Early Paleozoic subduction in Cathaysia: evidence from tectonic mé lange in the northwest Yunkai Domain

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Abstract

The early Palaeozoic tectonic history of the South China has been extensively debated in the last two decades, two contrasting groups of models have been proposed, i.e. subduction collisional belt vs. intracontinental orogen. The Yunkai Domain is one of the most important pre-Devonian metamorphic basement, which is located in the west Cathaysia Block. In this study we report an early Paleozoic subduction-collision related tectonic mélange in the northwest Yunkai Domain, South China. The mé lange is consisted of volcanic rocks, ophiolite fragments and forearc accretion sedimentary complex, with strong deformation of lineation, foliation, fold and thrust fault. We present the detailed LA-ICP-MS zircon U-Pb dating, major and trace element geochemical and Lu-Hf isotopic data for the volcanic rocks and ophiolite fragments. Zircon U-Pb dating shows that the volcanic rocks were erupted at 460 –443 Ma and the intrusion age is 430 Ma. The ophiolite fragments yield the formation age of 455 –437 Ma. The volcanic rocks are composed of high magnesian-magnesian basaltic andesite, allgovite, andesite and dacite rocks, show the affinities of arc related rocks (mostly like sanukite), with LREE, LILE (Rb, Ba, Th and U) enrichment and HFSE (Nb, Ta and Ti) depletion. The ophiolite fragments (basalt, diabase and amphibolite) are similar to those of mafic rocks from supra –subduction zone (SSZ), with LILE (Rb, Ba, Th and U) enrichment HFSE (Nb, Ta, Zr, Hf and Ti) depletion. The volcanic rocks and the ophiolite fragments are similar to those from forearc or arc setting. Zircon Lu-Hf isotopes of the volcanic rocks give negative initial ε Hf(t) values between -4.7 and -0.5. Zircon Lu-Hf isotopes of mafic rocks in the ophiolite give scattered negative initial ε Hf(t) values between -11.0 and +2.3. The ε Hf(t) values of the volcanic rocks and the ophiolite fragments indicate different degrees addition of crustal material into the mantal source. The volcanic rocks and ophiolite fragements of the mélange indicate an ealy Palaeozoic subduction progress was happened in this area. Briefly, our research on the mélange, in combination with early Paleozoic metamorphic features and the widely distributed early Palaeozoic igneous activities, reveal that the tectonic history have experienced subduction accretion orogenic process in the early Palaeozoic, Yunkai Domain, South China.

Acknowledgments

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Keywords: Yunkai Domain, Yunkai tectonic mélange, volcanic rocks, High-magnesia andesite, ophiolite fragments

Zircon record for prolonged magma chamber processes before the largest Quaternary Toba super-eruption

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The enormous amount of eruptible magmas and the time intervals between large volumes of major eruptions suggest that magmas may need a significant period of time (~ a million years) to accumulate before a supereruption. However, radiometric ages show that the resident time of a magma reservoir is significantly shorter. This study, for the first time, used in situ zircon U-Pb dating and Hf-O isotopes to decipher Toba magma chamber processes, which gave birth to the largest Quaternary eruption on Earth. Besides the well-recognized four eruptions in Pleistocene, magmatic activities of Toba magma chamber can be traced back to 10.5 Ma, followed by infrequent magma intrusion at 5.2 Ma. Age spectrum of zircon indicates that the volume of eruptions correspond to time of magma storage and evolution. The Youngest Toba Tuff (YTT), in particular, record ~ 450,000 years of crystal accumulation in the upper crustal magma chamber before eruption. Such long periods of magma chamber processes were unlikely to be sustained directly by recharge of voluminous basaltic magmas in terms of zircon Hf-O isotopes, but were probably maintained by periodic influx of fluids and silicic magmas melted in depth. Fractional crystallization and accumulation of crystal mush during this interval help to increase the viscosity of the magma and therefore trap the fluids beneath the chamber roof until triggered for explosive eruptions.

Keywords: volcano, super-eruption, zircon U-Pb dating , magma chamber

Metamorphosed tectonic blocks in the Yuli belt, eastern Taiwan: a petrological perspective

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Rare and small meta-mafic/-andesitic and serpentine bodies scattered in the Yuli belt have long been interpreted as tectonic blocks in literature. Although a mélange-like environment has been proposed, the tectonic setting(s) and geological evolution of the whole Yuli belt remain debating. It is obvious that the tectonic blocks differ greatly from the matrix meta-sediments (mainly pelitic and psammitic with minor chloritic) in terms of whole-rock geochemistry and protolith origin. However, whether they were metamorphosed under the same or different conditions is a critical question yet to be answered. High-pressure metamorphic minerals, such as glaucophane and omphacite, have been identified in many of the tectonic blocks but not in the matrix meta-sediments by far. However, more field observations indicate that the former are embedded within the latter. Therefore, it seems less likely that both were metamorphosed at different physical conditions as previously thought. We have investigated representative litho-types from tectonic blocks and adjacent meta-sediments by using electron-beam microscopy, traditional geothermobarometry, and equilibrium phase diagram modeling. Peak metamorphic temperatures for tectonic blocks and country rocks are fairly consistent at around 500-570˚C, whereas peak metamorphic pressures, although less well constrained, are in the range of 10-17 kbar. These P-T estimates indicate that both tectonic blocks and surrounding meta-sedimentary rocks are coeval in petrotectonic evolution and represent a type of subduction zone metamorphism. The apparent difference in mineral assemblage, metamorphic grade, and texture for some similar or different rock types is misleading and probably reflects complex nature or superimposition controlled by bulk-rock composition, deformation, retrogression, metasomatism, and/or fluid activities.

Keywords: high-pressure metamorphism, subduction, glaucophane, omphacite, melange

Significance of Zr-in-rutile thermometry for deducing the decompression *P–T* path of a garnet-clinopyroxene granulite in the Moldanubian Zone of the Bohemian Massif

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This work aims to show the importance of Zr-in-rutile thermometry for evaluating the *P–T* history of granulite facies rocks, where higher diffusion rates in the main constituent minerals impede the use of geothermometers based on element distributions. We apply Zr-in-rutile thermometry to a garnet-clinopyroxene (Grt-Cpx) granulite from the Moldanubian Zone of the Bohemian Massif. Three major metamorphic evolutionary stages are identified from the Grt-Cpx granulite. The early high-pressure (HP) stage is represented by an inclusion assemblage in garnet: a high-Ca garnet core (32–38 % grossular, 30–32 % pyrope and 32–35 % almandine) + omphacite (36–39 % jadeite and 3–5 % Ca-Tschermak) + plagioclase (18 % anorthite) + pargasitic amphibole + rutile + zircon + quartz. The subsequent medium-pressure (MP) stage is represented by matrix minerals composed of augitic clinopyroxene (2–6 % jadeite and 2–6 % Ca-Tschermak) + orthopyroxene + ternary feldspar (17–23 % anorthite, 41–44 albite, 33–43 % orthoclase; re-integrated compositions from antiperthite grains in the matrix) + rutile + ilmenite + quartz. The final low-pressure (LP) stage is represented by a symplectic corona composed of calcic plagioclase (~90 % anorthite) + orthopyroxene + magnetite. Application of Grt-Cpx and/or jadeite-quartz-albite geobarometers gives pressures of ~1.8 GPa for the early HP stage and 1.3–1.4 GPa for the MP stage. The final LP stage is constrained to lower than ~0.7 GPa using conventional geothermobarometers. Rutile inclusions in high-grossular garnet have a rather low and limited range of Zr contents (mostly 1100–1500 ppm), regardless of inclusion size. This suggests that rutile inclusions preserved the initial Zr compositions without much modification by later re-equilibration. Application of Zr-in-rutile thermometry yields a temperature of ~830°C at ~1.8 GPa for the early HP stage of granulite evolution. Rutile grains in undeformed clinopyroxene-rich domains of the matrix generally occur as small euhedral crystals and have higher Zr contents (mostly 8000–10000 ppm), corresponding to 980–1066°C at 1.35 GPa using Zr-in-rutile thermometry. In contrast, those in strongly deformed quartz-rich domains of the matrix occur as coarser and more elongated grains with lower Zr contents (3000–5000 ppm), yielding slightly lower temperatures due to retrogressive re-equilibration. Based on these results, we reveal that the studied Grt-Cpx granulite underwent a significant heating by about 200°C during the early stage of decompression from the peak pressure. SHRIMP U-Pb dating for the zircon inclusions in high-grossular garnet indicate that the HP stage of the studied granulite occurred at c.340 Ma, which is indistinguishable to reported LP zircon ages from South Bohemia. Thus, the studied granulite was rapidly heated and exhumed from mantle depth to middle to upper crust in a short period. This rapid heating associated with exhumation was caused by incorporation of the Grt-Cpx granulite into higher temperature felsic granulites which exhumed from deeper parts of the continental collision zone.

Keywords: Zr-in-rutile thermometry, garnet-clinopyroxene barometry, high-pressure granulite, continental collision zone, Bohemian Massif

Igneous zircons preserving protolith age but internally deformed during the high-pressure metamorphism

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Zircon, a mineral highly resistant to alteration and secondary effect, generally serves as a robust tool to provide accurate age data of the magmatic, metamorphic or detrital origin of the rocks in which it is crystallized, recrystallized or trapped. Most of the published articles on zircon age data mainly report U-Pb age data and associate their results with the geological or tectonic events to their research areas. No doubt, most igneous rocks (plutonic and volcanic both) yield age data fairly accurate and identify the geological event of the rocks which contain those dated zircons.
However, in case of zircons formed or occurring in metamorphic rocks may not yield straight-forward age results. The reasons are (1) presence of inherited detrital or igneous-origin core domains, (2) the overgrowth domains, could be igneous or metamorphic, and (3) the outer rim or late-stage domains. Studying zircons via CL-imaging enables to distinguish such domains if present. However, those domains have been deformed or subject to U, Pb and trace element mobility is not easy to understand. Studying zircon for EBSD may be a useful tool to identify those internal deformations in single zircon crystals. In this paper an EBSD results on already dated zircons form the Himalayan HP eclogites have been presented. The age-data suggest their magmatic origin but several domains preserve internal deformation, probably occurred during the HP Himalayan eclogite facies event.

Keywords: Zircon, age, Eclogites, Internal deformation, High-pressure metamorphism

Origin of the garnet amphibolites from the Mitsuishi area, western Hokkaido Japan -constraints from the metamorphic petrology and structural analysis-

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Kamuikotan high P/T metamorphic rocks preserve one of the coldest geotherm (0.6 –0.8 GPa/°C) in the Jurassic subduction zone in circum Pacific orogenic belt. The Kamuikotan metamorphic rocks distribute as a belt extending north-south directions in central-western Hokkaido Japan. They suffered blueschist and subsequent greenschist facies metamorphism. However, the origin of the garnet amphibolites is still debatable because they suffered relatively higher P and T conditions, and exhibits as blocks in the serpentinites. Ueda et al. (2013) and Ueda & Orihashi (2014, 2015) have revealed several important new discoveries as follows, 1) origin of the garnet amphibolites are subducted warm oceanic crust 2) they overprinted blueschist facies metamorphism. Based on these important contribution of Ueda`s work, we have described garnet amphibolite blocks. Additional new things are follows. 1) Garnet amphibolites had reached amphibole decomposition temperature fields, producing rutile and zircons. 2) Garnets have relative high Ca core and Ca poor rims. 3) The garnet amphibolite blocks suffered L-tectonite (constrictional) type strain during cooling stage. Amphibole and white mica were rotated along YZ axis and garnets had overgrown and recrystallized showing snowball and S shape structure in the YZ sections. Above these features suggest that garnet amphibolites were separated from suducted crustal layers in dehydration/melting process, and that hydration and constrictional strain process were operated during exhumation stage in cold subduction zone.

Keywords: high grade blocks in serpentinite, dehydrated warm blocks into cold subduction zone, constrictional strain in exhumation

Tectono-metamorphic evolution of the Kurosegawa tectonic belt in Southwest Japan

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The Kurosegawa tectonic belt distributed in Southwest Japan (from Kii peninsula to Kyushu) has a significant role in understanding the tectonics and formation of Japanese Island. The belt is underlain by a serpentinite melange with complicated tectonic block assemblage of granitic rocks, high-temperature (HT)-type metamorphic rocks (metagabbros: Grt-Cpx granulite, Grt amphibolite and Cpx-bearing amphibolite, metapelites: Grt-Crd-St gneiss and Grt-Bt gneiss) and high-pressure (HP)-type metamorphic rocks (metagabbros: Jd-Gln rock, Gln-bearing matagabbro, metabasalt: Lws-Gln schist, metasediments: Phn-Gln+/-Lws schist and Grt-bearing quartzite).
The granitic rocks and the protoliths of the HT-type metagabbros are supposed to be derived from volcanic arc at an active continental margin based on their major, trace, and rare earth element (REE) chemistry. On the other hand, geochemistry of the protoliths of the HP-type metagabbro and metabasalt indicate mid oceanic ridge basalt (MORB)-like precursors. The LA-ICP-MS U-Pb zircon dating of granitic rocks (collected from Nabaenohana, Anan, Mitaki and Yatsushiro areas) gave the Upper Ordovician magmatic ages of ca.450 Ma with the older inherited core ages of 570-3090 Ma. The U-Pb ages of the HT-type gabbros (from Nabaenohana and Yatsushiro areas) have similar magmatic age ranging *ca.* 439, 446 and 453 Ma concordant clusters. The HP-type gabbros (from Engyoji and Yatsushiro areas) show the igneous age of the Late Cambrian (ca. 490 Ma). The detrital U-Pb zircon ages from the HP-type metasediments (from Anan and Yatsushiro areas) range from 430 to 3000 Ma, therefore the sedimentation would be finalized after Silurian. The Rb-Sr isochron ages for the Lws-Gln schist (typical HP-type blue schist) gave 300-270 Ma, which may indicate the age of HP-type metamorphism.
These results show that the Cambrian oceanic magmatic sequence (protoliths of the HP-type gabbros and basalts) covered by Silurian pelagic sediments (protoliths of the HP-type metasediments) subducted to the already existed palaeo-Asian continent and formed an active margin arc system during the Upper Ordovician. The protoliths of the HT-type gabbros and the granitic rocks would be situated in the lower crustal portion and the upper crustal portion of the arc system, respectively. The similar assemblages are present in the South-Kitakami belt and the Nagato tectonic belt suggesting similarities in their origin.

Keywords: U-Pb zircon dating, granitic rocks, HT-metagabbro, HP-metagabbro, Kurosegawa tectonic belt

Deep subduction and the ultrahigh-pressure metamorphism of a Cretaceous accretionary prism, the Nishisonogi metamorphic rock, western Kyushu, Japan: Finding of diamond-graphite aggregates

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This paper reports new findings of diamond-graphite aggregate (DGA) from the Nishisonogi metamorphic rocks, western Kyushu, which is an ancient subduction complex of Cretaceous in age. The DGA occurs in serpentinites and pelitic schists from a serpentinite melange. There are two occurrences in serpentinites; one is in pseudotachylye-like veins developing in quartz-carbonate rocks associated with serpentinites and the other is in chromitites (Nishiyama et al., 2014). In pelitic schists, the DGA occurs in strongly deformed pyrite porphyroblasts.

Thin sections of the rocks containing DGAs were polished with Al_2O_3 sheets to avoid possible contamination of diamond. No carbon coating was used. All DGAs occur as inclusions of 1 to 10 mm in size. EDS analysis of DGA samples coated with Au shows C peaks, and the Raman spectra of the samples with no coating show 1330 cm^{-1} diamond band together with 1580 cm^{-1} (G) and 2680 cm^{-1} (S1) graphite bands. The SEM-SXES (scanning electron microscope combined with soft X-ray emission spectrometer) methods confirms coexistence of sp^2 and sp^3 structures in the samples, indicating this material is a mixture of diamond and graphite.

Chromitites rarely occur as 1 to 50 cm thick layers in serpentinites, and consist of chromite grains several 100 mm across. DGA occurs as pseudosecondary inclusions in chromite, which show curved alignment of tiny (1 mm in size) inclusions with termination at both ends. Some chromite in the chromitite contains SiO_2 up to 2 wt % and water by 6 - 8 wt %, showing concentric zoning with SiO_2-free chromite.

Quartz-carbonate rocks occur as veins or as massive bodies replacing serpentinite, suggesting its origin as carbonation of serpentinite. They consist mostly of quartz and magnesite with a small amount of dolomite. The pseudotacylyte-like veins occurs as 1 cm thick veins, showing branching and fluid structures. They are completely recrystallized to aggregates of very fine- grained quartz and magnesite with no remant of glass. The DGA occurs as rounded or ovoidal grains 10 mm across, associated with various minerals such as fayalite, wollastonite, Zr-rich rutile, anatase, natural copper, zircon, xenotime, pyroxene ($Na_{0.27}Ca_{0.32}Mg_{0.80}Fe_{0.42}Al_{0.19}Si_{2.02}O_6$), amphibole ($Na_{0.30}Ca_{1.73}Mg_{4.09}Fe_{0.85}Al_{0.13}Si_{8.00}O_{22}(OH)_2$), and unknown mineral of $MgSi_4O_9$ composition. They are all tiny crystals of several mm in size. SiO_2-mineral inclusions in anatase show Raman spectra either of quartz or of none, and the latter may possibly be amorphous.

The pelitic schist in the serpentinite melange consists of chlorite + phengite + albite + quartz with minor pseudomorphs after garnet. It contains strongly deformed pyrite porphyloblasts, in which numerous inclusions of quartz and DGA are found. The quartz inclusions shows Raman spectra of quartz but have peculiar features normally not found in quartz; they are easily damaged by electron beam under the SEM observation, and they show peculiar shapes with promontries. The promontries may be possibly formed by volume increase owing to transition from coesite, and the damage by electron beam may show that they are very fine-grained polycrystalline aggregates.

These DGAs strongly suggest that the serpentinite melange have subducted into the depth of the diamond stability field, although each DGA may have specific origin. The coexistence of diamond and

graphite in DGAs indicates either graphitization of diamond during the exhumation or diamond formation from graphite during the deep subduction. Some DGAs show platy form, suggesting the latter possibility. However, we have no definite interpretation on this issue at present.
The metamorphic conditions of crystalline schists in the Nishisonogi metamorphic rock is up to 500 ^{o}C and 1.5 GPa (Moribe, 2014MS), not reaching to the stability field of coestie. However, our new finding of DGAs from the pelitic schist may indicate the possibility of deep subduction of not only the serpentinite melange but also the whole metamorphic rocks in this region.
Neither coesite nor diamond has been found from subduction zones in an island arc setting. Our new finding of DGAs shed new light on the subduction zone dynamics at the island arc setting, by indication the deep subduction can occur in these tectonic settings.

Keywords: deep subduction, ultrahigh-pressure metamorpshim, diamond graphite aggregate, Nishisonogi metamorphic rock, pseudotachylyte, serpentinite melange

Origin of ophiolite pulse and thermal state of the upper mantle in the Ordovician time constrained from the Hayachine-Miyamori Ophiolite

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It is critical to know the thermal history of the mantle in order to better understand the evolution of the earth because the mantle under thermal convection occupies 80vol% of the earth.
The mantle potential temperature (MPT) is a temperature of mantle material adiabatically brought to the surface. The thermal history of the mantle has been examined by revealing secular change of MPT estimated from non-arc basalts and modeled with a parametarized convection model. The so far obtained MPT change and the model, however, cannot resolve episodicity, the critical feature of the earth’s thermal history, which can only be tackled by accumulation of data with higher resolution.
Ophiolite pulses, in which a large number of ophiolites formed in a confined period, are thought to reflect thermal episodes. However, the relationship between the Ordovician ophiolite pulses and the proposed plume model are not clear because of the predominance of arc ophiolites and scarcity of LIPS for the Ordovician pulse. This must be resolved by MPT estimation for the Ordovician mantle, for which two difficulties relevant to arc magma genesis must be overcome: the involvement of H2O and complex thermal state.
In this study, we develop a novel method for MPT estimation for arc environment by using ultramafic dikes from Hayachine-Miyamori Ophiolite, northern Japan. The estimated MPT, melting depth and water content in source mantle are ~1360˚C, ~170km and ~0.15wt% respectively. The geochemical data of the dike indicate passive upwelling of NMORB source-like garnet peridotite from sub-slub mantle without strong influence of slab-derived fluids. The estimated MPT may reflect the global value if operation of small-scale convection is considered. We conclude that the Ordovician upper mantle has a thermal state similar to the current upper mantle. Surface tectonics, such as assembly and breakup of supercontinents and a peculiar water delivery, might be responsible for the Ordovician ophiolite pulse.

Keywords: thermal state of the mantle, mantle potential temperature, ophiolite pulse, arc ophiolite

Geochemical study of P-type jadeitites (jadeite precipitates) from the New Idria serpentinite body, California

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P-type (fluid precipitation) jadeitite (Tsujimori and Harlow, 2013) is an excellent media to decipher subduction zone fluids and fluid-induced geochemical processes. As the best example of P-type jadeitite, veined jadeitite from the New Idria serpentinite body of the Diablo Range (California, U.S.A.) was investigated. Vein-network textures and growth textures of oscillatory-zoned jadeite crystals suggest that the jadeitite suffered brittle deformations and subsequently brittle microcracks were filled by jadeite precipitates repeatedly. An integrated study of LA-ICPMS trace elements and lithium isotope geochemistry constrain a property of jadeitite-forming high-pressure/low-temperature aqueous fluids and a possible scenario for formation of the veined jadeitite. Compositions of the jadeitite-forming fluids estimated using partitioning coefficients between clinopyroxene and fluids have trace element patterns similar to experimentally-determined fluids in equilibrium with coesite-bearing metasedimentary rocks. In-situ analyses confirmed a wide variation of isotopic composition (from −12 to +7 permil) and abundance (4–68 μg/g); those values show a systematic distribution fitting a curve led by the fluid–rock interaction equation. Geochemical data suggest that deep fluids enriched with some specific elements and light lithium might have migrated to forearc depths along slab–mantle interface from a great depth. During the migration/upwelling process, fluids interacted substantially with various metamorphic rocks in the interface. Various degrees of fluid–rock interaction and stepwise fluid infiltration at forearc depth recorded in New Idria jadeitite give new insights into the behavior and dynamics of aqueous fluids in subduction zone.

Keywords: jadeitite, lithium isotope, subduction zone

Petrographical and chemical evolution of a troctolites rich section of oceanic crust located directly above a spreading centre, example from Wadi Mahram, Oman ophiolite

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Petrographical and chemical evolution of a troctolites rich section of oceanic crust located directly above a spreading centre, example from Wadi Mahram, Oman ophiolite
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The Maqsad or Sumail massif in the Oman Ophiolite is known for its well defined mantle structural diapir well matching other petrographical and chemical data, allowing us to locate the axis of a former spreading centre. However, most of the studies conducted on this famous massif concerned the mantle section and published data include mantle harzburgites and mantle dykes and intrusions petrology and chemistry. The crustal section in this massif is only locally known in its lowest part located near the mantle/crust boundary. In this study, we conducted a sequential study of the 2 km thick Wadi Mahram crustal section (from mantle-crust boundary to sheeted dyke transition) located directly above the mantle diapir, i.e. directly above the Oman spreading axis.
The crustal column above the Maqsad diapir is exceptionally rich in troctolites as this lithology represent more than the three quaters of the observed facies and is present at any level from the basis to top of the section. Troctolites are layered in the lower levels, close to the mantle-crust transition zone, intercaled with minor olivine gabbros layers, and the layering is crosscut by centimeter scale olivine gabbro dykes. From the middle to the top of the section, vary textured troctolites progressively become become isotropic at the boundary with the sheeted dyke complex. Meter scale olivine gabbros and olivine-free layers are more abundant at the top. Dolerite dyke cutting troctolite and gabbro structures are abundant near the sheeted dyke complex and probably represent its root system.
Down section mineral chemistry evolution show a considerable contrast between the troctolites and the olivine gabbros. The troctolites chemical characteristics seem to be evolving on a large scale with 2 superposed main bodies at the top and the bottom of the section, about 800 m thick, showing a regular evolution probably in relation to magmatic differentiation during fractional crystallisation. A minor block between these 2 main troctolite bodies show a strong chemical scatter in association with variabke textures and minéralogies suggesting that melt mixing and melt/rock reaction were the dominant processes during its formation. Between the layers of troctolites, olivine gabbros layers show petrographical and chemical properties that could have been aquired by local magmatic processes like differentiation in small scaled trapped melt pocket or local melt/rock reaction during melt migration to the surface. As it was already shown by studies on magmatic dykes in the mantle, the presence of differentiated dykes cutting the layered structure at the section bottom show that significant differentiation degree may be reached within the mantle and differentiated melt can be injected from the mantle into the crust. These differentiated melts melt s are however injected during during the late magmatic history of the section as they cut already cooled lower troctolite. Traces of mixing with these differentiated melts are found only at 2 levels kn the crust: at the intermediate vary textured level or at the topmost level, below below the sheeted dyke complex.

Keywords: Oman Ophiolite, Gabbroic Crust, Mantle diapir, Troctolite

Detailed imaging of the subduction front in the locked and 2010 Mentawai tsunami earthquake rupture zones from full waveform inversion of seismic reflection data

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The Sumatran subduction zone is one of the most seismically active zones on earth. Since 2004, three great earthquakes (Mw > 8.0) occurred (2004, 2005, 2007), rupturing the forearc region along the megathrust. The 2004 earthquakes also ruptured the frontal section of the megathrust, supposed to be aseismic, generating a destructive tsunami. While the 2005 and 2007 great earthquakes did not generate a powerful tsunami, the 2010 Mw 7.8 earthquakes did by unexpectedly rupturing the updip part of the Mentawai segment, which has already ruptured in 2007 in the forearc region. The northern part of the Mentawai segment, between the 2007/2010 and 2005 rupture zones is still locked and might generate a great earthquake, and possibly a destructive tsunami. Therefore, the understanding of rupturing processes and differences between the different segments of the Sumatran subduction zone are critical to assess rupture potential.

We combined downward continuation, traveltime tomography and full waveform inversion on this 15-km-long streamer and low frequency seismic data to characterize the nature of the accretionary wedge and the plate interface. The downward continuation of the streamer data to the seafloor enhanced the refraction arrivals to be observed from near-zero offset up to far offset. Then, the travel time tomography was used to determine the background velocity from the upper sediments down the top of the oceanic crust. Starting from these velocities, we perform an elastic full waveform inversion to determine the detailed velocity structure of the sub-surface. In both regions, the combination of pre-stack depth migrated seismic images and high resolution velocity results show a low velocity subduction channel with high porosity at the plate interface that connects active frontal thrusts at the toe of accretionary wedge, suggesting that the frontal section of the prism is seismogenic. Computation of the porosity of the sediments determined fluid content along these channels and faults. Active seawward and landward-vergent faults at the front of the subduction could generate a powerful tsunami by moving the seafloor at high depth.

Keywords: Sumatra subduction zone, Tsunami earthquake, Full waveform inversion

Pressure estimation for diamond anvil cell under very-low pressures, hydrostatic conditions - re-evaluation for quartz Raman peak shifts -

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Pressure shift of the ruby R1 luminescent has been used as primary pressure gauge in diamond-anvil experiments. However, the pressure calibration under low-pressure conditions (<1 GPa) was poorly constrained although crustal hydrothermal experiments are important. For calibration of the R1 luminescent shifts at low-pressure conditions, we have done diamond anvils experiments at room temperature conditions. H_2O and ethanol were used as pressure transmitting medium and all experimental pressures was below ice stability field keeping hydrostatic-pressure conditions. We could get well-constrained new calibration line. Our new pressure estimation based on the quartz Raman peaks gives lower pressures than that of previous experiments reported by Schmidt and Ziemann (2000). For example, it would give 0.6 GPa from our experimental study although the previous study estimated at 1 GPa. This discrepancy causes significant overestimates for residual pressures determined by quartz Raman analysis from the natural rocks.

Schmidt, C., and Ziemann, M.A., 2000, American Mineralogist, v. 85, p. 1725–1734.

Deformation history of Sanbagawa eclogites and their relation to Higash-Akaishi garnet peridotites

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We present Electron Back Scattered Diffraction (EBSD) maps and crystal preferred orientations (CPO) of the eclogites in the subduction-related high-pressure/low-temperature type Sanbagawa metamorphic belt, central Shikoku, Japan. The Sanbagawa metamorphic belt, extends over >800 km along the southwest Japan, bounded to the north by the Ryoke belt (a Cretaceous high-temperature and low-pressure regional metamorphic belt) along the Median Tectonic Line and to the south by the Chichibu and Shimanto belts, forming the well-known paired metamorphic belts of Miyashiro (1961). Eclogites investigated in this study were collected from the Iratsu body in the Besshi area.
Our EBSD data reveal mainly L-type fabric (strongest CPO along [001]-axes and {011}-poles, suggesting intra-crystalline flow along [001]{110} and <110>{110} slip systems) in omphacite, random or weak fabric in garnet, and almost an identical CPO to that of omphacite was observed in hornblende. In addition, actinolite shows irregular CPO pattern. The L-type fabric in omphacite and weak or irregular fabric of garnet indicate constrictive deformation under the eclogite facies stage. Hornblende was formed around omphacite however retained the original fabric from that of omphacite. Our results are consistent with the garnet and omphacite presented by Muramoto et al. (2011) for the garnet-peridotite from the Higashi-akaishi ultramafic body. Our results suggest that the ultramafics and eclogites experienced similar deformation regime therefore considering eclogites and garnet peridotites as separate tectonic blocks needs reappraisal.

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Keywords: Eclogite, Higashi Akaishi peridotite body, Sanbagawa metamorphic belt

Mineralogical and petrological features of the Sanbagawa eclogites and amphibolites: pseudosection modelling

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We present a summary on the mineralogical and petrological features of eclogites and amphibolites from the Sanbagawa metamorphic belt, southwest Japan. The Sanbagawa metamorphic belt, extending over> 800 km along the southwest Japan, bounded to the north by the Ryoke belt (a Cretaceous high-temperature and low-pressure regional metamorphic belt) along the Median Tectonic Line and to the south by the Chichibu and Shimanto belts, forming the well-known paired metamorphic belts of Miyashiro (1961). The belt is composed of basic, quartzose, pelitic-psammitic schists and several eclogites and ultramafic bodies. In this study, we investigated samples from the Iratsu eclogite body and Tonaru amphibolites for detailed mineralogical, petrological, and tried to understand the metamorphic history using the pseudosection modelling. Based on petrography, eclogite samples contain porphyroblastic garnets, highly cracked and surrounded by amphibole, quartz, chlorite, and epidote. Hornblende and clinopyroxene show penetrative along-strike foliation. Mineralogically garnets are weakly zoned and Alm-rich, and the contents of Grs increase slightly from core towards rim. Amphibole is mainly hornblende and actinolite with minor barroisitic composition. Pseudosection modelling, using THERMOCALC, was applied to constrain the metamorphic P-T path. The work is in progress, but preliminary results show a prograde path for eclogites which could have possible transformed into amphibolites during retrogression.

Reference
Miyashiro, A. (1961). Evolution of metamorphic belts. *Journal of Petrology 2,* 277-311.

Keywords: Sanbagawa, Petrology, eclogite

High-pressure epidote-amphibolites in the Yuli belt, eastern Taiwan: new thermobarometric constraints and petrological implications

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Recent studies on Tamayen glaucophane schists show that metamorphic conditions of the Yuli belt might have been underestimated previously (Baziotis et al., 2017). Epidote amphibolites are closely associated with glaucophane schists, but P-T conditions of the former are less certain. We investigated a suite of Tamayen epidote amphibolites by computing equilibrium assemblage diagrams with the THERIAK/DOMINO software package. Peak mineral assemblage is garnet ($Alm_{61-63}Grs_{17-18}Prp_{14-16}Sps_{03-05}$) + amphibole (pargasite) + epidote + paragonite + rutile + quartz. In rare cases, glaucophane rims on pargasite locally. The computed phase diagrams show that paragonite-in fields represent high-pressure conditions, although paragonite is not commonly considered as a high-pressure index mineral. Based on petrographic features, mineral compositions and computed equilibrium assemblage diagrams, peak P–T conditions are constrained as 13-15 kbar and 530-570 ˚C, which are compatible with those of Tamayen glaucophane schists. Both rock types represent metamorphic products in a subduction zone setting and were exhumed from depths of 40-50 km.

Keywords: equilibrium assemblage diagram, subduction zone, paragonite

New geochronological constrains on high-pressure meta-plagiogranites in the Yuli belt, Taiwan: results from LA-ICP-MS zircon dating

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We analyzed zircon separated from high-pressure meta-plagiogranites in the Chinshuichi mélange unit with LA-ICP-MS facilities. The mélange contains blocks of serpentinite, meta-gabbro, pillow-structured metabasite, epidote amphibolite and meta-plagiogranite in a matrix of meta-sediments. The meta-plagiogranites commonly contain meta-mafic enclaves, indicating an intrusive protolith origin. Glaucophane and omphacite occur in some of the meta-plagiogranites (Keyser et al., 2016). From the LA-ICP-MS analyses, three samples yielded mean 206Pb/238U dates of 13.1 ±1.9 Ma, 15.7 ±0.4 Ma and 16.3 ±1.4 Ma. On the basis of zircon petrographic features (e.g. no obvious overgrowth in CL images), we conclude that the dates represent timing of magmatic crystallization of the meta-plagiogranites. These zircon ages place geochronological constraints on a late-stage shallow intrusion in a mid-Miocene oceanic section, which is likely of origin from the South China Sea domain.

Keywords: ophiolite, mélange, high-pressure metamorphism

Fast and Slow Schists: Constraints from phengite geochronology

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A systematic K-Ar age mapping along transects perpendicular to metamorphic thermal gradients have been carried out in the Sanbagawa *HP* schist belt in central Shikoku where the highest grade rocks occur in the middle part of the apparent stratigraphy. This reveals a positive correlation in age–*T* relationship that the ages are progressively older with increasing metamorphic temperature. It is impossible to explain the relationship based on the closure temperatures (CT) by the thermally activated diffusion model because CT would be much higher (ca. 600℃) than is currently generally accepted as revealed by the argon geochronology of the polymetamorphic terrains and because the metamorhic sequences formed in the temperatures lower than the CT. The *HP-UHP* schists have been deformed severely during the exhumation of their host rocks and the phengites have experienced the argon release from the phengite crystals by their dynamic recrystallization. The K-Ar ages are related directly to the ductile deformation history of the matrix phengite during exhumation and cooling of the schists. This suggests that the argon release cease when the ductile deformation of phengites stopped and the K-Ar ages are related to the timing of cease of ductile deformation. The coherent schist unit having an inverted thermal structure with large-scale recumbent folds may have undergone ductile deformation for a longer time at lower temperature, suggesting a relatively low strain rate for deformation of metamorphic pile. The duration of deformation during the exhumation after the peak metamorphism shows the average values from the peak metamorphism to the deformation ceasing level. It is 31 Myr in the biotite zone schists in the Sanbagawa *HP* schist belt in central Shikoku and much longer in the garnet and chlorite zone schists.
Multi-stage exhumation models have been proposed for *HP-UHP* metamorphic sequences. The models are that the exhumation rates were high from the deepest level to the lower crust and the rates decrease to the shallow crustal levels. In the Sanbagawa *HP* schist belt in central Shikoku, the eclogite facies metamorphic rocks exhumed faster than the lower grade rocks. The early stage of exhumation from the eclogite facies to the overprinting amphibolite facies gives 9 mm/y. The rates are much lower in the later stage of exhumation. Lago di Cignana *HP-UHP* units in the western Alps have very short duration of deformation, in particular, less than 5 Myr in Lago di Cignana *UHP* unit, suggesting the exhumation rate is higher than 18 mm/y in the early stage of exhumation from the deepest level (ca. 120 km) to the lower crust (ca. 30 km), being two times higher than that of the Sanbagawa *HP* schist belt. Lago di Cignana *HP-UHP* units and Sanbagawa *HP* schist belt both are Pacific-type *HP-UHP* metamorphic belts consisting of the metamorphosed oceanic lithology that usually record only a single metamorphic cycle though the former has been considered to be part of collisional orogeny. Lago di Cignana *HP-UHP* units having the higher exhumation rate are likely due to the subsequent continental collision event because Sanbagawa *HP* schist belt with the lower exhumation rate did not experience the subsequent continental collision event. Thus, the former with the high exhumation (strain) rate makes “Fast schist” sequence that the several unit boundaries are distinct fault and the later with the low exhumation (strain) rate, “Slow schist” sequence having the large scale recumbent fold.

Keywords: Pacific-type HP-UHP metamorphic belts, Exhumation rate, strain rate, phengite geochronology, Fast and Slow Schists

Cathodoluminescence petrography of P-type jadeitites from the New Idria serpentinite body, California

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Because of strong emissions, cathodoluminescence (CL) observation is a powerful technique to characterize growth textures of nearly end-member jadeite. We applied this technique for a P-type (fluid precipitation) jadeitite from the New Idria serpentinite body of the Diablo Range (California, U.S.A.). The investigated New Idria jadeitite is a veined rock, consisting of pale-greenish jadeitite matrix with numerous veins of white jadeitite. Overall, nearly pure (> 95 mol%) jadeite crystal exhibits enough CL emissions for optical observations. The brightness of the emission divide into two contrasting portions, i.e., dark (pale-greenish matrix) and bright portions (veins). In the bright-CL portions, jadeite crystal shows a core–rim texture and/or an overgrowth texture; typically the blue-CL (or dull-blue-CL) cores are overgrown by the red-CL rims. Fine oscillatory growth, with rhythmic changes of red- and (dull-) blue-CL emissions, parallel to growth faces are also developed. Notably CL emissions from veins of older generation are somewhat obscure, likely due to intercrystalline deformation. The CL spectra shows broad overlapping peaks at ~320 and ~360 nm. In the blue-CL segments of jadeite crystals, intensity of these peaks is up to 10,000–120,000 arbitrary units (a.u.). In contrast, these of the red-CL segments of jadeite crystals reach up to 10,000–80,000 a.u. and have an additional peak at ~700 nm (5,000–70,000 a.u.). Electron microprobe analyses confirmed that less-bright CL-emission portions (dull-blue- or dark-CL) are more impure than the bright CL-emission portions (red-or blue-CL jadeites). Growth segments with blue or dull-blue-CL-emission has a higher aegirine component and TiO_2 than those with red-CL jadeites. The spectrum type (color) and brightness are basically controlled by impurities as CL activators.

Keywords: cathodoluminescence, jadeitite

Petrological comparison between Siberian and NW Pacific lithospheric mantle: A preliminary evaluation of the lithosphere stacking model

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Understanding nature of subcontinental lithospheric mantle (SCLM) is of considerable importance as underscored by the abundance of studies in different Solid Earth Sciences, including petrology, geochemistry, volcanology, seismology, and geodynamics. So far many researchers have endeavored to accurately visualize heterogeneity of SCLM and its evolution. One possible model to form lithologic heterogeneity is the lithosphere stacking model proposed by Helmstaedt and Schulze (1989). In order to evaluate the model, two contrasting mantle peridotites from cratonic (continental) and oceanic lithospheres were investigated. Deformed garnet peridotite xenoliths from the Udachnaya kimberlite pipe, as a representative material of SCLM, record multiple mantle processes beneath a craton. In-situ trace elements analyses of garnet and clinopyroxene of the garnet peridotite, confirmed at least two times of mantle–melt interaction and possible fluid infiltration at the latest process. Comparing petrological features of Siberian SCLM xenolith together with an oceanic lithospheric mantle xenolith (spinel peridotite) from the Miyagi offshore petit spot volcano, the lithosphere stacking model was revisited. No matter whether the model is realistic or not, this study confirmed that deep SCLM materials contain geochemical and mineralogical evidences of the presence of “water”, likely supplied from deeply subducted oceanic lithosphere.

Keywords: lithospheric mantle, mantle xenolith, lithosphere stacking, trace element, garnet

Magma sources and petrogenesis of middle Paleozoic ultramafic-mafic rocks from the east part of the Qilian block, NW China: Implications for subduction and underplating

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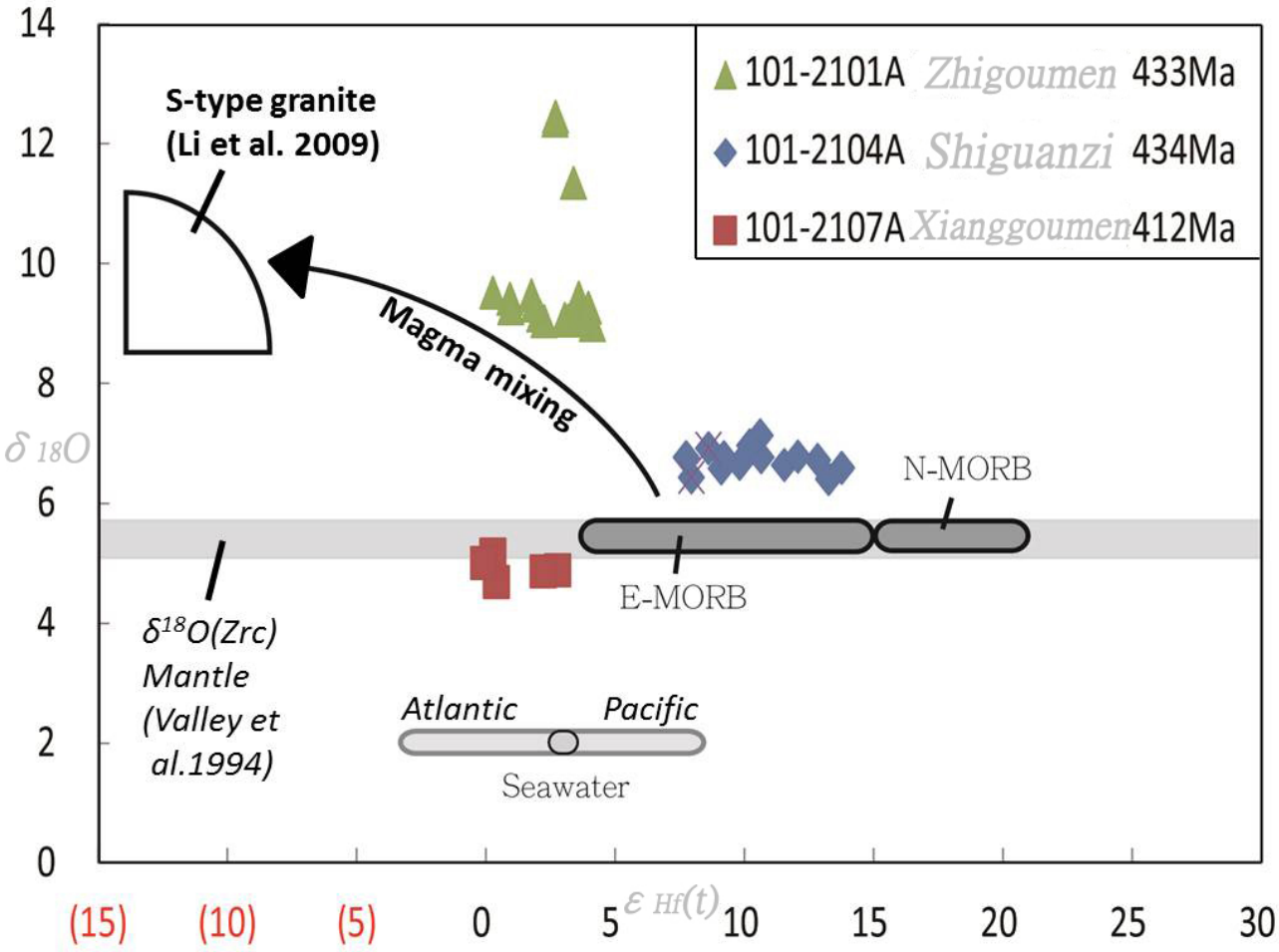
Field relationships, mineralogy, petrology, geochemistry, geochronology, and Nd-Hf-O isotopes of the ultramafic-mafic rocks from the east part of the Qilian block are studied in the present work. The Aganzheng intrusive body only exposed in the Zhigoumen, Shiguanzi, Xianggoumen outcrops and includes olivine pyroxenite, clinopyroxenite, pyroxene hornblendite, hornblendite, dioritic norite. The gabbroic and dioritic rocks are also layered or massive cumulates with rock types varying continuously from noritic gabbro through hornblende gabbro to dioritic norite. Contact metamorphic zones are well developed between the Aganzheng intrusive body and the country rock.
Major element contents of Aganzheng ultramafic-mafic rocks show subalkalic series and are characterized by low SiO_2 contents (38.09-54.96 %), low TiO_2 contents (0.09-0.72 %), low P_2O_5 contents (0.00-0.36 %) and alkali contents (Na_2O+K_2O 0.01-5.35 %), but high MgO contents (9.68-33.06 %), Ni contents (116-1505 ppm), Cr contents (713-2808 ppm). Similar LREE-rich pattern ($(Ce/Yb)_N$ = 0.95-3.80 except two Samples) and tiny Eu anomaly (Eu/Eu* = 0.6-1.2) indicate the Aganzheng ultramafic-mafic rocks have the same magma source. Trace elements are enriched in LILE (Rb, Th, U, K), relatively depleted in HFSE (Nb and Ta), and the La/Yb, Ce/Yb, Th/Yb, Nb/La, La/Sm values suggest the limited crustal contamination during the rise of the magma.
The ε_{Nd}(430 Ma) values are −6.9–+2.5 and T_{DM} values are 3.6–1.4 Ga. The SHRIMP ages are 433±2 Ma for the Zhigoumen pyroxenite (101-2101A), 434±3 Ma for Shiguanzi gabbro (101-2104A) and 412±3 Ma for the Xianggoumen serpentinite (101-2107A). In situ zircon O-Hf isotope, the $\delta^{18}O$ compositions of vary from +9.03 to+9.50 (except three points +11.33, +12.38, +12.44) and ε_{Hf}(t) value is +0.29 to +4.13 for the Zhigoumen pyroxenite (101-2101A), the $\delta^{18}O$ compositions of vary from +6.39 to +7.12 and ε_{Hf} (t) value is +7.76 to +13.26 for Shiguanzi gabbro (101-2104A). and the $\delta^{18}O$ compositions of vary from +4.68 to+5.31 and ε_{Hf}(t) value of +0.28 to +2.79 for the Xianggoumen serpentinite (101-2107A).
According to the above datum, we suggest that middle Paleozoic magmatisms last ~20 m.y. (434-412 Ma) on the northern margin of the Qilian Block was related to the Early Paleozoic continental collision between the Qilian and Qaidam blocks, and to subsequent subduction or thermal underplating.

Keywords: Ultramafic-mafic rock, SHRIMP, Nd-Hf-O isotope, Qilian Block, Underplating



Zircon Hf isotopic constraints on the Jurassic-Oligocene magmatic rocks in the Lut-Sistan region, eastern Iran: Implications for the magmatic evolution

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This study presents new zircon Hf isotopic results for 28 magmatic rocks of Jurassic-Oligocene ages in the Lut-Sistan region to better understand the magmatic evolution of eastern Iran before and after the Lut-Afghan collision. The Middle Jurassic (~168 Ma) granitoids yielded a wide range of zircon $\varepsilon_{Hf}(T)$ values from +8 to -1, revealing the similarity of variable isotopic feature of the coeval magmatic rocks forming along the Sanandaj-Sirjan zone, in agreement with the hypothesis of anti-clockwise rotation of the Lut block. The Early Cretaceous (113-107 Ma) gabbros that belong to the Birjand ophiolite indisputably show depleted mantle-derived zircon Hf isotope compositions of $\varepsilon_{Hf}(T)$ values from +16 to +12 and thus confirm their oceanic crustal origin. Another ~110 Ma diorite without ophiolitic affinity has relatively lower zircon $\varepsilon_{Hf}(T)$ values from +9 to +6, and it also contains abundant inherited zircons that show $\varepsilon_{Hf}(T)$ values between +5 and -2 at ~168 Ma, indicative of the widespread distribution of the Middle Jurassic magmatism in northern part of this region. In the Late Cretaceous, the emplacement of ~86 Ma granitoids also yielded depleted mantle-like zircon Hf isotopes of highly positive zircon $\varepsilon_{Hf}(T)$ values from +17 to +10, and the other granites yielded lower zircon $\varepsilon_{Hf}(T)$ values from +12 to +4 at 74-71 Ma. After the closure of the Sistan ocean during the Late Cretaceous (to Paleocene), the 57-53 Ma granitoids gave zircon $\varepsilon_{Hf}(T)$ values from +12 to +3 in the Early Eocene. Then, the zircon Hf isotopic results of extensive Eocene-Oligocene (46-24 Ma) magmatic rocks show a much variable signature of zircon $\varepsilon_{Hf}(T)$ values between +14 and -2, indicating the heterogeneity of widespread post-collisional magmas during this period. On the whole, the highly radiogenic zircon Hf isotopic features were mostly obtained from dated magmatic rocks in the Lut-Sistan region, similar to our recent observation on the magmatic rocks developed by the Neotethyan evolution in the Urumieh-Dokhtar magmatic arc, which suggest that the depleted-mantle component has played a critical role on the magmatic evolution since at least the Jurassic time.

Keywords: Zircon Hf isotopes, Lut-Sistan region, Iran, magmatic evolution

Petrological and Geochemical Study of Sundoro Volcano, Central Java, Indonesia: Temporal Variations in Differentiation and Source Processes in the Growth of an Individual Arc Volcano

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We reported new Sr-Nd-Pb radiogenic isotope ratios in addition to the complementing whole rock geochemistry and trace elements combined with mineral chemistry of representative rocks of Sundoro volcano, central part of Java sector of Sunda arc. Collected samples represent stratigraphically well-constrained volcanic products from 34 to 1 ka activities. The rocks of the volcano span from basalt (SiO_2 51.5 wt. %) to andesite (62.9 wt.%) and are dominated by basaltic andesite. Least evolved rocks contain MgO less than 6 wt.% and are considered as evolved basalt. The rocks can be grouped into three magma types on the basis of isotopic compositions. The three magma types are named A-, B-, and C-type and characterized by low, medium, and high Sr-Pb isotopic compositions, respectively, which are in tune with variations of Ba/Zr, La/Yb, and Th/Yb ratios.
Against progressive silica content, evolution trend of the three magma types are separated: relatively parallel to each other in $^{87}Sr/^{86}Sr$, ratios of Ba/Zr, and La/Yb, diverge in ratios of Th/Yb, and discretely varied in Pb-isotope. Combination of these discrete geochemical evolution trends with petrographic disequilibrium features and wide-range bimodal compositions of plagioclase crystal core (An46-94) suggest that 1) magma mixing is dominant process in intra-crustal level. 2) The three magma types correspond to mixing of three distinct couples of mafic- and felsic-end member magmas. 3) The felsic end-member magma cannot be produced from fractionation of corresponding mafic end-member magma and might come from different melt source. 4) The three mafic-end member magmas are not related co-genetically, thus relative correlation of their mafic rocks might represent magma source characteristics. Trace elements as proxies of slab contributions (e.g. Ba/Zr, Th/Yb, La/Yb) of the representative mafic rocks of the three magma types show positive correlation to Sr- and Pb-isotopic compositions but negative to Nd-isotopic ratios. We proposed that magma of A-, B-, and C-type corresponds to three distinct slab-derived fluxes containing sediment-derived melt contributions approximately 50%, 55%, and 60%, respectively, which were added to the mantle wedge in a rates of ~1%, ~1.5%, and ~2%, respectively. Temporal variations of the magma type shows the existence of A-type in 20-9 ka, co-existence of A- and B-type in 14-17 ka, and abrupt change from A- to C-type after 9 ka. Reconstruction of the supply magma system in these periods indicate that time interval between the three slab-derived fluxes is about 3-8 ky and shows increasing portion of sediment contribution and rate of slab-fluxes through time. Further application of these approaches to dataset of Merapi volcano revealed increasing rate of slab-derived flux to the magma genesis beneath volcanic front region of central part of Java through time.

Keywords: Sunda arc, Temporal variation, Multiple magmas, Slab contribution, Sundoro volcano

