

The Van, Turkey Earthquake of October 2011: Seismicity, Mechanism and its Aftershocks

KALAFAT, Dogan^{1*}

¹Bogazici University Kandilli Observatory and ERI Cengelkoy, Istanbul Turkey

On 23 October 2011, a strong earthquake ($M_w=7.1$) occurred east of Van Lake. The earthquake destroyed damage along the Van Fault Zone. Generally, it is caused significant damage in the city of Van with Ercis town, as well as in many villages. The epicenter of the main shock was located in Tabanlı Village between Van city and Ercis town. Shortly afterwards the November 9, 2011 earthquake ($M_w=5.6$) occurred southeastern part of Van Lake, Edremit town area. The main shock and second shocks caused significant damage and deaths of 644 people.

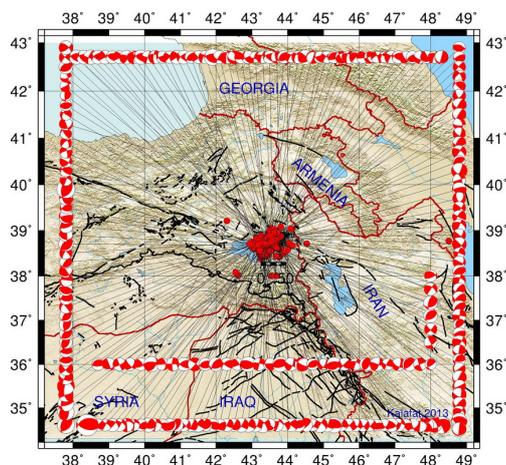
After the main shock 11 important earthquakes ($5.0 \leq M \leq 6.0$) were occurred in the region which has hypo-central distances of 8-38 km. from the main shock location. The main shock triggered mass movement, spreading, and local liquefaction. The important earthquakes and the aftershocks distribution showed that the E-W and NE-SW oriented fault segments caused the earthquake activities. The distribution of the aftershocks supported the presence a rupture of approximately 70 ± 10 km. Aftershocks occurred within an area of approximately 2300 km².

Fault mechanism solution has supported 23 October 2011 Van Earthquake was a reverse fault with a northward dipping fault plane. The fault plane solutions of about 225 important earthquakes ($M \geq 4.0$) were calculated using MT inversion solution technique by this study.

In addition, the stress tensor analysis was completed using the focal mechanism solutions. The stress tensor values of the region were calculated using the azimuth and plunge pairs of P and T axes for 225 earthquakes. The maximum principal stress (P-compressional) of the main shock is aligned in an N-S (NNW/SSE) direction and the tensional axis (T-dilatation) is aligned in an E-W (ENE-WSW) direction. The results of the focal mechanism and stress analysis solutions show that earthquakes have occurred on the reverse faulting and the seismic activity has been continuing under the compressional regime in the region. The Van earthquake activity initiated and caused an increase in seismic activity of the region. This may be explained by the triggering of small faults by the Van Earthquake. The Van earthquake is a good example of compressional deformation and the activity of blind reverse faulting.

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Keywords: Van Lake, aftershocks distribution, focal mechanism, stress analysis, reverse faulting



Microstructural observation of quartz and K-feldspar in quartzo-feldspathic granulite in Sri Lanka

ATHURUPANA, Bhatiya madhura bandara^{1*} ; FUKUDA, Jun-ichi¹ ; MUTO, Jun¹ ; NAGAHAMA, Hiroyuki¹

¹Department of Earth Science, Tohoku University, Japan

Sri Lankan basement has been considered as high grade terrains which have suffered poly phase deformation and also upper amphibolite to granulite facies metamorphism during Pan-African amalgamation. In order to illuminate the rheological properties of felsic granulite in deep crustal level associated with high grade metamorphism, microstructural and petrographic observations were conducted.

A quartzofeldspathic gneiss sample (Quartz~40%, K-feldspar~55% and plagioclase <5%) contains highly elongated ribbon quartz which demarcate lineation, in K-feldspar matrix. The sample was collected from the hinge zone of kilometer scale large upright cusped antiform between two large synforms named Dumbara and Huluganga in Sri Lanka. The lineation as maximum elongation direction is N35°W/horizontal. Thin sections were made parallel and perpendicular to the lineation for petrographic and microstructural observations. Based on energy dispersive X-ray spectroscopic (EDS) measurement, most of K-feldspars in the matrix are sanidine [(K_{0.59}Na_{0.41})AlSi₃O₈] composition. Plagioclase is albite (An 0.1) composition and occurs in clusters and exsolution lamellas in K-feldspar. The grain size of sanidine is from ~50 μm to 2 mm. Large sanidine porphyroclasts are partly recrystallized and show core and mantle structures. Grain boundaries of sanidine are sub polygonal to amoeboid shapes with increasing grain size, while plagioclase grains in clusters show perfect polygonal boundaries with grain size ranging from 50 to 200 μm. Around the plagioclase clusters, scapolite reaction corona exists with crosscutting elongated ribbon quartz. Sericite presents in the same region as very low temperature alteration of plagioclase and scapolite. Most importantly ribbon quartz grains are boudinaged in K-feldspar matrix. Any sign of undulatory extinction or dynamic recrystallization is absent in both boudinaged and large ribbon quartz. Measured average axial ratio of ribbon quartz grains is 21:7:1 with respect to X, Y and Z directions.

The crystallographic orientations of both quartz and sanidine were measured by electron backscattered diffraction (EBSD) method, including large ribbon quartz and boudinaged quartz and also matrix sanidine. The lattice preferred orientation (LPO) patterns of sanidine manifest (010)<001> as a dominant slip system with a minor activation of (010)<100> slip system. The quartz LPO indicates the activations of prism<a> and rhomb<a> slip systems.

According to the presence of K-feldspar as sanidine and their slip systems, we can point out that the sample has prevailed high grade conditions (~550-800°C and ~0.4-0.8 GPa) during deformation [e.g. Menegon et al. 2008]. Scapolitization which occurs at granulite facies could be indicative of peak metamorphism. Also, reaction coronas of scapolite crosscutting ribbon quartz can be interpreted as strong deformation prior to the peak metamorphism. Exsolution of K-feldspar indicates the post dated cooling relative to the strong deformation and the peak metamorphism.

Reference:

Menegon, L., Pennacchioni G., Spiess R., 2008. Dissolution-precipitation creep of K-feldspar in mid-crustal granite mylonites. *Journal of Structural Geology* 30(5): 565-579

Keywords: Microstructures, Quartz, K-feldspar, Quartz micro boudins

Multiple events of metamorphism in lenses of eclogite within marbles of Maykhan Tsakhir Formation, Lake Zone, Mongolia

JAVKHLAN, Otgonkhoo^{1*}; TAKASU, Akira¹; BAT-ULZII, Dash²; KABIR, Md fazle¹

¹Department of Geoscience, Shimane University, Japan, ²School of Geology and Petroleum, Mongolian University of Science and Technology, Mongolia

The eclogite-bearing Alag Khadny metamorphic complex in the Lake Zone, SW Mongolia located in the central part of the Central Asian Orogenic Belt, consist mainly of orthogneisses which interleaving with marbles including lenses of garnet-chloritoid schists of Maykhan Tsakhir Formation. Eclogites have two modes of occurrence, i.e. lenses and boudins *eclogite-1* in orthogneisses and *eclogite-2* in marbles. Thermocalc calculations for the peak eclogite facies metamorphism for *eclogite-1* with the assemblage of Grt + Omp + Brs ± Ph ± Ep yielded 570-630 °C and 22-25 kbar (Javkhlan et al., 2013a). In contrast, pressure conditions of the garnet-chloritoid schists (10-11 kbar) are distinctly lower than those of the eclogite-1, whereas temperatures (560-590 °C) are similar (Javkhlan et al., 2013b).

Eclogite-2 in marbles consists of small grains of garnet (<0.1 mm) and omphacite with minor amounts of amphibole, epidote, paragonite, plagioclase, chlorite, calcite, biotite, quartz, titanite and rutile. The matrix of *eclogite-2* shows a pseudomorphous texture, where small grains of garnet crowd cemented by titanite forming isomorphous round shape. Some of cores of garnet grain contain relics of garnet ($X_{Ca}=0.32-0.42$; $X_{Mg}=0.06-0.08$) indicating previous mineral were larger porphyroblastic garnet. In addition, small grains of omphacite forming rectangular prismatic nature surrounded by garnet grains.

Garnet grains have compositionally zoning with core ($X_{Ca}=0.08-0.20$; $X_{Mg}=0.10-0.16$), mantle ($X_{Ca}=0.24-0.39$; $X_{Mg}=0.08-0.17$), rim ($X_{Ca}=0.22-0.26$; $X_{Mg}=0.18-0.23$) and outer-rim ($X_{Ca}=0.20-0.22$; $X_{Mg}=0.12-0.18$). Few omphacites preserved their core ($X_{Jd}=0.27-0.31$; $Fe_2O_3=1.34-2.22$ wt%) whereas most of grains have compositional heterogeneity with X_{Jd} from 0.34 to 0.48 ($Fe_2O_3=0.04-2.31$) and locally with rims of higher Fe_2O_3 (3.79 wt%)-bearing omphacite ($X_{Jd}=0.32$). Omphacites partially replaced by symplectites of Pl (An=15-17), amphibole (Ed, Act, Mg-hbl) and Ep. Three types of amphibole are distinguished by their texture, amphibole (Amp1) [zoned with Act ($X_{Mg}=0.79-0.81$) core, Brs ($X_{Mg}=0.54-0.69$) mantle and rims with Ts, Mg-Trm and Prg in compositions] coexisting with Grt and Omp, poikiloblastic barroisitic amphibole (Amp2) ($X_{Mg}=0.65-0.75$) containing eclogitic minerals of Grt and Omp with their symplectitic assemblage and finally actinolitic amphiboles (Amp3) partially replacing Omp and Grt.

Based on the textures we distinguished two metamorphic events, i.e. eclogite facies metamorphism and poikiloblastic barroisitic amphibole metamorphism. The peak eclogite facies metamorphism characterized by assemblages of Grt (mantle) + Omp + Amp1 (Brs) + Ep + Pg + Rt. Thermocalc calculation yielded 487 ± 46 °C and 19.7 ± 2.1 kbar (sigfit=1.80). Thermocalc calculation of Grt (rim) + Omp (rim) + Amp1 (Mg-Trm) + Ep + Pl yielded 666 ± 45 °C and 13.7 ± 1.6 kbar (sigfit = 2.11) suggesting a decompression stage after the eclogitic metamorphism. The poikiloblastic barroisitic Amp2 shows decreasing Si (7.01-6.69 pfu) and increasing NaB (0.61-0.70 pfu) from core to rim, suggesting that the Amp2 grew after the peak eclogite facies metamorphism, and probably during the second prograde metamorphic event. Approximate P-T conditions of the poikiloblastic barroisitic Amp2 are estimated as 5-7 kbar at c. 450 °C.

⁴⁰Ar/³⁹Ar muscovite ages for eclogites (543 ± 3.9 Ma) in marbles (probably eclogite-2) and the garnet-chloritoid schists (537 ± 2.7 Ma) were determined (Stipska et al. 2010). K-Ar ages for eclogite-1 [603 ± 15 Ma, 602 ± 15 Ma (Amp) and 612 ± 15 Ma (Ph)] within orthogneisses have been obtained (Javkhlan et al., 2014). These ages are interpreted as the exhumation ages for the eclogites (-1 and -2) and the garnet-chloritoid schists.

The peak temperature conditions of eclogite-2 considerably lower than eclogite-1 whereas the pressure conditions are similar. The peak P-T conditions garnet-chloritoid schists are correlated with the poikiloblastic Amp2 metamorphism of the eclogite-2.

Keywords: eclogite-2, pseudomorphous texture, garnet-chloritoid schists, Maykhan Tsakhir Formation, Lake Zone, SW Mongolia

Multiple exhumation episodes recorded in orogenic garnet peridotites from the Bohemian Massif (Czech Republic)

NAEMURA, Kosuke^{1*}; SVOJTKA, Martin²; ACKERMAN, Lukas²; SHIMIZU, Ichiko¹; HIRAJIMA, Takao³

¹Department of Earth and Planetary Science, Graduate School of Science, The University of Tokyo, ²Geologický ústav Akademie, Czech Republic, ³Department of Geology & Mineralogy, Faculty of Science, Kyoto University

Presence of garnet peridotites in *HP/UHP* metamorphic terranes is taken as evidence for interaction between crust and mantle during orogeny. In order to constrain the timing of interaction, *P-T* paths for both peridotites and crustal rocks have been constrained, which demonstrated that there are significant gaps between peak pressure of peridotites and host continental crust. In this contribution, we will show an evidence for multiple exhumations recorded by clinopyroxene (*Cpx*) megacryst discovered in the garnet peridotite from the Bohemian Massif, and will constrain the timing of crust-mantle interaction in the light of the new data.

The Gföhl Unit experienced the highest metamorphic grade in the Moldanubian zone of the Bohemian Massif, and it mainly consists of quartz-feldspathic garnet-kyanite granulite with peak condition at 2.2-2.3 GPa and 1000 °C (Vrana et al., 2013, *J. Geosci.* **58**, 347-378), although Kotková et al. (2011, *Geology* **39**, 667-670) recently found diamond and coesite from the Saxony-type granulite. Gföhl granulite occurs as tens km-sized isolated blocks and contains garnet peridotites whose peak conditions were estimated as 2-6 GPa and 850-1350 °C (Medaris et al., 2005, *Lithos* **82**, 1-23). We studied *P-T* path for the garnet peridotite at Lom pod Libínem quarry in the Prachatice granulite massif in the south Bohemia. Lom pod Libínem (*LPL*) peridotite generally displays granoblastic texture consisting of mm-sized (0.1-5.0 mm in diameter) garnet, pyroxenes, olivine, and most garnet grains are transformed to kelyphite and are replaced by phlogopite. *LPL* peridotite includes a lot of cm-size *Cpx* megacrysts. Among them, the largest megacryst (3×5 cm) shows a strong chemical zoning consisting of three zones (Fig. 1), namely, core, mantle and rim: (1) the "pale-green core" is poor in Ca-Tschemak (CaTs, ~6 mol.%) and rich in Enstatite (En, ~9 mol.%) (components after Simakov, 2008, *Lithos* **106**, 125-136) and includes phlogopite and orthopyroxene, (2) the "mantle" is lower in CaTs. (4-5 mol.%) and En. (4 mol.%), and includes hornblende, chlorite, apatite, titanite, andradite, olivine, and celsian, and (3) the "rim", rich in CaTs. (7-9 mol.%) and En. (9 mol.%), includes olivine, phlogopite, and hornblende, respectively. The mm-size *Cpx* has identical composition to the megacryst-rim, and (4) the smaller *Cpx* is richer in CaTs. (12 mol.%) and poorer in En. (7 mol.%). Four mineral stages can be identified: **Stage 1** is defined by megacryst-core coexisting with phlogopite, orthopyroxene. Assuming the co-existence with garnet, the equilibrium condition was estimated at ~4 GPa and 1000 °C by use of the single *Cpx* geothermobarometer (Nimis & Taylor, 2000, *Contrib. Mineral. Petrol.* **139**, 541-554), **Stage 2** is defined by the "mantle" coexisting with hornblende, chlorite, orthopyroxene, and andradite, which were equilibrated at ~700 °C, *P*<2.5 GPa. **Stage 3** is defined by the core of mm-size pyroxenes, garnet and olivine that were equilibrated at ~3.0 GPa and 1000 °C in the garnet lherzolite facies. **Stage 4** is defined by the matrix spinel lherzolite assemblage equilibrated at *T*~800 °C at 1-2 GPa.

We envisaged the following juxtaposition mechanism: *LPL* peridotite originally came from the upper mantle (4 GPa) that exhumed to the depth of <2.5 GPa and was partially transformed to chlorite peridotite. Assuming that *LPL* peridotite was entrained in the crust at Stage 2, peridotite and host continental crust could have shared the Variscan *UHP* metamorphism at 3 GPa (Stage 3), followed by final exhumation. Although the peak *P-T* condition of Stage 3 is still higher than that of country granulite (<2.3 GPa), this could reflect different degree of retrogression during the final exhumation. Our study suggests some orogenic peridotites were exotically derived from the *UHP* mantle (>4 GPa), where continental crust have not subducted more than 3 GPa. This will give another solution to the observed pressure gaps between orogenic peridotites and host continental crust.

Keywords: orogenic peridotite, *UHP* metamorphism, crust-mantle interaction, Bohemian Massif, multiple exhumations

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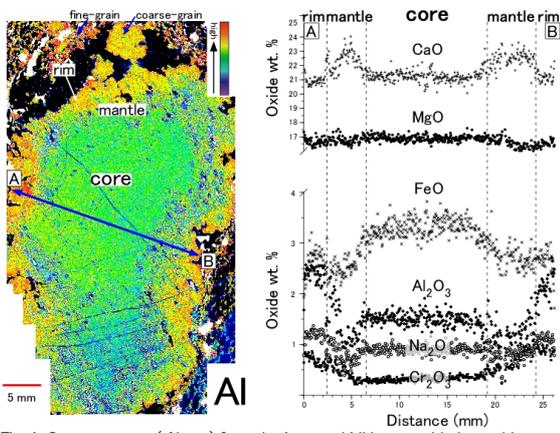


Fig. 1. Cpx megacryst (*Al map*) from the Lom pod Libinem peridotite and its compositions along the line.

Modelling of the Phase Relations in High- and Ultrahigh-pressure Metabasic Rocks

WEI, Chunjing^{1*}

¹School of Earth and Space Sciences, Peking University

Pseudosections calculated with THERMOCALC predict that for glaucophane-lawsonite eclogite facies conditions (500-600 °C and 18-28 kbar), MORB compositions in the NCKMnFMASHO system will contain glaucophane, garnet, omphacite, lawsonite, phengite and quartz, with chlorite at lower temperature and talc at higher temperature. In these assemblages, the pyrope contents (X_{py}) in garnet is mostly controlled by variations in temperature, grossular content (X_{gr}) is strongly controlled by pressure, and the silica content (Si-) in phengite increases linearly with pressure. As the P-T conditions for these given isopleths are only subtly affected by common variations in bulk-rock compositions, the P-T pseudosections potentially present a robust geothermobarometric method for natural glaucophane-bearing eclogites. The maximum X_{py} content may define the temperature peak (T_{max}) and the minimum X_{gr} content constrains the pressure peak (P_{max}) conditions. An isothermal decompression of these lawsonite-bearing assemblages would result in epidote-bearing assemblages through dehydration reactions such as lawsonite + omphacite = glaucophane + epidote + H₂O, releasing a large amount of bound fluid. Thus, most natural HP epidote eclogites may have experienced a metamorphic stage of lawsonite stability.

Under low-T UHP conditions (>28 kb, 550-650 °C), basic rocks are predicted to contain garnet, omphacite, lawsonite, phengite, coesite and talc. In this assemblage, the X_{py} contents steadily increase as temperature rises and the Si-in phengite increases linearly with pressure. However, the X_{gr} content is very sensitive as pressure changes, showing slowly decrease as pressure rises. The peak P-T conditions for low-T UHP eclogites can be determined using the isopleths of maximum X_{py} and Si-in phengite in P-T pseudosections. An isothermal decompression of these low-T UHP eclogites at temperature i.e. 600 °C would result in disappearance of lawsonite and talc in the peak stage, but appearance of glaucophane, epidote and kyanite, forming the mineral assemblages involving garnet + omphacite + glaucophane + epidote + kyanite + quartz/coesite + phengite commonly observed. Moreover, garnet in the low-T UHP eclogites is characteristic of growth zoning with its rims containing lower X_{gr} and higher X_{py} contents.

Under Medium-T UHP conditions (>28 kb and >650 °C), basic rocks are predicted commonly to contain garnet + omphacite + lawsonite + phengite + coesite. In this assemblage, the X_{py} in garnet mostly depends on bulk compositions, whereas the X_{gr} in garnet and the Si-contents in phengite regularly increase, respectively, as temperature and as pressure rise, and thus, can provide robust thermobarometric constraints. Decompression of the eclogites with lawsonite in the peak stage is inferred to be dominated by lawsonite dehydration, resulting in increase in the mode of anhydrous minerals, or further eclogitization, and formation of epidote porphyroblasts and kyanite-bearing quartz veins in eclogite. As lawsonite dehydration can facilitate evolution of assemblages under fluid-present conditions, the UHP eclogites with lawsonite are hard to memorize their real peak P-T conditions.

Keywords: HP-UHP eclogites, pseudosection, geothermobarometer, basic rock

DEHYDRATED FLUID AND SEISMIC DEFORMATION IN DEEP SUBDUCTION ZONE ?constraints from lawsonite eclogite and olivine-opx sp

OKAMOTO, Kazuaki^{1*}

¹Saitama University, ²Joint Graduate school, Tokyo Gakugei University

Introduction: It has been considered that there is a correlation between the double seismic zone and metamorphic dehydration reaction in deep slab. The location of the upper limits of the upper seismic plane correspond to metamorphic facies boundary where H₂O contents change in subducting crust; numerous earthquakes from 60 to 110 km depths in the lawsonite-blueschist facies, many earthquakes in the lower crust of the slab from 110 to 150 km depths in the lawsonite-amphibole eclogite facies and few earthquakes in the lawsonite eclogite facies. It was considered that the dry eclogite is distributed in the area where there is few earthquake [1]. However, ultrahigh pressure experiments and thermodynamic calculation are both demonstrating that the lawsonite eclogite is stable [2] in the area. In order to unravel relation between dehydration and seismic deformation, we have investigated dehydration process of natural metamorphic rocks recording very cold geo-thermal history in the crust and lithosphere in the slab.

Lawsonite eclogite (Alpine Corsica): Alpine Corsica is the best representative field area exhibiting lawsonite eclogite and blueschist as a coherent high pressure, low temperature metamorphic belt. Ophiolite sequence (oceanic plate structure) is also well-preserved, and the pillow structure is clearly recognized in the lawsonite eclogite. Recent petrological researches have revealed that both blueschist (rims of the pillow) and lawsonite eclogite (core of the pillow) are stable in the same pressure and temperature condition [3] because chemical variation including water content creates both lawsonite-amphibole eclogite and lawsonite eclogite in different portion of subducted crust. We carefully observed microtexture of the lawsonite eclogite and blueschist and have found that omphacite vein and lawsonite vein in mylonitized blueschist matrix.

Olivine-opx spinifex in serpentinite (Cerro del Almirez, Nevado complex): Metamorphic olivine after antigorite has been described in Italian Alps and also from the Mt. Shiraga, Japan. However, the olivine was formed with talc and fluid by antigorite breakdown reaction in pressures lower than 1.5 GPa. Spinifex olivine with opx in the Cerro del Almirez, is the product at pressures ($P > 1.5$ GPa) relevant to the lower seismic plane beneath Northeast Japan. In Cerro del Almirez, olivine-opx rocks underlie antigorite schist by a contact [4]. In the olivine-opx rocks, the blade-like, elongated olivine and opx were grown, representing spinifex texture. It clearly indicates the presence of large amount of water facilitate crystallization of elongated olivine with opx.

Discussion and conclusion: In the lawsonite eclogite in the Alpine Corsica, blueschist and lawsonite coexist together reflecting chemical difference in pillowed structure or lithology. Omphacite and lawsonite veins are observed along the shear band in mylonitized blueschist. It suggests that decomposition of glaucophene caused hydro-fracturing and precipitate omphacite and lawsonite vein. Garnet was grown statically close to the vein.

Olivine-opx spinifex in the serpentinite, Cerro del Almirez, were probably recrystallized in the presence of large amount of water. The estimated dehydration reaction has a negative P-T slope at pressures higher than 1.5 GPa. The reaction is volume reducing reaction and the olivine-opx spinifex texture was formed under volume reducing reaction.

References: [1] S. Kita et al., *Geophys. Res. Lett.*, 33, doi:10.1029/2006GL028239. (2006). [2] K. Okamoto et al., *Geochemistry*, 46 205-215 (2013). [3] A. Vitale Brovarone et al., *J. Met. Geol.*, 29, 583-600, (2011). [4] V. Trommsdorff et al., *CMP*, 132, 139-148 (1998).

Keywords: double-seismic zone, upper seismic plane, Lawsonite eclogite, lower seismic plane, olivine-opx spinifex, dehydrated vein

Ultrahigh-pressure eclogites: paleo-environment indicators

UR REHMAN, Hafiz^{1*}

¹Department of Earth and Environmental Sciences, Graduate School of Science and Engineering, Kagoshim

Ultrahigh-pressure (UHP) eclogites generally form by the metamorphism of mafic lithologies (gabbros or basalts) at depths greater than 90 km (minimum stability field of coesite) indicating P-T conditions of >2.7 GPa and 600-800 °C. At such conditions most minerals reequilibrate their chemical elements (e.g. major and trace and even isotopes) and new minerals crystallize or grow at the expense of other minerals formed during the magmatic crystallization. Some chemical elements, considered as relatively less mobile or immobile (e.g. Sm, Nd, Lu, Hf), are widely used for the extraction of past records the rocks have evolved through. Besides those elements, oxygen, the major component of silicates and oxides, impart important information related to protolith formation of rocks and their metamorphism. In general, most basaltic rocks show a narrow range of $\delta^{18}\text{O}$ (ca. $+5.7 \pm 0.3$ ‰ relative VSMOW) and values for altered basalts vary from 0 to +12 ‰.

In this paper, I discuss the origin of low or negative $\delta^{18}\text{O}$ values; recently we found in the Himalayan UHP eclogites of Kaghan Valley and explain the mechanism how these low values were acquired. These eclogites are formed during Eocene by the India-Asia collision and their protoliths were the Panjal Trap basalts which were emplaced in Permian when Indian Plate was part of Gondwana. The $\delta^{18}\text{O}$ values are as low as -2.25 ‰ in the fresh parts of eclogites and increase towards more positive in the retrogressed or amphibolitized parts. The unusually low $\delta^{18}\text{O}$ values in eclogites are interpreted to have resulted from the hydrothermal alteration of the protoliths by meteoric water interaction when Greater India was still at southern high latitudes (>65 degrees S) during the Permian indicating glacial paleo-environment. These low $\delta^{18}\text{O}$ values were frozen-in in the protolith rocks and did not change during subduction-related UHP metamorphism. However retrogressive process, due to infiltration of ^{18}O -rich fluids during exhumation, shifted these values towards more positive range.

Keywords: Ultrahigh-pressure eclogites, Himalaya, Oxygen isotope, Paleo-environment

Role of the second continent

KAWAI, Kenji^{1*} ; ICHIKAWA, Hiroki² ; YAMAMOTO, Shinji⁴ ; TSUCHIYA, Taku² ; MARUYAMA, Shigenori³

¹Department of Earth and Planetary Sciences, Tokyo Institute of Technology, ²Geodynamics Research Center, Ehime University,

³Earth-Life Science Institute, Tokyo Institute of Technology, ⁴Department of Earth and Astronomy, Graduate School of Arts and Sciences, The University of Tokyo

It has been thought that granitic crust, having been formed on the surface, must have survived through the Earth's evolution because of its buoyancy. Recent geological studies have suggested that a significant amount of crustal material has been lost from the surface due to delamination, continental collision, and subduction at oceanic?continental convergent margins (von Huene and Scholl 1991; Yamamoto et al. 2009; Ichikawa et al. 2013a). If so, then the subducted crustal materials are expected to be trapped in the mid-mantle due to the density difference from peridotitic materials induced by the phase transition from coesite to stishovite (Kawai et al. 2013). In order to study the effect of the subducted granitic materials floating around the mantle transition zone, we conducted two-dimensional numerical experiments of mantle convection incorporating a continental drift with a heat source placed around the bottom of the mantle transition zone. We found that the addition of heat source in the mantle transition zone considerably enhances the onset of upwelling plumes in the upper mantle, which further reduces the time scale of continental drift. The heat source also causes massive mechanical mixing, especially in the upper mantle. The results suggest that the heat source floating around the mantle transition zone can be a possible candidate for inducing the supercontinent cycle (Ichikawa et al. 2013b).

Keywords: Second continent, Wilson's cycle, Granite, Tectonic erosion

Where had the primordial continent gone?

MARUYAMA, Shigenori^{1*}; KAWAI, Kenji²; TSUCHIYA, Taku³

¹ELSI Tokyo Institute of Technology, ²Tokyo Institute of Technology, ³Ehime University

There are no Hadean rocks on the Earth's surface. This indicates (1) there was no continents on the primordial Earth, or (2) continents were present in the Hadean but lost afterwards. It is well-known that Moon surface was covered by anorthositic continental crust with KREEP basalts with ca. 50-60km thickness. Those rocks are the fractionated final residues of magma ocean after the giant impact at 4.56Ga.

The Earth must have been completely melted if giant impact was correct, but due to 6 times larger gravity, the thickness of anorthositic continents must be 21 km. Moreover, during the consolidation of magma ocean, bulk of anorthositic blobs could be transformed into (1) zoisite+kyanite+quartz, (2) grossular+kyanite+quartz, (3) grossular +kyanite+coesite, (4) grossular +kyanite+stishovite, in 300km depth.

Absence of TTG rocks in the Hadean and nearly absent in early Archean less than 5% among the surface of present continents must be caused by extensive tectonic erosion by subducting slabs which are present even today at trench. Therefore, it is wrong to believe that low-density granite must have accumulated on the surface once formed on the surface of the Earth.

Density calculation of anorthosite, MORB, harzburgite, and pyrolite using first principles calculation showed that anorthosite was heavier if it convected at depth in mantle transition zone. If it turns into lower mantle, it becomes to be heaviest among those as mentioned above, suggesting the stability field at D" layer on the bottom of mantle which is right above CMB.

However, it depends on the geothermal gradient on which phase change of Al₂O₃ occurs to determine whether or not the heaviest among all rocks at CMB. Depending on cooling the CMB, meta-anorthosite could have been buoyant particularly after the mantle overturn at 2.7-2.6Ga.

Before the overturn, if the basal magma ocean was present in the Archean, the lost primordial continents must have been melted into basal magma ocean where anorthosite-KREEP basalts mixed with FeO-enriched primordial basal magma ocean. The possible bulk chemistry can be estimated, though qualitatively; it must be super-enriched in anorthositic component. It can be expressed in Ca-Pv, Mg-Pv, Ferro-periclase as major components.

When, mantle overturn occurred at 2.7-2.6Ga, low-temperature materials of upper mantle must have cooled down the basal magma ocean to consolidate to crystalize Ca-Pv rock, bi-mineral Ca-Pv + Mg-Pv rock, and the tri-mineral Ca-Pv + Mg-Pv + FM periclase rock. According to the formation of these rocks, those three rocks would have been behaved differently, although depends on not only density but also mass.

Assuming the enough volume of Ca-Pv rocks, those rocks may be floating in mid-depth of lower mantle.

Subduction origin for UHP chromitite from the Nishisonogi metamorphic rocks, Western Kyushu, Japan

NISHIYAMA, Tadao^{1*}; MORIBE, Yousuke¹; ISHIMARU, Satoko¹; ARAI, Shoji²; MORI, Yasushi³; SHIGENO, Miki³

¹Graduate School of Science and Technology, Kumamoto University, ²Department of Earth Sciences, Kanazawa University, ³Kitakyushu Museum of Natural History and Human History

Ultrahigh-pressure (UHP) chromitite from the Luobsa Ophiolite in non UHP terrane has been an enigma because of its peculiar occurrence. We newly found a UHP chromitite from serpentinite in the Nishisonogi metamorphic rocks (NMR), a member of the Nagasaki Metamorphic Rocks, in Western Kyushu, following our finding¹ of it from the Higo Metamorphic Rocks (HMR), Central Kyushu. The UHP chromitite from NMR documents well a fluid-chromite interaction, showing partial graphitization of microdiamond. Such a fluid-chromite interaction is not observed in HMR chromitite. The NMR are high P/T (epidote-glaucophane schist subfacies) metamorphic rocks of Cretaceous in age, mainly consisting of pelitic and psammitic schists intercalating with minor basic schists². The peak metamorphic condition of the crystalline schists is estimated as 1.4 GPa and 520 °C by an assemblage of garnet with inclusions of chloritoid and omphacite, glaucophane, paragonite, and phengite in a garnet galucophanite³. Serpentinite and serpentinite melanges occur as elongated bodies or lenses concordant with schistosity trending N-S of the country schists¹. Jadeitite and omphacite occur as tectonic blocks in the serpentinite melange, showing the peak condition of 1.5 GPa and 500 °C by coexistence of jadeite and quartz⁴. Microdiamond-bearing chromitite was found from serpentinite in a melange at Ooseto Town, Saikai City. Chromitite occurs as a thin layer several cm thick and meter-size long in a serpentinite with numerous magnesite (or ankerite) veins. The layer is strongly deformed to show a schlieren-like structure. The serpentinite consists of fine-grained antigorite with no relics of olivine and pyroxenes. The chromitite consists of an aggregate of rounded and fractured chromite crystals with small amounts of talc and magnesite as a matrix and veins. Microdiamond occurs as aligned crystals in narrow zones ranging from a few μm to several tens of μm in chromite. Chromite is zoned, consisting of Mg-rich core ($\text{Mg}_{0.33}\text{Fe}^{2+}_{0.65}\text{Mn}_{0.03}$)($\text{Cr}_{0.84}\text{Al}_{0.12}\text{Fe}^{3+}_{0.04}$) $_2\text{O}_4$ and Fe-rich rim ($\text{Mg}_{0.06}\text{Fe}^{2+}_{0.89}\text{Zn}_{0.02}\text{Mn}_{0.03}$)($\text{Cr}_{0.85}\text{Al}_{0.12}\text{Fe}^{3+}_{0.04}$) $_2\text{O}_4$. The microdiamond-bearing zones are conspicuously richer in Fe_2O_3 [$\text{Mg}_{0.03}\text{Fe}^{2+}_{0.94}\text{Mn}_{0.04}\text{Zn}_{0.01}$)($\text{Cr}_{0.67}\text{Ti}_{0.01}\text{Fe}^{3+}_{0.31}$) $_2\text{O}_4$], observed as a brighter zone in a BSE image, than other part of chromite in the same grain. The network-like distribution of the zones clearly indicates fluid infiltration associated with the following exchange reaction of trivalent cations between chromite and the fluid: $\text{Cr}^{3+} + \text{Al}^{3+}$ (in chromite) = Fe^{3+} (in fluid)

Microdiamond occurs either as polyhedral or as platy crystals, 1 to several μm across. Identification of diamond was carried out with an energy dispersive X-ray spectroscopy (EDS) analysis (carbon peak) and Raman spectroscopy with a He-Ne laser. We observed a broad Raman peak at 1331 cm^{-1} , which is comparable to the peak (1332 cm^{-1}) characteristic of diamond. Graphite peak at about 1600 cm^{-1} is also observed, showing partial graphitization of microdiamond. These lines of evidence show that the fluid infiltration may have occurred after inclusion of microdiamond.

It is quite astonishing that microdiamond is preserved in such a completely serpentinitized ultramafic rock. Chromite can be a good container of microdiamond to prevent graphitization during geologically long duration of exhumation and serpentinitization. Our finding suggests the subduction origin of UHP chromitite from NMR rather than mantle migration origin⁵ in the case of the Luobusa Ophiolite.

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Keywords: microdiamond, UHP chromitite, subduction zone, Nishisonogi metamorphic rocks, ultrahigh-pressure metamorphic rocks

Melt-Peridotite Reactions In The Upper Mantle: Geochemistry Of Peridotite And Pyroxenite From The Beni-Bousera Massif

CHETOUANI, Kamar^{1*} ; AMRI, Isma¹ ; TARGUISTI, Kamal¹

¹departement de geologie, Faculte des sciences de Tetouan. Maroc

The Beni-Bousera massif contains ubiquitous pyroxenites of various types, organized into conspicuous layers ranging from 0.5 to 100 cm in thickness, hosted by peridotites. Integrated field features, petrographic observations, and geochemical analyses from 92 samples (whole rock major and trace elements data: 55 samples, microprobe data for minerals: 48 samples, and mineral trace elements data: 30 samples) from pyroxenites provide information to classify the rock types into four different groups typified as: (1) garnet pyroxenites, (2) spinel-garnet websterites, (3) spinel websterites, and (4) spinel chromium websterites. Type 1 rocks, occurring at the base of the massif, are considered as the most primitive type, garnet pyroxenites layers represent the vestiges of an old veined subcontinental lithosphere. They generally indicate temperatures <970°C (based on two-pyroxene thermometry) and a low to very low Mg# (<76%). Trace element contents show enrichment in heavy and middle rare earth elements but strong depletion in light rare earth elements (LREE). Paradoxically, the host peridotites show enrichment in LREE, which give new insights into their genesis history. Based on our field observations and geochemical results, we suggest that garnet-pyroxenite layers metasomatised the host peridotite successively by the partial melting as a consequence of subsequent heating phase(s) of the lithosphere. The magmatic event that led to the diversity and zoning of mafic layers was caused by melting of the base of thinned subcontinental lithosphere by upwelling asthenosphere, followed by infiltration of asthenospheric melts. The different groups of mafic layers record several stages of this event.

Keywords: Geochemistry, Beni Bousera, Pyroxenite, Peridotites

Petrology and geochemistry of the ultramafic metamorphic rocks from the Masora domain, east-central Madagascar

ICHIKI, Takashi^{1*} ; ISHIKAWA, Masahiro¹ ; KIMURA, Jun-ichi² ; SENDA, Ryoko²

¹Yokohama National University, ²JAMSTEC IFREE

Madagascar is located within the interior of the Neoproterozoic East African Orogen (Jacobs and Thomas, 2004) that marks the join between East and West Gondwana. In the east Madagascar, the Paleo-Mesoarchean Antongil-Masora domains are exposed (Collins, 2006; Tucker et al., 2011). In this study we report the petrological and whole rock and REE geochemical characteristics of the ultramafic metamorphic rocks exposed within the Masora domain and we discuss their origin and tectonic settings. The Masora domain is mainly composed of the Paleo-Mesoarchean felsic metamorphic rocks with subordinate amounts of metasedimentary rocks (e.g. Randriamananjara, 2008; Tucker et al., 2011). This domain was intruded by Neoproterozoic granitoids and mafic-ultramafic rocks (e.g. Smith et al., 2008).

The ultramafic metamorphic rocks are exposed in the north and south Masora domain. Three types of ultramafic metamorphic rocks are identified in the north: peridotite, pyroxenite and hornblendite. The peridotite is mainly composed of olivine and anthophyllite with subordinate amounts of serpentine, magnesite and magnetite. The pyroxenite is mainly composed of clinopyroxene and hornblende with subordinate amount of magnesite and magnetite. The hornblendite is mainly composed of hornblende with subordinate amount of actinolite and magnetite. Some of the hornblendite has spinel. An ultramafic metamorphic rock body occurs as a lens within metasedimentary rock in the south. This metasedimentary rock is kyanite+biotite+muscovite schist. The mineral assemblage of the ultramafic lens differs between core and rim. It is mainly composed of olivine, tremolite, actinolite and chlorite with subordinate amounts of serpentine, magnetite and altered minerals in the core. The rim is mainly composed of tremolite, actinolite and chlorite with subordinate amount of magnetite and ilmenite.

The ultramafic metamorphic rocks except for the hornblendites have $\text{SiO}_2 = 42.7\text{-}51.7$ wt.%, $\text{Al}_2\text{O}_3 = 1.5\text{-}7.5$ wt.%, $\text{MgO} = 19.8\text{-}35.4$ wt.%, and $\text{CaO} = 3.5\text{-}16.5$ wt.%. They have high Mg# (molar ratio of $\text{Mg}^{2+}/(\text{Mg}^{2+} + \text{Fe}^{2+})$) of 0.76-0.83. On the basis of bulk rock CIPW normative Ol-Cpx-Opx composition, the ultramafic metamorphic rocks except for the hornblendites plot in the field of the lherzolite, olivine websterite and websterite (Streckeisen, 1976). Compared with the geochemical characteristics of abyssal peridotites (Niu, 2004), the ultramafic metamorphic rocks shows lower MgO, higher TiO_2 and CaO than those in the abyssal peridotites. On the MgO-Ni diagram (Pfeifer, 1990 in Katzir et al., 1999) one of the samples plot in the typical abyssal lherzolite field whereas the others plot in higher-Ni (orogenic) field. Chondrite normalized REE patterns of the ultramafic metamorphic rocks show flat HREE with variable LREE patterns. One of the samples shows enriched LREE pattern and the others show depleted LREE patterns. The depleted LREE samples have flat HREE with about twice amount of chondritic HREE abundances. This is typical characteristic of an orogenic lherzolite such as Ronda massif in the southern Spain and Lanzo lherzolites in the Italian Alps (Bodinier and Godard, 2003). Enriched LREE pattern is also a typical characteristic of pyroxenites occurring in orogenic peridotites (Bodinier and Godard, 2003). On the basis of petrological and geochemical characteristics, their protoliths are orogenic lherzolite, websterite and pyroxenite.

Keywords: Gondwana supercontinent, east-central Madagascar, geochemistry, Masora domain, ultramafic metamorphic rocks

Zircon Nano-SIMS U-Pb dating from the country gneiss beside Horoman peridotite, Hokkaido, Japan

SUZUKI, Ryosuke¹ ; OKAMOTO, Kazuaki^{1*}

¹Saitama university, Japan

Hidaka Metamorphic Belt, Hokkaido, Japan includes the youngest granulites and the Horoman peridotite complex in the highest grade zone. Age of the Hidaka gneiss and amphibolite have been determined by various methods (e.g. K-Ar, U-Pb, Rb-Sr and etc). However, the age of Horoman peridotite complex has not been determined yet. Only Yoshikawa et al (1993) reported the cooling age of the complex as 23 Ma based on whole rock Rb-Sr isochron method. This study performed U-Pb dating of zircons from the paragneiss surrounding the Horoman peridotite complex in order to determine the intrusive age of the Horoman peridotite complex from the upper mantle into the lower crustal conditions. The zircons have detrital cores and thin rims (<20 microns). Therefore we used Nano-SIMS because it is possible to focus the secondary beam diameters down to submicrons for the analysis. As a result of this measurement, rim ages of the zircons show that ²³⁸U-²⁰⁶Pb age are 7-11Ma (n=7) and detrital core ages show 25.6 Ma, 34-35 Ma, 78 Ma and 150 Ma (n=8). The rim ages are the youngest in Hidaka metamorphic rocks and there is a discrepancy with zircon rim ages (19Ma) from the granulite (Kemp et al. 2007; Usuki et al. 2006). The present rim ages (7-11 Ma) fit well with the tectonic scenario of the collision process of Hokkaido Island proposed by Yamamoto et al. (2010). It is considered that the Horoman peridotite complex was juxtaposed onto the Hidaka metamorphic belt at 7-11Ma by the subducting Pacific plate after the collision between North American and Eurasian plates.

Keywords: Zircon, U-Pb, Nano-SIMS, Horoman peridotite, country gneiss, juxtaposition age

3 types of Ca-Amp found from Nove Dvory UHP eclogites and their origin, Moldanubian Zone of the Bohemian Massif

YASUMOTO, Atsushi^{1*} ; HIRAJIMA, Takao¹

¹Department of Geology and Mineralogy, Graduate School of Science, Kyoto University

The upper-stability limit of Ca/Na amphibole (Amp) in meta-mafic rocks are considered to be around 2-3 GPa in pressures (Schmidt & Poli, 1998). Thus, most Ca-Amp in (ultra)-high pressure metamorphic rocks have been considered as retrograde products. The peak metamorphic conditions of Nové Dvory eclogites are estimated to be 4.5-4.9 GPa and 1050-1150°C. However, some Ca-Amp inclusions in Grt are likely to be interpreted as prograde relicts survived the ultra-high pressure metamorphism. This paper reports the mode of occurrence and the chemical compositions of Ca-Amp and the coexisting minerals in Nové Dvory eclogite, and discusses when Ca-Amp crystallized. Investigated two eclogite samples, ND0107 and ND120, collected from the same outcrop, are composed mainly of garnet (Grt) and Omphacite (Omp) with minor amounts of apatite (Apt) and rutile (Rt) at the UHP stage, and suffered hydration reactions, represented by Ca-Amp and plagioclase (Pl) formation, with various degree during the exhumation stage.

Ca-Amp in studied eclogite can be classified into 3 types based on their modes of occurrence; Type 1 Amp occurs in sporadic euhedral shaped polyphase mineral aggregates (PMAs) in Grt along with Omp, Rt, and Apt. Type 1 Amp is identified only from ND0107, and is classified as pargasite (Prg) or kaersutite (Krs). Omp inclusions associated with Type 1 Amp are homogeneous and have high X_{Jd} of 40-45, suggesting that the associated Omp did not suffer retrogressive reactions. On ACF diagram, Type 1 Amp is plotted between the associated Omp and host Grt. It suggests that Type 1 Amp could be a relict of the following reaction, $Amp = Omp + Grt + W$, during the subduction stage. Type 2 Amp is identified as a member of PMAs in Grt along with spinel (Spl) and diopside (Di). Those PMAs with Type 2 Amp show unidiomorphic shapes and straight alignment in Grt. They are classified as Prg or magnesio-hastingsite (Mg-Hs). Type 3 Amp is a member of the symplectite along with Omp, Di, Spl, and Pl developed at Grt rim. These facts suggest that Type 2/3 Amp were formed during the exhumation stage reacted with infiltrated fluids to the host eclogite.

The different stage origins of Type 1/2 Amp mentioned above is supported by F and Cl contents in them. Type 1 Prg contains 0.21-0.30 wt% of F, but is almost free from Cl (<0.01wt%). Type 2 Prg contains 0.43-1.17wt% of Cl. Type 2 Prg in ND0107 with Type 1 Amp contains 0.05-0.29wt% of F. On the other hand, Type 2 Prg in ND120, which is free from Type 1 Amp, is scarce in F (<0.05wt%). Type 3 Amp is free from Cl.

It is generally considered that Ca-Amp enriched in $(Na+K)^A$, ^{IV}Al , and $^{VI}Fe^{2+}$ can incorporate more Cl (Makino, 2000). However, Type 1/2 Amp have a similar major element compositions such as $(Na+K)^A = 0.79-0.95$ pfu (for $O+OH+F+Cl=24$ basis), $^{IV}Al = 2.01-2.45$ pfu, and $^{VI}Fe^{2+} = 0.56-0.97$ pfu, in spite of a scarce but significant difference in Cl content among them. Cl-free Type 3 Amp contains similar amount of $(Na+K)^A$ (0.75-0.96 pfu) and ^{IV}Al (1.95-2.38 pfu), but less in $^{VI}Fe^{2+}$ content (<0.47pfu) compared with those of Type 1/2 Amp.

As a present stage conclusion, Type 1 Amp crystallized under F-bearing and Cl-poor environment during the prograde stage, and Type 2/3 Amp crystallized during the retrograde stage along with supply of Cl from outside of the rock. F identified in Type 2 Amp in ND0107 with F-bearing Type 1 Amp could be supplied from the Type 1 Amp through the retrogressive reactions.

Keywords: Eclogite, Amphibole, Ultra-high pressure metamorphism, Bohemian Massif, Fluorine, Chlorine