observed microstructures suggest that these xenoliths might represent the restite of a former pelitic protolith that experienced HP dehydration melting.

Overall, the analysed xenoliths provide new data on the lithospheric structure of a still poorly known segment of the TP, that could potentially have implications for the understanding of the crust-mantle interaction in the deep roots of active orogens.

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New ultra-high ptessure belt in Borborema province, NE Brazil: implications for western Gondwana assembly

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The assembly of western Gondwana in the NE Brazil was marked by late Neoproterozoic closure of Pharusian-Goianides ocean (Santos et. al, 2009; Ganade de Araujo et. al., 2014). In this portion, the Borborema Province correspond to a piece of the Dahomeyide-Pharusian belt in the South America. The convergence was responsible for generation of the elongate NE-SW to E-W Santa Quitéria Continental Magmatic Arc (SQCMA) (Fetter et. al., 2003). Surrounding this arc to the west, Santos et. al., (2015) identified the UHP Forquilha eclogite zone. New whole-rock geochemistry, U-Pb geochronology and Lu-Hf ratio in zircon, as well as thermobarometric studies along the eastern margins of the SQCMA support a new tectonic model. This eastern margin, from the arc, is composed by tonalite to granodiorite gneiss (partially migmatized), schist, quartzite marbles, calc-silicates, metamafic rocks (garnet clinopyroxenite and garnet amphybolite) and paragneiss with sillimanite, kyanite, garnet and clinopyroxene. The mafic orthogneiss, in contact with the SQCMA, comprise a rest of island arc with U-Pb zircon ages range 790 to 900 Ma. Provenance U-Pb zircon and geochemical analyses of the metasedimentary sequence, indicate several sources for this material, from: i) passive margin of Archean-Paleoproterozoic basement; ii) island arc with higher Tonian – Calymian zircons contribution, and; iii) active margin that encloses zircons grains range Archean to Neoproterozoic ages. The metamafic rocks represented by metric to decametric lenses and elongated boudin of isotropic to weakly anisotropic garnet clinopyroxenite occur enclosed within paragneiss migmatite and calc-silicate rocks. Although this rock was extensively retrograted, the more isotropic mafic rocks present coesite inclusion in garnet. This new discovery of coesite-bearing eclogite by petrography and Raman spectroscopy records a new ultra-high pressure (UHP) zone in the Borborema Province and brings new insights for the late Neoperoterozoic assembly of the western Gondwana.

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Paired metamorphic belts in the Usagaran orogen of Tanzania: evidence for one-sided oceanic subduction in the Palaeoproterozoic

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The eclogite occurrences in the Ubendian and Usagaran orogens along the southern border of the Archaean Tanzania Craton mark the sites of two Palaeoproterozoic sutures between the Tanzania Craton and adjoining Archaean crustal blocks (Bangweulu block in the SW and an unnamed Archaean block in the East African Orogen). Both occurrences of Palaeoproterozoic eclogites show trace element patterns (depleted in LREE) similar to those of MORB, indicating that the precursor melts formed in a depleted mantle source and that the eclogites formed from oceanic crust. Despite numerous plagioclase 'exsolutions', up to 30 mol% jadeite component is preserved in omphacite and points to minimum pressures of ca. 18–20 kbar at ca. 750–800 °C for the Usagaran eclogites. For the Ubendian eclogites, the peak conditions are lower, at least 15 kbar and 700 °C, which are not well constrained due to later penetrative orogenic overprinting. The ages of eclogite metamorphism have been constrained by U-Pb zircon and monazite dating at 2.0 Ga (Usagaran) and 1.87 Ga (Ubendian). In both orogenic belts the eclogites are associated with belts of low-P/ high-T granulites (garnet±cordierite-sillimanite) with ages (CHIME monazite dating) nearly identical (1.96–2.05 Ga) to those of the subduction metamorphism. The granulite belts are interpreted as spatially and temporally paired to the high-P/ low-T oceanic subduction belt and formed in the hot plate above a subduction zone. This indicates the operation of one-sided oceanic subduction during the Palaeoproterozoic. In the Usagaran Belt the granulites (820 °C/6.5 kbar) are high-T mylonites characterised by an anticlockwise P-T evolution and a strong late-stage hydration after mylonitisation. The African eclogites (all with MORB chemistry) indicate that during the formation of the Nuna supercontinent the Palaeoproterozoic oceanic lithosphere around the Congo-Tanzania Craton was thick, cold and rigid enough to become subducted in a similar fashion as cold oceanic lithosphere in the modern plate tectonic regime. However, apparent geothermal gradients of 12–14 °C/km for the Palaeoproterozoic eclogites are higher than those of Neoproterozoic and Phanerozoic eclogites and are interpreted as the result of warm subduction in a hotter Palaeoproterozoic Earth.

Other known Palaeoproterozoic subduction related eclogites of MORB chemistry are those from the Nyong complex of Cameroon (2.09 Ga; Loose and Schenk, 2018), from the Kasai block (2.09 Ga; DRCongo; Françoise et. al., 2018) and from the Belomorian province (1.9 Ga; Russia; Skublov et. al., 2011).

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Jadeite-rich rocks and their blueschist host from Queyras (Pennine Units), Western Alps, France: The neglected locality

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Since the early petrological work on jadeitite in the 1950s and 1960s, an increasing focus on jadeite-bearing rocks has led to a better understanding of their origin and has also helped, especially with respect to archeological studies, to locate the original sources of ancient tools and cultural objects manufactured from these rocks. A few previous studies of the Queyras jadeite-rich rocks focused on tectonics or on associated high-pressure metamorphic rocks they are associated with. Detailed mineralogical and geochemical information, especially in the light of new interpretations such as vein precipitation (P-type) versus metasomatic replacement (R-type) formation, is missing. Early studies that describe different occurrences of jadeite from the French Western Alps were presented by Saliot (1979) and Caby (1990).

Our studies focus on five outcrops from the Queyras area which are considered part of the subducted Piemont-Ligurian ocean. Four different types of jadeite-bearing rocks were distinguished: (I) discordant jadeitite and jadeite-rich veins; (II) jadeite blueschist and amphibole-free jadeite metabasites as country rocks; (III) jadeite blueschist and amphibole-free jadeite metabasites without veins; (IV) jadeite-quartzite. Jadeitite is composed of jd + omp + ab ± cal ± ap ± czo ± white mica, while their blueschist and amphibole-free metabasite country rocks contain jd + omp + ab + ttn ± gln ± lws ± di/aug ± czo ± ph ± cal ± chl ± ap ± rt ± zrn (and in one case quartz). Jadeite-free blueschist can additionally contain epidote. In some types of blueschist, magmatic relics of diopside may contain lamellae of jadeite and omphacite. Strong evidence exists for the formation of the jadeitite veins by precipitation from a Na-Al-Si-Ca-CO_2-P-rich fluid (P-type), whereas in jadeite quartzite, a metasomatic replacement formation (R-type) is likely. Local occurrences of omphacite enveloping older jadeite crystals point towards a change in fluid composition with time. Bulk rock composition suggests an overall gabbroic nature of the protolith of the jadeite blueschist and amphibole-free jadeite metabasite, whereas the jadeite-quartzite likely represents former oceanic plagiogranite. Pressure-temperature pseudosections suggest peak metamorphic conditions for jadeite blueschist of 315–405 °C and 8–11 kbar, whereas for the jadeite-quartzite PT conditions of 340–450 °C and 10.3–13 kbar were derived. Both rock types thus experienced blueschist-facies conditions along a geothermal gradient close to 10 °C/km. The jadeitite and jadeite-rich rocks from Queyras are not directly related to a serpentinite mélange and represent one of the few localities worldwide that exhibit a direct contact to blueschist country rocks.

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From oceanic to continental subduction in the Kokchetav subduction-collision zone: two contrasting types of eclogites from the Sulu-Tyube area

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Two types of eclogites were identified in the Sulu-Tuybe area (Kokchetav massif). The coarse-grained eclogites occur as large body (1.5 × 0.5 × 0.5 km). Besides the large body of the Sulu-Tyube, hill in the northwest there are numerous outcrops of fine and medium-grained eclogites, forming separate boudins, tracing the outline of original layers. In the coarse-grained eclogites, garnet porphyroblasts bear inclusions of titanite, carbonate, zoisite and epidote, which imply metabasites of epidote-amphibolite facies as a protolith. The primary minerals in the matrix are omphacite, amphibole and zoisite. Medium- and fine-grained eclogites are composed of garnet, omphacite, quartz, rutile, with optional phengite, amphibole and zoisite. The estimated equilibrium temperatures of coarse-grained eclogites range between 600 and 650 °C. Equilibrium temperatures for the medium-grained eclogites vary from 650 to 740 °C. The coarse-grained eclogites have REE patterns typical for N-MORB basalts with $(La/Yb)_N$ ratios within 0.65–0.84, whereas the medium-grained eclogites show slight enrichment of LREE ($(La/Yb)_N$ of 0.87–1.12). Coarse-grained and some medium grained eclogites display multi-element patterns resembling that of N-MORB. Two medium-grained samples have pronounced negative Nb, Zr and Ti anomalies. The coarse-grained eclogites have Sm/Nd ratios higher than that of medium- and fine-grained eclogites (0.198–0.210 and 0.189–0.198, respectively). Coarse-grained eclogites possess $_{Nd}$(T) similar to those of the depleted mantle (+7.2-+7.9), while $_{Nd}$(T) values of medium-grained rocks are apparently distinct (+4.0 -+1.0). The (T_{DM}) ages for the medium-grained eclogites show a range of between 2.1 and 1.6 Ga. The protholite age of coarse-grained eclogites it’s difficult to determine because its $^{147}Sm/^{144}Nd$ ratio is close to that of depleted mantle reservoir (DM). The coarse-grained eclogite (St-95-3) with the lowest Sm/Nd ratio yield the youngest Neoproterozoic Nd model age of 670 Ma. This age is close to the initiation of the destructive rifting processes in the Tarim-Tien-Shan-Kazakhstan paleocontinent (750–700 Ma) related to an intense break-up of Rodinia.It appears that the eclogites of the Sulu-Tyube area have both oceanic and «continental» affinities and mark two stages (oceanic and continental, respectively) of the Neoproterozoic-Cambrian convergence.

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Alluvial diamonds from northeast of Siberia craton: evidence for their formation in subduction environment

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Inclusions of the eclogite facies minerals are predominant in alluvial diamonds from northeast of Siberia craton (>72%): garnet, omphacitic clinopyroxene, jadeite, kyanite, coesite, K-feldspar, rutile and corundum. According to Orlov's classification (Orlov, 1977), diamonds from placers in the northeastern Siberian Craton may be divided into three groups as follows: (group 1) typical octahedral-to-rounded diamonds of variety I in Orlov's classification; (group 2) yellow-orange or dark grey cuboids of varieties II and III in Orlov's classification; (group 3) rounded dark crystals of variety V in Orlov's classification. The diamonds of variety V are derived from unknown primary sources. Nitrogen concentrations in diamonds with eclogitic inclusions are generally high (median value of 950 ppm) compared with diamonds of the ultramafic suite (median value of 513 ppm). Diamonds of group 3 (variety V) have relatively high nitrogen levels (from 1500 to 3500 ppm, median value of 2549 ppm). The average nitrogen content in Group 3 diamonds is five times higher than the worldwide average. $\delta^{13}C$ values of the diamonds range from -27 to – 3‰ for eclogitic. Diamonds belonging to variety V have $\delta^{13}C$ values from –24.1 to – 17%. Many placer diamonds on the diagram $\delta^{13}C$ – N fall outside the sector for kimberlitic and lamproitic diamonds as defined by the upper levels of nitrogen for a given $\delta^{13}C$ (Cartigny et al., 2001). All diamonds of variety V fall outside the limit defined by Cartigny et. al. (2001). The diamonds we studied lack $\delta^{13}C$–N correlations, but the $\delta^{13}C$ trends in some crystals may correspond to the mixing of sedimentary carbon from subducted slabs with mantle material. The trace element composition of eclogitic garnet inclusions supports a crustal origin for at least the high-Ca garnets, which show flat HREE patterns and in some cases a positive Eu-anomaly. Garnets with strong positive Eu anomalies also have high Sr contents. The subduction origin of diamonds of eclogitic paragenesis with low $\delta^{13}C$ is also favored by the negative correlation of the $\delta^{13}C$ values of host diamonds with the oxygen-isotope composition of garnet inclusions. High-Ca eclogitic garnets show the heavier oxygen isotope compositions ($\delta^{18}O$ 6.5–9.6‰) whereas low-Ca eclogitic garnets have a range of from $\delta^{18}O$ 5.7 to 7.4‰ (Zedgenizov et al., 2016). It suggests that O isotopes and trace elements are both inherited from crustal protoliths, which however had variable composition.

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Vestigial UHP mineral assemblages in the Archean rocks from the Kuru-Vaara quarry, Belomorian Province, Kola Peninsula, Russia

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A central problem in the Earth Sciences is when plate tectonic began, and hence, when a deep subduction of oceanic crust had started. There is a growing lot of geological and isotope-geochemical data testifies that the Early Precambrian geodynamics was to some extent similar to the modern plate tectonics. Nevertheless, a lack of Archean crustal ultra-high pressure (UHP) rocks remains mainly responsible for number ideas on a specific Precambrian tectonism.

So far a key question, as UHP mineral assemblages were survived in the Early Precambrian crustal records or they are lacking at all, is of crucial importance for a deep insight into the Earth geodynamic history. As a result of ours studies we report findings of vestigial UHP mineral assemblages in the Late Archean eclogitic rocks of ocean crust provenance, which in turns coupled with metamafics of mantle wedge origin, from the Belomorian poly-metamorphic high-grade Province, NE Baltic/Fennoscandian Shield. UHPM is recorded by abundant graphitized diamond, exsolution tiniest lamellae of phlogopite and quartz in clinopyroxene precipitated of silica- and potassium-rich clinopyroxene-precursor and plentiful zoisite inclusions with rare relics of lawsonite armored in pyrope-rich garnet. The inferred peak UHPM falls in range P ~ 5.5–6 GPa and T ~ 900–1000 °C thus corresponding to apparent geothermal gradients of 6–7 ^{o}C/km similar to those found in recent cold subduction regimes. On the other hand, these resulting values follows a conductive geotherm roughly consistent with the 35 mW/m^2 average surface heat flow of Archean cratons coupled with underlying diamond-bearing subcontinental lithosphere mantle. By this means the Belomorian crustal eclogites and related meta-ultramafic rocks may be considered as the best candidate to clarify a provenance of mantle diamondiferous eclogite or peridotite xenoliths brought up by kimberlites in Archean cratons. Another result of the UHPM finding implies that partial melting of deeply subducted Archean oceanic crust should be commenced at the mantle depths in the course of eclogite exhumation and culminated at the depths of amphibole stability field thus leading to forming TTG gneisses of the early continental crust.

Zircon U-Pb and O isotope response to differential fluid environments during continental subduction-zone metamorphism

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Zircon is one of most common accessory mineral widespread occurring in various types of rock. Due to its robust physical and chemical properties, zircon is widely used in geochronology and geochemical tracing. Generally, it is suggested that either new growth or recrystallization of metamorphic zircon would involve a fluid phase. Here, a case study is carried out on zircon U-Pb and O isotope response to differential fluid environments during the continental subduction-zone metamorphism from the Dabie orogen in central-eastern China. Zircon separates from Bixiling eclogites show oscillatory or patch zonation in CL images, and gives high Th, U concentrations with Th/U ratios > 0.1, suggestive of their magmatic origin. They yield concordant or near concordant Neoproterozoic U-Pb ages and homogeneous O isotopes with a weighted mean of 3.04 ± 0.08‰ and 3.46 ± 0.11‰, respectively. This indicates their formation during Neoproterozoic magmatism with slight hydrothermal alteration of meteoric water due to the subtly lower O isotopes relative to normal mantle values, without significant U-Pb and O isotope modification under relative close-system fluid environment. On the other hand, the majorite of zircon populations from Shuanghe eclogites, which closely envelop a metamorphic quartz vein, show no or faint zoning in CL images, and give low Th, U concentrations with Th/U ratios < 0.1, suggestive of their metamorphic origin. They yield concordant or nearly concordant Triassic U-Pb ages and homogeneous negative O isotopes with a weighted mean of -1.03 ± 0.14‰, demonstrating that they would form through either new growth or dissolution-recrystallization of preexisting inherited zircon with the involvement of vein-forming metamorphic fluid under open-system fluid environment. Even though, several zircon separates from Shuanghe eclogites exhibit pre-Triassic ages and scattered positive O isotopes ranging from 3.93 to 11.65‰, indicative of their detrital origin. They would survive the vein-forming fluid activity with more or less modification of U-Pb and O isotopes under such a fluid environment, possibly due to their relative perfect crystallinity. Collectively, zircon U-Pb and O isotope would exhibit various behaviors response to differential fluid environments during continental subduction-zone metamorphism. This reminds us to be cautious on the application of geochronology and geochemical tracing with zircon extracted from metamorphic rocks.

An update on the exhumation path of the late Paleozoic eclogite in Japan: Significance of retrograde pumpellyite in garnet blueschist

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Late Paleozoic high-pressure and low-temperature metamorphic rocks, known as the Renge metamorphic rocks, are sporadically exposed in southwest Japan. The presence of lawsonite-blueschist and glaucophane-eclogite provides evidence of a relatively 'cold' geotherm in the paleosubduction zone (Tsujimori, 2002). Recently, retrograde pumpellyite (Pmp) was newly found in a garnet blueschist that is Mg-rich equivalent of retrograde eclogite of the Yunotani Valley in the Omi area of the Hida Mountains (Shinji & Tsujimori, 2019). The pumpellyite with high Al/(Al + Mg + Fe) was found only in pressure shadows around garnets; it is associated with secondary glaucophane (Gln), epidote (Ep/Czo), chlorite (Chl), titanite, phengite, albite (Ab), and quartz, which all characterize a retrograde blueschist-facies mineral assemblage after peak eclogite-facies mineral assemblage. The compositional range of the pumpellyite is very similar to that of blueschist-facies pumpellyite rather than that of prehnite–pumpellyite-facies pumpellyite. These features are comparable with retrograde pumpellyite in late Paleozoic garnet blueschist (with relict eclogite-facies mineral assemblage) in the Osayama area of the Chugoku Mountains. Equilibrium phase calculation confirmed that the pumpellyite is stable at a low temperature and pressure portion of the lawsonite–blueschist-facies. The retrograde pumpellyite might have been formed by the univariant reaction Gln + Czo + H_2O = Pmp + Chl + Ab in the NCMASH with excess chlorite, albite, quartz, and H_2O. *T*–bulk-composition (Mg) pseudosection suggests that pumpellyite appears preferentially in high Mg/(Mg + Fe) bulk compositions. The limited occurrence of retrograde pumpellyite in the Yunotani garnet blueschist and retrograde eclogite would be explained by Mg-rich bulk compositions. Also, the limited occurrence in pressure shadows around garnets suggests that the fluid trapped in the pressure shadows might have enhanced growth (or precipitation) of pumpellyite. The presence of abundant fluid inclusions in retrograde albite and calcite in pressure shadows around garnets supports this idea. This finding provides strong evidence that the deeply subducted (eclogite-facies) metabasaltic rocks both in the Hida Mountains and the Chugoku Mountains were subjected to a very similar blueschist-facies overprinting locally reached the pumpellyite stability field. The 'Franciscan-type' cooling path suggests a 'steady-state' underflow of the paleo-Pacific oceanic plate in late Paleozoic at a convergent margin of the South China Craton.

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Nature and (in-)coherent metamorphic evolution of subducted continental crust in SW Mongolia

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Despite the abundance of continental arcs and microcontinents in the Central Asian Orogenic Belt, most HP complexes show intraoceanic affinity, whereas there is only limited evidence for subduction of the continental crust. Recently, a new high-pressure assemblage of eclogites, orthogneisses and metasedimentary rocks (^{40}Ar-^{39}Ar, 537–548 Ma) was discovered in the Early Caledonian accretionary complex of SW Mongolia located southwest from Dzabkhan-Baidrag microcontinent (Štípská et. al., 2010; Skuzovatov et. al., 2018). Coupled geological position and geochemical inheritance of metabasites indicate possible formation of rock protoliths in a rifted-margin setting in the Early Neoproterozoic followed by continental subduction in the Late Ediacarian (Buriánek et. al., 2017; Skuzovatov et. al., 2018). However, the nature of subducted crust, coherence of metamorphic history of eclogites and associated rocks, and their relation to Neoproterozoic accretion processes in the southern CAOB have not been justified so far. Detailed studies revealed that a major part of the subducted heterogeneous complex is composed of Neoproterozoic (~0.96 Ga) and Mesoproterozoic (~1.6 Ga) felsic gneisses, which exhibit variable development of deformation fabrics and degree of metamorphic recrystallization, recorded by fine-grained quartz matrix and newly formed garnet and epidote. Associated metasedimentary rocks with the precursor formed at different depths of an Early Neoproterozoic or older passive continental margin, bear two distinct (single-stage and two-stage) records of ductile deformation. Thermobarometric and pseudosection modelling studies showed metamorphism of felsic gneisses at 570–600 °C but relatively low-pressure estimates limited to 1.4–1.6 GPa dependent on the implied X_{Fe3+}. In contrast, garnet- and kyanite-bearing metapelites with multi-stage foliation record colder subduction (<500 °C) but to greater depths corresponding to 2.0–2.3 GPa. Therefore, some metasediments might follow a coherent evolution with eclogites, whereas subduction of the thicker and buoyant felsic crust might have terminated at shallower crustal levels.

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Archean-Paleoproterozoic crustal evolution the Belomorian Province (north-eastern Fennoscandian Shield) and position of eclogites

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The crustal section of the Belomorian Province (BP) formed during the Meso-Neoarchean Belomorian accretionary-collisional orogeny. The BP was under the influence of a 2.40–2.45 Ga superplume. Then the BP was the south-western foreland of the Paleoproterozoic Lapland-Kola collisional orogen (LKO) and was reworked during the Lapland-Kola orogeny.

In the BP the oldest crustal rocks consist of a ca. 2.9 Ga ophiolite-type complex, which formed an initial stage of the continental crust growth apparently due to a subduction initiation process. Subduction-type crust-forming events took place from ca. 2.88 Ga to ca. 2.72 Ga as indicated by occurrences of arc metavolcanics, metagraywacks, TTG and remnants of supra-subduction ophiolite and eclogites. The Archean eclogites occur as numerous blocks in the TTG matrix and are well studied in the Gridino area on the western shore of the White Sea, and the Salma and Kuru-Vaara localities in the Kola Peninsula. These rocks all stem from Archean basalt of MORB geochemical affinity. Collisional events were predominant at ca. 2.7–2.6 Ga time span and are manifested by S-type and anatectic granites coupled with HP amphibolite- to granulite-facies metamorphism. These collisional events were manifested themself mostly in crustal stacking and later crustal extension marked both by leucogabbro and molasse-type volcanoclasic rocks.

At the end of the Archean the BP continental crust together with other Archean nuclei of the Fennoscandian Shield (FS) was apparently assembled into the Kenorland supercontinent. At the beginning of the Paleoproterozoic, this supercontinent began to breakdown due to a superplume impingement. Its initial manifestation is traced by LIP-type bimodal volcanics and large layered mafic-ultramafic intrusions. In the BP these are represented by numerous dykes and small intrusions of gabbronorite and rare massifs of charnokite.

The Archean nuclei of the FS began to breakdown ca. 2.1–2.0 Ga ago, which is evidenced by the Jormua and Outokumpu ophiolite and numerous tholeiitic dykes. The Lapland-Kola Red Sea type ocean was opened in the northern part of the FS, which is documented by the ca. 2.0 Ga MORB-type metabasalts in the Pechenga rift-belt located between the Kola and Belomorian provinces. Its closure resulted in the formation of metasediments (khondalites) and arc-type plutonic rocks in the Lapland and Umba granulite belts, arc-related volcanic suites and TTG rocks in the Inari and Tersk terranes. The final closure and consequent collision occurred 1.93–1.90 Ga ago in the Russian part of the FS and 10–30 Ma later in the Finnish part thus forming the LKO. The BP experienced a strong tectono-metamorphic reworking which encompassed its whole crustal section as evidenced by the available seismic data. These data reveal a complex thrust-type architecture, which suggests dismembering of the Archean crust during both the Belomorian and the Lapland-Kola orogenies.

Despite this, the Archean vestigial HP eclogite mineral assemblages do occasionally occur and provide insight into the nature of early continental crust-forming geodynamics. The Lapland-Kola orogeny led to a thickening of the BP crust and gave rise to metamorphism of eclogite-HP granulite facies at deep crustal levels as clearly evidenced by partial eclogitization of the Paleoproterozoic basic dykes most prominent in the Gridino area and Archean eclogite.

Systematics of oriented inclusions in garnet from pyroxenite in Mg-Cr type peridotites from the Western Gneiss Region, Norway

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The Western Gneiss Region (WGR) in Norway exposes nearly 20 garnet-peridotite bodies (Brueckner, 2018), which enclose layers and lenses of garnet-pyroxenite and garnetite. The latter rock types can contain garnet with oriented lamellae of pyroxene interpreted to be formed by exsolution from majoritic garnet (northern WGR: van Roermund & Drury, 1998; central WGR: Spengler et. al., submitted). Here we state that oriented lamellae in pyroxenitic garnet characterise many ultramafic bodies. New samples from Aldalen, Almklovdalen, Gurskebotn, Kalskaret, Nogvadalen and Raubergvik differ in the degree of dynamic recrystallisation, but share porphyroclastic garnet with homogeneously distributed lamellae of either silicates or oxides or both in crystal cores. These lamellae vary in shape from acicular to short-prismatic, in width from 45 µm to sub-micron size, and in spacing from a few 100 µm to a few microns. As a rule: the smaller the size and spacing of the lamellae as shorter is their prismatic shape. Smaller lamellae can fill the space between larger lamellae, which suggests consecutive generations. However, most porphyroclasts show only one generation. Electron microprobe analyses and Raman spectroscopy characterise the lamellae as clino- and orthopyroxene, rutile, ilmenite, Mg-chromite and amphibole. They occur monophase and polyphase. Oxides and silicates are spatially closely associated and interconnected, which suggests a joint origin from siliceous and titaniferous precursor garnets. The largest lamellae are made up of pyroxene only. Based on element diffusion length and lamellae size, the exsolution process may have formed the largest pyroxene lamellae first, followed by those of pyroxene and oxides. The microstructural systematics suggests that all studied pyroxenites have a shared origin, which is related to high-temperature mantle processes (Spengler et. al., 2018). Some samples have an additional, younger generation of lamellar and other inclusions that occur lined-up along planar, parallel structures cutting across cores but not rims of garnet. These inclusions comprise oxides, silicates, carbonates (aragonite, calcite, magnesite) and fluid inclusions (N_2, CO_2, H_2O) indicating a hydrous environment typical for mantle wedge metasomatism prior to Caledonian recrystallisation.

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Construction of system of FT-IR micro-spectroscopy -- studies on reaction-dynamics of material in situ

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This project is launched to develop a custom in-situ infrared (IR) microscope for high-pressure and high/low temperature FT-IR Studies using a Bruker Vertex 70v vacuum FT-IR spectrometer. This microscope system is specially designed with horizontal IR beam together with a ruby pressure calibration system and a temperature control system of external heater, an ideal platform for in-situ high-pressure and high/low temperature IR spectroscopic research on the properties and structures of the materials in the deep interiors of planets. High pressure and temperature IR spectra of epidote were obtained with this experimental platform to simulate and investigate its structure and water solubility under different temperature and pressure conditions existing during subduction, together with mineral chemical characteristics and Raman data, to look insight into the dynamic evolution of mineral's physicochemical property and water cycle in the whole process of subduction. The data of epidote on IR spectroscopic and Raman spectroscopic research were gathered in-situ under high-pressure and high temperature and show that the structure of the epidote remains stable, while temperature is increasing from room temperature to 873K (IR) /773 K (Raman), pressure from 0.1 GPa to 11.87 GPa (IR)/12.73 GPa (Raman). In particular, the M-O bond with weak compressibility of the epidote is related to the substitution of Fe-Al on the octahedron. OH vibration bands in infrared spectrum are suddenly increasing and disappearing, which may be related to redox or changing redox conditions. Our results demonstrate that epidote can be stable at least within the range of P = 11.87–12.73 GPa and T = 773-873K. Therefore, epidotite, as a hydrous mineral, can be an important carrier of water into mantle depths.

Evidence for resubduction of lawsonite-eclogite during return flow, Southern New England Fold Belt, Australia

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Translating burial and exhumation histories from the petrological and geochronological evolution of high-pressure mineral assemblages in subduction channels is key to understanding subduction channel processes. Convective return flow, either serpentinite or sediment hosted, has been suggested as a potential mechanism to retrieve deeply buried rocks and exhume them to the surface. Numerical modelling predicts that during this convective flow, fragments of oceanic crust can be cycled within a serpentinite-filled subduction channel, experiencing multiple burial cycles. Geochronological and petrological evidence for such cycling during subduction is preserved in a lawsonite-eclogite from serpentinite mélange in the Southern New England Fold Belt, in eastern Australia. Lu–Hf garnet and lawsonite, U–Pb zircon, U–Pb titanite and Ar–Ar and Rb–Sr phengite geochronology, supported by phase equilibria modelling and garnet zonation, suggests two cycles of burial that accompanied more than 1000 km of trench migration. Lu–Hf garnet and lawsonite and U–Pb zircon ages constrain the first burial event to ca. 500–490 Ma. This initial subduction of the eclogite formed Lu- and Mn-rich garnet cores, porphyroblastic lawsonite and micro zircons at *P–T* conditions of at least 2.3 GPa and 550 °C. Partial exhumation to ca. 1.9 GPa and 500 degrees is recorded by approximately 11 vol% garnet dissolution. Reburial of the eclogite resulted in renewed growth of new garnet, and prograde-zoned phengite and recrystallization of titanite at *P–T* conditions of 2.7 kbar and 590 °C. U–Pb titanite, phengite Rb-Sr and Ar-Ar ages record the recrystallization of these minerals during this second event at ca. 460 Ma. This was then followed by a second exhumation event, where chlorite and glaucophane partially replaced garnet and omphacite respectively, and garnet rims were again reabsorbed, at approximately 2.0 GPa and 500 °C. These conditions fall along a cold approximate geotherm of 7 °C/km, supported by the presence of pristine lawsonite. Partial exhumation and reburial occurred over ca. 30 Ma over an approximate pressure and temperature fluctuation of 1.2 GPa and 140 °C, providing some estimation on the rates of subduction channel material cycling.

Timescale of eclogite-to-granulite transition in continental collision zones

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Eclogites and eclogite-facies rocks in most H*P*–UH*P* metamorphic complexes have generally experienced retrograde metamorphism. In collision zones, deeply-subducted continental material undergoes recrystallization/overprinting during exhumation. Subsequently it stabilizes at lower crustal depths and increases the thickness of the crust. During the crustal stabilization after collisional event, granulite- and/or upper amphibolite-facies metamorphism often obliterates the records of prograde and/or metamorphic peak (H*P*–UH*P* metamorphism) during exhumation toward lower-crustal levels. Such polymetamorphic feature of eclogite-to-granulite transition offers a great opportunity to explore the dynamic crustal process from continental subduction/collision and subsequent subduction/collision-induced crustal thickening. Thus far, such polymetamorphic evolution have been studies in many continent–continent collision zones. However, geochronological data for the time interval (Δt) between peak eclogite-facies metamorphism and later H*P* garnet-bearing granulite-facies recrystallization are limited. For example, similar REE-signatures for zircon in equilibrium with garnet for both stages and limited growth during often diminish the utility of zircon for dating the polymetamorphic evolution.

To constrain the timescale of collision zone metamorphism, we conducted petrological and geochronological research for partially granulitized eclogite and associated metamorphic rocks of the Neoproterozoic Ufipa Complex, Southwestern Tanzania. As shown in another contribution by Morita (2019), our new study revealed that time interval Δt between peak eclogite facies metamorphism and later HP granulite-facies recrystallization was ~26 m.y.; zircon LA-ICP-QMS U–Pb dating combined with inclusion mineralogy, REE geochemistry and in-situ dating using petrographical thin-section could separate the timing of eclogite-facies stage at 588 ± 3 Ma and the later HP granulite-facies recrystallization at 562 ± 3 Ma.

Comparing with the Δt in other continental collision zones in both Paleozoic and Cenozoic orogens, the values overlap within a similar range of ~20–30 m.y. regardless of the age of each collision event. In other words, the Δt of ~20–30 m.y. might be a general rule of eclogite-to-granulite transition in collision zones. The comparison also suggests that collision/subduction of continental crustal materials into at least ~60 km depth would increase thickness of lower crust up to ~40%. This type of crustal thickening can be achieved during ~20–30 m.y. in a single collisional event.

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Rock functional properties steered by the metamorphic P-T-t-d evolution – a case study of eclogite- and high-pressure granulite-bearing terranes in the Sveconorwegian orogen

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In the petrological community, it is well-known that the P-T-t-d evolution of a metamorphic unit (e.g. a high-pressure unit) holds key information on its tectonic history. It has rarely been emphasized, however, that the same factors determine the physical properties of the rock and thus its technical properties. This is important in communication to the public and the industry, in order to justify basic research and contribute to the benefit of the society by providing data that lead to quarrying of proper materials.

We have studied the correlation between petrological characteristics and technical properties of an eclogite-bearing terrane and its high-pressure granulite-bearing footwall in SW Sweden. Our data show that felsic orthogneiss from the granulite gneiss domain have the best technical properties (most suitable for road and railway), in contrast to felsic orthogneiss in the eclogite-bearing domain. Micro-textural differences are obvious, and include complex grain boundaries and microperthitic texture in granulites; furthermore, these rocks have low biotite content, subtle stretching lineation, and absence of pronounced banding (segregation of light and dark minerals) and veining. These properties are in contrast to the coarser, even-grained and granoblastic texture in migmatites of the eclogite-bearing domain (Lundgren, 2012). Thus, petrographic parameters govern the technical differences (cf. also Lundqvist & Göransson, 2001).

Measurements included the Los Angeles, MicroDeval and Nordic Abrasion value tests. The Los Angeles test value is a measure of the resistance to fragmentation (EN 1097-2, 2010). The Nordic Abrasion value and MicroDeval tests measure resistance to wear. High values for these tests represent poor technical properties. The Nordic Abrasion, MicroDeval and Los Angeles values for felsic gneisses in the granulite and eclogite domains, respectively, reflect that rocks which underwent partial melting give high values. These have poor properties for production of road aggregates and are suitable only for unbound layers. In contrast, gneisses that recrystallized under high-temperature and dry conditions, with no or low degree of partial melting, have low test values. This group includes rocks of high quality for production of road aggregates, suitable for many different asphalt paving. Our continued studies will test the properties of felsic orthogneiss and metagabbro, respectively, along a 120-km metamorphic field gradient grading from lower amphibolite- to high-pressure granulite-facies.

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Generation and evolution of fluid/melt during exhumation of deeply-subducted continental crust

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Although partial melting of deeply subducted continental crust has been widely recognized in the last decade, the mechanism of melt generation during HP–UHP metamorphism remains controversial. Here we discuss the petrogenesis of dm- to m-scale dykes of leucosomes that occur in retrogressed migmatitic eclogite at General's Hill, central Sulu belt, eastern China. This study provides insight into the generation and evolution of fluid/melt during exhumation of deeply-subducted continental crust. Although the leucosomes show variable mineral abundances, displayed as differentiated and undifferentiated varieties, generally they comprise Qz + Ph + Ab + Aln/Ep + Grt and scarce Ttn, Zrn and Ap. Leucosome compositions are trondhjemitic to granitic with low Rb, high Sr and low Rb/Sr. They have trace element compositions that are enriched in LREE relative to HREE, and enriched in LILE relative to HFSE, with variable Eu anomalies, consistent with crystallization from a solute-rich supercritical fluid or hydrous melt. U–Pb dating on new zircon domains from the leucosomes yields crystallization ages of *c.* 223–219 Ma, within the accepted range of *c.* 225–215 Ma for HP eclogite facies recrystallization in the Sulu belt. Ti-in-zircon thermometry combined with Si-in-phengite barometry indicates crystallization of the leucosomes at 805–770 °C, but over a wide range of pressure from 3.5 to 2.2 GPa. The leucosomes have Sr–Nd isotope compositions intermediate between those of the host eclogites and surrounding gneisses, implying derivation from both sources. At the metamorphic peak, the source rocks were likely fluid deficient or absent. We posit that during exhumation from UHP conditions, structural water stored in NAMs was exsolved to form a grain boundary supercritical fluid in both eclogite and gneiss. By migrating from grain boundaries into channels and draining from the volumetrically dominant gneiss through the eclogite, the fluid acquired a blended Sr–Nd isotope composition intermediate between these two end-members. By the transition from UHP to HP eclogite facies, the ascending fluid had evolved to a denser, more viscous and more polymerized hydrous melt by dissolution of the silicate mineral matrix. Based on phengite barometry, the leucosomes crystallized from the margins into the interior, probably by diffusive loss of water to the host eclogite at temperatures above the wet solidus. Subsequently, low degree of melting in the leucosome is recorded by aggregates of Pl + Bt around Ph and thin films, cuspate veinlets and patches of Kfs along grain boundaries, consistent with Ph-breakdown partial melting at lower pressure. Phase equilibrium modelling indicates that this late stage melting occurred at the transition from HP eclogite to amphibolite facies, with the final subsolidus equilibration around 1.04–0.87 GPa and $T < 640$ °C.

PTt-paths of high pressure metamorphic rocks in the Sierra Pie Palo (W-Argentina): evolution of a flat exhumation wedge during a continent-arc collision

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The Sierra Pie de Palo (W-Argentina) is part of a collision zone between the Cuyania microcontinent and the Ordovician Famatina arc at the W-Gondwanan protomargin. The exhumed collisional wedge is unusually wide (≥100 km) with shallowly E-dipping foliations which have accommodated multiple shear events (Mulcahy et al., 2011). In the west metasediments of the Cuyania margin predominate, in the centre metasediments intruded by Mesoproterozoic plutons prevail, and in the east few intrusions attributed to the Famatina arc occur. We provide pressure-temperature-time (PTt)-paths from various parts of the collisional wedge derived by PT pseudosection modelling and dating of metamorphic events.

The range of peak PT conditions (8.5–13.4 kbar/475–570 °C) and types of PT-paths are similarly distributed throughout the wedge. Three types of PT-paths were recognized: (1) clockwise PT-paths show burial to maximum depth in the lower part of the wedge followed by early thermal relaxation, (2) anticlockwise PT-paths were caused by underthrusting of cold material during convergence or juxtaposition against an upper colder plate, (3) mixed clockwise/anticlockwise PT-paths begin as clockwise PT-paths followed by reburial. Exceptions are samples with granulite facies peak PT-conditions (8–10 kbar/700–760 °C) and an anticlockwise PT path similar to occurrences east of the Sierra Pie de Palo (Mulcahy et al., 2014). We attribute these as parts of the overriding Famatina arc.

Isotopic ages of metamorphic imprints include: 429 ± 2–434 ± 7 Ma (Lu/Hf mineral isochrones), 460 ± 6 Ma (U/Pb monazite), 404 ± 7–422 ± 8 Ma (Rb/Sr mineral isochrones) and 402 ± 2–440 ± 8 Ma (Ar/Ar white mica). Combined with similar previous age data (Mulcahy et al., 2011, 2014) they cluster around major age peaks at 404 ± 2, 437 ± 2 and 467 ± 7. All isotopic systems used can be shown to date (re)crystallization of metamorphic minerals. Recrystallization and/or nucleation of new metamorphic minerals was induced by transport of dissolved matter in rising and channelled metamorphic fluids accompanying localised thrusting.
The exposed part of the wide wedge formed during three stages: (1) partial subduction and subsequent extrusion of the leading edge of Cuyania (2) exhumation by normal faulting at structural levels and (3) dissection of the wedge by mid- and upper crustal thrusts generated in the overriding plate, leading to partial reburial of the exhumed wedge. Scattered klippen of the overriding arc were emplaced during stages 2 and 3.

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Discussion on the validity of geobarometers applied to mantle xenoliths

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Currently, exist several geobarometers that are theoretically applicable to mantle rocks, *i.e.*, the garnet-orthopyroxene, garnet-clinopyroxene, olivine-clinopyroxene, Cr-in-spinel and two-pyroxene geobarometers. To test the precision and accuracy of these barometers, they have been applied to experimental data of phase equilibrium experiments and natural mantle xenoliths including the garnet- or spinel-bearing lherzolites and the garnet-spinel-bearing lherzolites, as well as mantle xenoliths containing graphite or diamond, collected from kimberlites or alkaline basalts. It is concluded that the present garnet-orthopyroxene barometers (Nickel and Green, 1985; Taylor, 1998; Brey et. al., 2008) are relatively the most valid ones, and the garnet-clinopyroxene barometers (Nimis and Taylor, 2000; Simakov & Taylor, 2000) are also applicable. Other kinds of barometers are obviously far from accurate and precise and should be much more precisely calibrated through phase equilibrium experiments. In applying the valid barometers, the two-pyroxene thermometers (Brey & Köhler, 1990; Taylor, 1998) or the garnet-olivine thermometer (Wu & Zhao, 2007) are to be simultaneously used to derive pressures and temperatures.

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Distinction between peritectic and anatectic garnets in anatectic rocks from the eastern Himalayan syntaxis in Southeast Tibet

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The amphibolite- and granulite-facies metamorphic rocks are common in the eastern Himalayan syntaxis in Southeast Tibet. They are mainly composed of gneiss, amphibolite and schist, experiencing various degrees of migmatization to produce leucogranites, pegmatites and felsic veins. Zircon U-Pb dating of mesosome, leucocratic vein and vein granite from the syntaxis yields consistent ages of ~49 Ma, indicating crustal anatexis during the collisional orogeny between the Indian and Asian continents. In terms of the occurrences, mineral inclusions, major and trace element zonations, garnets from the three rocks can be categorized into two types: peritecitc and anatectic. The peritectic garnet mainly occurs in the mesosome layer and leucocratic vein. It has anhedral shapes and abundant mineral inclusions such as high-Ti biotites and quartz, almost homogeneous major element compositions except Ca, and decreasing HREE from core to rim, indicating its growth during P- and T-increasing anatexis. The peak conditions at 760–800 °C and 9–10.5 kbar are well constrained by the phase equilibrium calculations, mineral assemblages and garnet isopleths. On the other hand, the anatectic garnet in the vein granite has round or subhedral shapes and quartz inclusions, increasing spessartine and trace element profiles from core to rim. Some garnet grains show two-stage zonings in major and trace elements, with the core similar to peritectic garnet but the rim similar to anatectic garnet. The garnet-biotite thermometer and garnet-biotite-plagioclase-quartz (GBPQ) barometry suggest that the anatectic garnet crystallized at ~620–650 °C and 4–5 kbar. Based on the mineralogy, whole-rock major and trace element compositions, as well as zircon oxygen isotopes, the two kinds of leucosomes, the leucocratic vein and vein granite, would form by hydration melting and dehydration melting, respectively. Therefore, the two types of melting regime would have occurred in the eastern Himalayan syntaxis.

Simultaneous measurement of sulfur and iron isotopes in pyrite using a femtosecond laser ablation system coupled with two multi-collector inductively coupled plasma mass spectrometers

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Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) has been applied in a wide range of fields because of its capacity to carry out rapidly in situ analyses of trace element and isotope compositions, such as geology, materials science, and archaeology. For geological studies on complexly zoned minerals, small grains and detrital/inherited minerals, researchers must obtain the maximum amount of geochemical information on a single ablated volume. For this purpose, the technique, termed laser ablation split stream (LASS) analysis, has been developing during past ten years, which combines laser systems with more than one MS system where the carrier gas flow is split between the mass spectrometers (Xie et. al., 2008; Yuan et. al., 2008).

In the hydrothermal gold deposits, the S and Fe isotopic compositions of pyrite (FeS_2) can effectively trace the sources of ore-forming materials and detailed metallogenetic processes, which are the key issues to study the metallogenesis of hydrothermal gold deposits. However, the formation of many sulfide deposits may have involved multiple stages. Consequently, applying bulk analytical methods to obtain S or Fe isotopic compositions of ores or minerals can be challenged. The existing in situ microanalyses techniques can analyze S or Fe isotopes, respectively, which may lead to the obtained S and Fe isotope compositions belonging to different mineralization stages. We herein report a femtosecond laser ablation system coupled with two MC-ICP-MSs to measure simultaneously S and Fe isotopes of pyrite using a single laser ablation. We applied the different distribution of ablated material between two MC-ICP-MSs (3:2, 3:1 and 5:1 for S and Fe isotopes analyses, respectively) to test if any obvious mass fractionation occurred during the aerosol being split. The results demonstrated that the splitting aerosol process did not produce obvious mass fractionation for S and Fe isotopes. The uncertainties are about 0.2‰ (2 s) for $\delta^{34}S$ and $\delta^{56}Fe$. The S and Fe isotopic compositions of four in-house reference material measured using our method were consistent with those obtained using other methods within an error of 2 s analytical uncertainties.

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Protoliths and Tectonic Implications of the Blueschists in Northeastern China

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The blueschists in northeastern China (NE China) are generally distributed as layers or blocks in the mélange. The typical outcrops of the blueschists in NE China include the Toudaoqiao Blueschists in the central Great Xing'an Range and the Yilan as well as Mudanjiang Blueschists in the western Jiamusi Massif. The major and trace element concentrations of these blueschists were investigated to understand their petrogenesis, which provides important constraints on the collision and amalgamation processes of the microcontinents in NE China.

Geochemical characteristics show that the protoliths of the Toudaoqiao Blueschists are alkaline basalts which are derived from partial melting of an enriched lithospheric mantle and contaminated by crustal components. The protoliths exhibit the affinities of oceanic island basalt (OIB). Combined with the previous studies, we proposed that the Toudaoqiao blueschist were formed during the continental collision. Geochemical features show that the protolith of the Yilan and Mudanjiang Blueschists are mainly alkaline basalts and some of them are subalkaline basalts, which are derived from partial melting of enriched lithospheric mantle and mixed by ocean sediments. These blueschists have the property of OIB, and a minority of samples present mid-ocean ridge basalt (MORB) characteristics. Combined with previous studies and regional geological observations, we suggest that the Yilan and Mudanjiang Blueschist were formed during the oceanic crust subduction.

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Comparative metamorphic evolution of eclogite and granulite boudins of the Belomorian Eclogite Province: an example from the Mt. Kuropachya

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Belomorian Eclogite Province (BEP) is a complex where eclogite-facies mafic and ultramafic rocks of different geochemical specificity and metamorphic history are conjugated together in Archean TTG, metamorphosed under HP-granulite facies conditions. The question, how these rocks have been combined in a single complex is controversial. The object for the present study were of the BEP rocks in a little-known area at the Mt. Kuropachya. In this locality, the Belomorian TTG gneisses include amphibolized boudins of eclogites. Along with them, boudins of amphibolized mafic granulites are also present. Eclogites and granulites in the locality show a good preservation of primary mineral assemblages. The protolith for these rocks was different. Geochemical characteristics of eclogites at the Mt. Kuropachya are close to N-MORB, that is characteristic for eclogites of the Salma rock association, a member of BEP. According to major elements and REE specifics, granulites are closer to gabbronorites of the Belomorian mobile belt.

Modeling of mineral assemblages in eclogites using the Purple_X software showed that the peak metamorphic parameters of these rocks were reached at 750–830 °C and 16–17 kbar. The retrograde transformations of eclogites began before their entrapment by the TTG gneisses and were manifested by the omphacite-garnet reactions with the formation of jadeite-poor clinopyroxene and plagioclase during decompression down to 11–14 kbar at temperatures close to the peak temperatures, 750–800 °C. At pressures of ~10–11 kbar, the amphibolization began in eclogites. This process was facilitated by cooling down to 680–700 °C. Amphibolitization of eclogites apparently began also before their inclusion into TTG gneisses. This process was near-isochemical with respect to major and most of trace elements. The amphibolization within the boudin continues the trend of retrograde metamorphism of eclogites to pressures of 5–6 kbar and temperatures of 600–650 °C (calculations based on the Amph + Pl equilibria).

P-T conditions for the formation of amphibole + plagioclase assemblage in country gneisses, 5–6 kbar and ~700 °C, are close to the retrograde P-T trend for eclogites. This may imply that at these pressures (i.e. at depths of 27–30 km), the boudins of partially amphibolized eclogites were trapped by the TTG gneisses. Their further evolution proceeded jointly, while the retrograde transformations developed just at the edges of the boudins at contact with the gneisses and did not significantly affect the internal zones of the boudins. Indeed, the trend of rock evolution to pressures < 4 kbar and temperatures about 600 °C continues with the parameters determined by the Amph + Pl equilibria in amphibolites surrounding the boudins.

The peak temperatures of granulites are 650–700°C and pressures are 9.5–10 kbar. Retrograde transformations of granulite blocks are expressed in amphibolization at 600–650 °C at the same depth level. Apparently, the granulites were bodies originally embedded in the Belomorian gneisses. During tectonic evolution, they were disrupted, but still represented a single unit with the TTG gneisses at the time of entrapment of eclogite boudins. However, the question how the blocks of rocks differing in nature of protolith, conditions and history of metamorphism were combined in the gneisses of the Belomorian complex remains open.

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Application of FIB-microsampling for cryo-FIB-SEM analysis of fluid inclusions

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Fluid inclusion is one of the common features in natural rocks. Despite its common occurrence, detailed characterization of fluid phase constituents still remains difficult in many cases. To perform direct-chemical analysis of the aqueous inclusion, we employed a scanning electron microscope (SEM) equipped with a focused ion beam (FIB), an energy dispersive X-ray spectrometer (EDX), and a cold stage. Previous study (Yoshida et. al., 2018) pointed out the powerful applicability of FIB to the fluid inclusion petrography, although simple micro-excavation analysis yields problems derived from the analytical geometry in SEM chamber. We developed a new analytical scheme designed for the analysis of individual fluid inclusions, including FIB-microsampling and cryo-FIB-SEM chemical analysis.

The new analytical scheme consists of two steps: 1) a small block (called "house") containing fluid inclusion(s) is cut out from the ordinary thinsection and put on a pre-tilt stage by FIB; 2) the house is cooled under cryogenic temperature (ca. –130 °C) and is cut and analyzed in the cryo-SEM-EDX chamber.

Fluid inclusions trapped in a natural metamorphic quartz collected from the Sambagawa metamorphic belt, Japan (Yoshida et. al., 2015), were analyzed by the newly developed analytical scheme. The EDX spectra showed the peaks of Na, Cl, Ca, and a small peak of K. Similar to the case of Kyrgyz sample (Yoshida et. al., 2018), presence of K was clearly shown even though it had been ignored in many fluid-related studies. Compared to the previous simple micro-excavation analysis, X-ray intensity from the ion-beam-originated Ga almost disappears and Si from host-phase showed a significant decrease. Although the FIB-microsampling approach turned out to improve EDX spectra drastically, small size of fluid inclusion still prevented the single-phase analysis of fluid (ice), i.e. the obtained EDX spectra contains a small peak of host-phase. However, the new approach is expected to be a powerful tool to detect minor solute components that are hardly to detect by microthermometry.

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Fabrics and water contents of peridotites from the Luobusa ophiolite in Tibet: implications for recycling of suprasubduction zone peridotites

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Fabrics of ophiolitic peridotites record thermodynamic processes from the mid-ocean ridge to a subduction zone, and their final emplacement at a convergent boundary. The ophiolites along the Indus-Tsanbo Suture Zone were first obducted onto the continental margin of proto-India, or onto a series of intra-oceanic island arcs (Xu et. al., 2015). Although the Luobusa ophiolite in Tibet records suprasubduction-zone signatures, preservation of ultrahigh-pressure and super-reducing phases (diamond, moissanite, etc.) indicates their deep origin down to the transition zone (Yang et. al., 2007; Griffin et. al., 2016; Dilek & Yang, 2018). Here we present composition, microstructure and water contents of dunites and harzburgites from boreholes of the Luobusa Scientific Drilling Project. These peridotites show equilibration temperature at ~950–1080 ºC. Electron backscatter diffraction analyses and TEM images reveal the A-, B- and E-type fabrics of olivine due to activation of slip systems [100](010), [001](010) and [100](001), respectively. Different from hydrated peridotites above the mantle wedge, the average water contents in olivine, orthopyroxene (Opx) and clinopyroxene (Cpx) from 24 peridotite samples are 16 ± 5 ppm, 90 ± 21 ppm and 492 ± 64 ppm, respectively. Trace-element compositions of Cpx excludes remarkable metasomatism after melt extraction. The water-poor olivine and high hydrogen partition coefficient between Cpx and Opx is 5.37, which suggests their origin at pressure >7 GPa based on experimental studies. Compared with deformation experiments, the B-type fabric may be formed in a subduction zone >200 km, whereas the A- and E-type fabrics were formed in the shallow mantle during exhumation. Combined with previous studies, we proposed a subduction channel model to explain the occurrence of ultrahigh-pressure and high-reducing mineral inclusions in the Luobusa peridotites and chromitites. Triggered by slab rollback, the Luobusa peridotites could be rapidly exhumed from a subduction channel and mixed with the fore-arc lithosphere. Hence the oceanic lithosphere has a more complex deformation history than the prediction from theory of plate tectonics.

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Xu, X.Z., Yang, J.S., Robinson, P.T., Xiong, F., Ba, D., Guo, G. (2015) Origin of ultrahigh pressure and highly reduced minerals in podiform chromitites and associated mantle peridotites of the Luobusa ophiolite, Tibet. Gondwana Research 27: 686-700.

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Deeply subducted crustal environments in sublithospheric mantle: evidences from superdeep diamonds

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Inclusions in sublithospheric diamonds are key the evidence for chemical heterogeneity in the transition zone and in the lower mantle, which may be related to subduction of the lithosphere, oceanic crust, and carbon bearing sediments and their interaction with primary mantle lithologies. The experimentally-derived composition of majoritic garnets indicates its origin in the lower part of the upper mantle, astenosphere and transition zone. Most majoritic garnets are attribited to the metabasic environments. Their major and trace element composition reflects the variations of protolith's and the degree of enrichment or depletion during interaction with melts. Many inclusions in superdeep diamonds are either pure $CaSiO_3$ or composites of $CaSiO_3$ and $CaTiO_3$ interpreted as retrograde products of $Ca(Ti,Si)O_3$-perovskite.

A light carbon isotope composition typical of biogenic sediments ($\delta^{13}C$ values from –10 to –25‰) and a heavier carbon isotope composition characteristic of marine carbonates ($\delta^{13}C$ values from –3 to +2.7‰) was observed exclusively in the diamonds containing inclusions of majoritic garnets, Ca-silicates, Al-silicates, and SiO_2 phases (Zedgenizov et al., 2014). Major and trace element compositions of the inclusions of these minerals in superdeep diamonds indicate that they crystallized from carbonatite melts that was derived from partial melting of eclogite bodies in deeply subducted oceanic crust in the transition zone or even the lower mantle. CO_2-rich crustal or lithospheric material buried in subduction zones to a great depth is commonly considered to be a possible source of carbonate in the mantle. Subducted carbonate can be preserved either in carbonatized basalts of the oceanic crust or metasomatized peridotites of the lithospheric mantle (ophicarbonates). A thin layer of carbonaceous and siliceous sediments may be buried together with basalts, whereas most of the terrigenous sediments are removed by erosion from the subducting slab in the accretionary wedge zone (Moore, 1975). The occurrence of merwinite or CAS inclusions in ultra-deep diamonds can serve as mineralogical indicators of the interaction of metaperidotitic and metabasic mantle lithologies with carbonatite melts. The discovery of the inclusions of carbonates in association with superdeep Ca minerals can not only provide additional support for their role in the diamond formation process but also help to define additional mantle reservoirs involved in global carbon cycle.

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Contrasting metamorphic evolutions of early Paleozoic UHP metamorphic rocks in the North Qaidam Mountains, northwestern China: Insight for exhumation mechanism of deeply subducted rocks

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Continental collision orogenic belt is characterized by the exposure of dominated felsic gneisses enclosing eclogites and garnet peridotite. Some medium-low temperature eclogites well record the peak eclogitic conditions, and the garnets always preserve the prograde growth zonings. In contrast, some eclogites and their country rocks have been turned to maifc granulite and felsic (pelites) granulites, indicating that they have a prolonged high temperature granulite facies overprinting history during decompression. The apparent discrepancy of two kinds of eclogites may reflect different exhumation mechanisms. Based on detailed field investigation and geological mapping, two ultrahigh pressure metamorphic (UHPM) units have been recognized in the western North Qaidam Mountains. The Yuka-Luofengpo UHPM unit is characterized by low-middle temperature eclogites and metapelites, whereas the Luliangshan UHP unit mainly consists of the granulitized eclogites and pelitic granulites. The two units are separated by an early Paleozoic arc magmatic-metamorphic unit.

Based on petrographic observation and P-T pseudosections, similar clockwise P-T paths with peak conditions at 25–34 kbar, 580–633 °C were obtained for eclogites and metapelites of the Yuka-Luofengpo UHPM unit. The recognition of lawsonite (pseudomorph)-bearing eclogite indicates that the subduction and exhumation of the Yuka-Luofengpo UHPM unit is fast and in medium-low temperature condition.

Petrology, mineral chemistry and phase equilibrium modeling suggest a multi-stage metamorphic history of the granulitized eclogites and pelitic granulites in the Luliangshan terrane. The metamorphic evolution of the granulitized eclogites can be divided into four stages: 1) an eclogite facies metamorphism (P>18.5 kbar, T>830 °C) characterized by relic omphacite in the matrix and within garnet.; 2) a protracted high pressure granulite facies stage (11.3–17.5 kbar and 852–858 °C); 3) the later medium pressure granulite facies stage (7.6–7.7 kbar and 878–883 °C); and 4) a retrogressive amphibolite facies stage (P<5 kbar and T<650 °C). The zircons of granulitized eclogites and the pelitic granulites both record the high pressure granulite facies metamorphic age of ~450 Ma and the medium pressure granulite facies age of ~430 Ma.

The disparate metamorphic evolutions of the UHP rocks from the Yuka-Luofengpo unit and the Luliangshan unit indicate that the two adjacent metamorphic units have different exhumation mechanisms. Combining with the published geodynamic numerical modeling, we infer that the UHP rocks were detached from subducted slab at different depths into subduction channel, and then were exhumated along the subduction channel. In contrast, the granulitized eclogites and the pelitic granulites of the Luliangshan unit vertically exhumated through the mantle wedge into overriding plate crust by diapir (relamination) and experienced a prolonged granulite facies overprint prior to uplifting to shallow crust.

Ultrahigh pressure metamorphism and tectonic evolution of southwestern Tianshan orogenic belt, China

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The Chinese Western Tianshan terrane is a well-known ultrahigh-pressure (UHP) metamorphic belt that mainly consists of subducted oceanic crustal materials. While two uplift stages have been recognized, the early exhumation history has not been fully constrained. We conducted U–Th–Pb and trace element microanalysis of titanite as well as zircon from UHP eclogites. Apart from several inclusions in garnet, three types of retrograde titanite have been identified based on their petrographic occurrences. They are homogeneous in chemical composition, low in Al, enriched in middle rare earth elements (REEs), and depleted in light REEs and heavy REEs, suggesting their growth during retrograde decompression. Sensitive high-resolution ion microprobe (SHRIMP) and LA-ICP-MS U–Pb dating of titanite from four samples, regardless of their textural occurrences, gave consistent ages of c. 306 Ma. Phase equilibria modelling and Zr-in-titanite thermometry indicate that titanite replaced rutile at ~14 kbar and ~570 °C, following a nearly isothermal decompression from the UHP peak conditions. SHRIMP zircon U–Pb dating yields three age groups: c. 320 Ma c. 305 Ma and c. 220–240 Ma. The former is generally interpreted to be the age of UHP stage. The age of c. 305 Ma, overlapping the titanite ages, represents the timing of titanite growth during exhumation. The latter c. 220–240 Ma, mineral inclusions such as paragonite and albite were identified in the host metamorphic zircon, which suggests that c. 220–240 Ma also should be the epidote–amphibolite facies retrograde metamorphic age. Based on the P–T pseudosection calculation and combined U–Pb titanite and zircon dating, the P–T–t path has been outlined as four stages: cold subduction to UHP conditions before c. 320 Ma whose peak ultrahigh pressure is about 30 kbar at 500 °C; heating decompression from the Pmax to the Tmax stage before 305 Ma whose peak temperature is about 600 °C at 22 kbar; then the early cold exhumation from amphibolite eclogite facies to epidote-amphibolite facies metamorphism before 220 Ma; and the last tectonic exhumation from epidote amphibolite facies to greenschist facies metamorphism. Combining with the syn-subduction arc-like 333–326 Ma granitic rocks and 280–260 Ma S-type granites in the coeval LP-HT metamorphic belt, a model of the tectonic evolution of Tianshan HP-UHP metamorphic belt during late Cambrian to early Triassic has been proposed.

Zircon in orogenic peridotites records crustal recycling in continental subduction zones

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More and more studies indicate that zircon grains are recoverable from orogenic peridotites in collisional orogens, providing mineralogical evidence for crustal metasomatism at the slab-mantle interface in continental subduction channels. For example, tens to hundreds of zircon grains were available from single outcrop of garnet peridotites in the Sulu orogen, China. Some zircon grains are visible on thin sections. The majority of zircon-bearing peridotites are characterized by abundant hydrous phases such as phlogopite and Ti-clinohumite. Such peridotites contain more zircon grains than the other peridotites. The metasomatic zircon contains crystal inclusions of olivine (Fo_{91-92}), enstatite, apatite, Ti-clinohumite, phlogopite and diopside, whose parageneses and compositions are consistent with derivation from the peridotite rather than contamination from the continental crust. SIMS U-Pb dating of newly grown zircon domains yields consistent ages of 221 ± 3 to 224 ± 8 Ma. Because these U-Pb ages are slightly younger than the known ages of 225–240 Ma for the UHP metamorphism in the Sulu orogen, the zircon would have grown during the initial exhumation. The newly grown zircon domains show highly variable Th/U ratios from <0.01 to >1.0, suggesting their growth not only through metamorphic reaction at temperatures below the wet solidus of crustal rocks but also through peritectic reaction at temperatures above the wet solidus. They exhibit crustal Hf-O isotope compositions, suggesting their formation by the crustal metasomatism. Based on the major and trace element compositions of zircon-bearing peridotites, metasomatic agents were enriched not only in LILE (such as Rb, Ba and K) and LREE but also in Zr. They are composed of either metamorphic fluids that were produced by crustal dehydration at temperatures below the wet solidus or anatectic melts that were generated by crustal anatexis at temperatures above the crustal wet solidus. Therefore, the orogenic peridotites were offscrapped at subarc depths from the overlying mantle wedge by the subducting/exhuming continental crust. This records the crust-mantle interaction during the continental collision in the Triassic.

Zircon is not a common accessory mineral in the primary peridotite because of its low Zr content and low Si activity. However, zircons with different U-Pb ages are often found in orogenic peridotites with fertile, enriched compositions. In combination with their structure and composition, these zircons can be categorized into two types: (1) newly grown, showing consistent U-Pb ages with the metamorphic age of subducting crust; (2) inherited, showing consistent to inconsistent U-Pb ages with the protolith age of host UHP metamorphic rocks. While the first type records the crustal metasomatism by subduction zone fluids at the slab-mantle interface in subduction channels, the second type indicates incorporation of detrital zircon grains into fragments of the mantle wedge by the metasomatic agents. However, caution must be exercised when interpreting the U-Pb ages of relict zircon in orogenic peridotites as the timing of crust-mantle differentiation. Because the ultramafic mantle lithology is principally undersaturated with Zr, no zircon is able to crystallize from it. Alternatively, the relict zircon was physically extracted by metasomatic agents from the subducting crustal rocks at the subarc depths. In other words, the crustal zircon of different sizes was physically transported by the metasomatic agents into the mantle wedge peridotite. On the other hand, there would be the chemical dissolution of zircon grains at different degrees during metasomatism, with metamorphic recrystallization of relict zircon grains at the same time. Thus, the relict zircon grains are those large ones that survived during the dissolution in the metasomatic agents.

Zircon evidence for the presence of Eoarchean (~3.7 Ga) crustal remnant in the Sulu orogen, east-central China

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Hadean to Eoarchean crustal rocks and mineral relics, despite rare preservation worldwide, are very important to decode the physicochemical properties of early Earth. Zircon provides one of the best records for the formation and reworking of continental crust in the early Earth. However, the occurrence of Hadean to Eoarchean zircons is relatively scarce worldwide. Here we report for the first time the occurrence of Eoarchean relict zircon in granitic gneiss from the Sulu orogen in east-central China. The present study deals with a gneiss sample in the Yangkou region, which is well known for the occurrence of UHP metamorphic rocks. This region is mainly composed of granitic gneiss, metagabbro, coesite-bearing eclogite and serpentinized peridotite. Based on internal structures, trace elements (especially Th and U contents and Th/U ratios) and U-Pb ages, we have identified four groups of zircon domains in the granitic gneiss, which show U-Pb ages of ~3.7 Ga, 2.1–2.0 Ga, 771 Ma and 730 Ma, respectively. Group I domains (~3.7 Ga) exhibit Th/U ratios from 0.07 to 0.85, steep HREE patterns and significant negative Eu anomalies. They have apparent $^{207}Pb/^{206}Pb$ ages varying from 2383 ± 46 Ma to 3680 ± 29 Ma with a discordia upper intercept age of 3675 ± 69 Ma and a lower intercept age of 1809 ± 77 Ma, indicating their growth from an Eoarchean magma and reworking in the Paleoproterozoic. They show negative $\varepsilon_{Hf}(t)$ values of -3.3 to –1.2 and two-stage Hf model ages (T_{DM2}) of 4.0 to 4.1 Ga, suggesting growth of the juvenile crust in the Hadean. The domains with concordant Archean ages have low P contents of 216–563 ppm and high (Y+REE)/P molar ratios of 1.08–1.53, in consistent with the igneous source of the Eoarchean magma. Group II, III and IV zircon domains generally have consistent T_{DM2} ages of 2.7 to 3.0 Ga, suggesting their growth from multiphase reworking of the Archean crust. Group II domains (2.1–2.0 Ga) exhibit highly variable Th/U ratios from 0.13 to 7.38 and steep to flattened HREE patterns, suggesting their growth through Paleoproterozoic crustal anataxis and magmatism at highly variable temperatures. Group III (771 ± 15 Ma) and Group IV (730 ± 19 Ma) zircon domains show distinct trace element contents of Ti, Al, P and REE and Th/U ratios, indicating their growth from distinct magmas during continental rifting in the Neoproterozoic. In view of the unique feature of Neoproterozoic rifting magmatism in South China, the relict zircon of Eoarchean age would primarily originate from the Yangtze Craton and underwent the multiphase reworking in the Paleoproterozoic and Neoproterozoic, respectively.

High pressure granulites and retrograded eclogite from the Badu Complex of the Cathaysia Block, South China

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The Badu Complex occurs in the south-western Zhejiang province, which is the oldest rock in the Cathaysia Block, South China (Hu et. al., 1991; Yu et. al., 2009). It consists of Paleoproterozoic metamorphic supracrustal rocks and granitic intrusions. Recently, both high pressure basic granulite (retrograded eclogite) and pelitic granulite were found in the Badu Complex (Zhao et. al., 2017, 2018). Mineral textures and reaction relationships suggest four metamorphic stages for retrograded eclogite. They are the eclogite facies stage (M1, Inferred mineral assemblage is omphacite + garnet + rutile + titanite + quartz), the clinopyroxene retrograde stage (M2, Mineral assemblage is composed of garnet + fine-grained matrix clinopyroxene + sodic matrix plagioclase + clinopyroxene and plagioclase symplectite around garnet), the amphibole retrograde stage (M3) and the chlorite retrograde stage (M4). Conventional geothermometers and geobarometers in combination with phase equilibria modelling give metamorphic PT conditions for each metamorphic stage of the retrograde eclogite at 550–600 ºC, 17–23 kbar (M1), 650–670 ºC, 17–18 kbar (M2), 730–750 ºC, 11–13 kbar (M3), respectively. The high pressure pelitic granulite also experienced four stages of metamorphism. Early prograde metamorphic stage (M1) was recognized from inclusions of biotite and muscovite in garnet. The peak metamorphic stage (M2) is characterized by the presence of garnet + kyanite + perthite, with PT conditions of 1.3–1.5 GPa at ca. 830–860 ºC. The post-peak decompression (M3) is indicative of an isothermally overprinting of sillimanite from kyanite with pressures of 0.6–0.8 GPa at ca. 800–830 ºC. Some fine biotite developed around garnet suggested a late-stage retrogression (M4). Both retrograded eclogite and high pressure pelitic granulite give a clock-wise P-T path, characteristic of a post-peak isothermal decompression (ITD) and followed by cooling, which is consistent with a thinning process of thickened continental crust. LA-ICPMS and SHRIMP zircon U-Pb dating show this high grade metamorphism occurred at 250–240 Ma (Zhao et. al., 2017, 2018), suggesting that the Indosinian orogeny in the South China block maybe caused by subduction and collision of microcontinental blocks.

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