

地殻・最上部マントルの高電気伝導度を担う流体連結の空間スケールについて On the space scale of fluid interconnection for the high electrical conductivity of the crust and uppermost mantle

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Our knowledge on the grain-scale fluid distribution is mostly based on microstructures of high-pressure experimental charges in a typically micrometer scale, whereas spatial resolutions of seismic tomography and magnetotelluric observations are both in a kilometer scale, thus there is a gap larger than 7 orders of magnitude. For estimating fluid fraction in the crust and mantle, it is necessary to clarify the critical length scale of fluid interconnection that determines the macroscopic physical parameters. A possible approach to lessen the gap is to observe xenoliths that were directly derived from the depths. For this purpose, we carried out X-ray-CT observation of uppermost mantle and lower crust xenoliths from several localities in the world, including Ichinomegata (NE Japan), Eifel (Germany), SanCarlos and Kilbourne Hole (USA). Intergranular pores were observed in all the lherzolite and Hb-gabbro xenoliths from these localities, showing that the rocks were saturated with a free-fluid phase. The pore fluids are localized in interphase boundaries between different mineral phases, as found in the grain-growth experiment in a biminerale system (Ohuchi and Nakamura, 2006, *J. Geophys. Res.*). Most of the monomineralic triple junctions are faceted and lack pore fluids, within the resolution limit of CT observation (typically 4-7 micrometer), thus pore fluids do not have larger scale interconnectivity. Although we do not rule out the possibility of presence of thinner, CT-imaginable fluid networks, such thin networks along grain edges and corners, if present, cannot account for the high electrical conductivity as observed for the crust and upper mantle of NE Japan arc. Fluid localization in a larger scale such as meterscale shear zones, or to the contrary, conductive 2D interphase boundaries of wet polycrystalline rocks are required.

キーワード: 地質流体, 地震波トモグラフィ, MT, X線CT

Keywords: geological fluids, seismic tomography, magnetotellurics, X-ray CT

中部地殻における流体の連結度 Connectivity of fluids at the mid-crustal depths

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Geophysical explorations have been conducted to study the composition, structure and dynamics in the Earth's crust. A lot of detailed profiles of seismic velocity and electrical conductivity have been reported.

The observed electrical conductivity is generally higher than those of dry rocks by several orders of magnitude, suggesting that fluids (mostly aqueous fluids) prevail within the crust. The observed spatial variation of seismic velocity and electrical conductivity should thus reflect the distribution of fluids. Based on the velocity variation at the mid-crustal depths, the spatial variation of fluid volume fraction must be no more than a few%.

The observed spatial variation of electrical conductivity is often up to 4 orders of magnitude. This large conductivity change must occur over a narrow range of the fluid volume fraction. If the connectivity of fluid is identical, the conductivity is proportional to the fluid volume fraction. A small change in the fluid volume fraction cannot make a change of orders of magnitude. The observed large change in conductivity requires the increase of connectivity with increasing volume fraction of fluid. Such an increase of connectivity suggests that crustal fluids are generally in a critical state of interconnection.

I think that this critical state of fluid connection is self-regulated. If fluids are fully interconnected, the permeability becomes high enough to expel fluids rapidly. It leads to the decrease of interconnection, and to the decrease of permeability. If fluids are supplied from depths, the fluid is accumulated there to increase the permeability.

キーワード: 地殻, 流体, 連結度, 電気伝導度, 地震波速度, 比抵抗
Keywords: crust, fluid, connectivity, electrical conductivity, seismic velocity, resistivity

流体を含む岩石の電気伝導度 Electrical conductivity of fluid-bearing rocks

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The electrical conductivity of dry crustal rocks is considerably lower than that of middle to lower crust determined by electromagnetic studies. On the other hand, the electrical conductivity structure of the crust determined by the MT method demonstrates that the regions showing high conductivity anomaly correspond to the root of a fault and hypocenter of an inland earthquake. Although it has been thought that these conductivity anomalies are originated from existence of fluid and melt, the conductivity of a fluid (especially water) under high pressure has not been measured because of its experimental difficulty. Therefore, in order to estimate the amount of fluid from electromagnetic observations, we need many assumptions such as the mixing model of fluid-rock system and given salt concentration. Since the supercritical fluid under high temperature and high pressure can contain high ion concentration, knowledge of fluid composition for typical crustal rocks is required to estimate fluid content from the observed conductivity values. However, electrical conductivity measurement of the fluid-bearing rock has not performed.

This study reports experimental results on electrical conductivity measurement of fluid-bearing rock. In our group, electric conductivity measurement of Quartz-H₂O, Quartz-H₂O-NaCl, and Albite-H₂O systems has been performed as simple analog materials of the crust. We have measured as a function of temperature and the amount of fluid by the pressure of 1GPa. The aqueous fluid phase in samples was sealed using single crystal quartz capsule sandwiched by metal electrodes. First, Quartz-H₂O system showed that electrical conductivity rises as the water content increases, and electrical conductivity also tends to increase with increasing temperature (Shimojuku et al. 2012). However, the electrical conductivity values were much lower than the observed ones. Because dominant solute in aqueous fluid in this system is electrically neutral Si(OH)₄, the conductivity of fluid phase cannot increase largely. Therefore, to explain the observed high conductivity value, high concentration of ion as an electric charge carrier in aqueous fluid is required. For the system adding NaCl to Quartz+H₂O, electrical conductivity showed almost no temperature dependency, but electrical conductivity increases with increasing salt concentration. Next we consider the case that the system contains alkali ion in fluid (Albite-H₂O system). Unlike the Quartz+H₂O system, temperature dependency was small but electrical conductivity once slightly decreases with increasing temperature then increases again at high temperatures. This trend agrees with the concentration change of a solute with the electric charge in the fluid via temperature. Thus, these observations suggest that even if temperature was low enough, fluid with certain ion concentration can produce the conductivity anomalies in the crust. If crust rock has dissolved into fluid as ionic charge, high NaCl concentration in fluid is not necessary to produce conductivity anomalies in the crust.

キーワード: 電気伝導度, 流体, 地殻

Keywords: electrical conductivity, fluid, crust

マグネトテルリック法による鳴子火山周辺の3次元流体分布 3D crustal fluid distribution by magnetotellurics around Naruko volcano

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We have carried out wideband magnetotelluric measurements in order to map the distribution of fluids and melts under the volcanic arc in the NE Japan around the Naruko volcano. The area has several Quaternary calderas, such as Naruko, Onikobe, Sanzugawa and Mukaimachi calderas. The area has also high shallow seismicity and has one of the largest intraplate earthquakes, M7.0, in 2008 near the Kurikoma volcano. Thus the area is thought as a good test field to study the relation of fluids and volcanoes and intraplate earthquakes. We have 224 sites in total with average site spacing of ~5km. From the three-dimensional modelling we have imaged (1) subvertical conductors which shallows towards the active volcanic zones under Onikobe, Naruko and Sanzugawa calderas, and (2) seismic activities over the resistive zones above the crustal conductors, which implies earthquake triggering by fluid migration into the brittle crust.

キーワード: 地殻流体, 電磁気, 鳴子, 火山, 地震

Keywords: geofluid, electromagnetism, Naruko, volcano, earthquake

秋田県森吉山付近の深部低周波地震，散乱波，地震のマイグレーションから示唆される地殻流体の流路

Possible pathway of geofluid suggested by deep low-frequency earthquakes, scattered phase, and migration of earthquakes

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Migration of seismicity, reflected phase, and anomalous deep low-frequency earthquakes are possible seismic evidence of geofluid in the crust. All of these phenomena are observed near the Moriyoshi-zan volcano in Akita Prefecture located to the west of the volcanic front of northeastern Japan. Seismic activity around the volcano became quite high after the occurrence of the great 2011 Off the Pacific coast of Tohoku (Tohoku-oki) Earthquake. Among some earthquake clusters the one to the north of volcano has been the most active from May 2011 to date. The size of this cluster is about 3 km both horizontally and vertically. Since there is only one nearby seismic station to the west of volcano, we deployed temporary stations above the most active cluster on September 2012. Relocated hypocenters using data of temporal observation shows increased depth accuracy by the concentration of hypocenters around a depth of 7 km, whereas the depth of catalog location by the JMA spans from 8 to 10 km. Seismic activity in the most active cluster exhibits clear migration, however, the direction and speed are variable. The activity started near the center in the horizontal location, then migrated to the northeast, and jumped to the west, and migrated again to the south and to the north. This complex pattern suggests repeated injection of geofluid below the cluster, however, the temporal rate of migration is not clear due to insufficient accuracy of hypocenter location for the period before the temporal observation.

A prominent feature of the seismogram is a reflected/scattered phase observed at the station to the west of volcano. The time interval between this later phase and S wave depends on the hypocenter location, suggesting gently dipping zone of scatterers to the west. This zone probably corresponds to a plane of reflection estimated previously from the 1982 earthquake swarm.

The Moriyoshi-zan area is one of the source areas of deep low-frequency earthquakes occurring mainly beneath active volcanoes in the northeastern Japan. The low-frequency earthquakes that occur well below the elastic plastic boundary are interpreted as the events generated by the activity of geofluid. The westward bottom of reflector/scatterers is close to the upper limit of low-frequency earthquakes and the eastward top seems to reach the bottom of earthquake cluster. From this we can image a pathway of geofluid from the upper mantle to the source of cluster. However, to verify this idea, we need to estimate the location and temporal change of reflector/scatterers accurately using arrival times and waveform characteristics of the later phase.

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キーワード: 地殻流体, 地震活動, マイグレーション, 散乱, 低周波地震

Keywords: geofluid, seismic activity, migration, scattering, low-frequency earthquakes

有馬型塩水・地殻中部のS波反射散乱体・地殻下部の低周波地震の関係を結ぶ地殻流体モデル

LF-earthquakes, S-wave reflectors and Arima-type Brine: A model for Geofluid circulation in arc crust

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<Introduction>: Kazahaya et al [2011] reported distribution of "Arima-type brine" in various part of Japan and they proposed that it represents fluid from deep source. "Arima-type brine" is featured by 1) high salinity: >3 times of sea water, 2) high CO₂, 3) oxygen and hydrogen isotopes similar to those of island-arc andesite magmas. They proposed that it may have two origins 1) fluids derived from dehydration of subducting oceanic plate, 2) fluids derived from solidifying magma in the lower crust. Because of its vital importance in understanding the nature of deep fluids, I discuss the origin of "Arima-type brine" in the latter case.

<"Arima-type brine" originated from crustal partial melt>: Considering average heat flow and distribution of Quaternary volcanoes in Japanese island arcs, temperature of the lowermost crust would be >800degC and small amount of partial melt would exist almost ubiquitously regardless of the distribution of the Quaternary volcanoes. If partial melting takes place in the lower crust, aqueous fluids derived from subducting plates and those migrating in the mantle wedge should be trapped there and the composition of fluids in the crustal depth should be controlled by melt/fluid equilibrium at the base of the crust. Very high Cl and CO₂ featuring "Arima-type brine" can be easily understood by considering melt/fluid element partitioning at the lower crustal depth, because Cl strongly partitions into fluid [2] and its CO₂ solubility is high.

<Water eruption during the Matsushiro Earthquake Swarm>: More than 60000 earthquakes took place in Matsushiro, central Japan in 1965-1967 [Mogi, 1989]. Matsushiro earthquake swarm is featured by ejection of large amount of saline ground water since 1968 until today. Tsukahara and Yohida[2005] discussed the origin of the ground water eruption associated with Matsushiro earthquake swarm and proposed a model that the water may have derived from mid crustal "S-wave reflector" which is a reservoir for deep crustal fluids. Chemistry of the ground water (including isotopes) ejected from Matsushiro is indistinguishable from that of the "Arima-type brine". The "groundwater eruption" in Matsushiro strongly suggests that "Arima-type brine" may be stored at some crustal level locally in large volume. "S-wave reflectors" found in many areas in Northeast Japan (typically at 10~15km depth, [Hasegawa et al.2005]) may correspond with the deep crustal ground water reservoirs. Very low electric conductivity anomalies found in middle crust of subduction zones [Ogawa, Y. et al, 2007] may also represent reservoirs for high salinity crustal fluids.

<Formation of "S-wave reflectors">: Close correlation has been found between location of the lower crustal DLF earthquakes and the distribution of the middle crustal "S-wave reflectors" in Northeast Japan. If lower crustal DLF earthquakes correspond with the emission of fluids from solidifying magma body, fluids derived from lower crustal magma should have >5wt% SiO₂ as well as Cl and CO₂. Thus, large amount of silica and carbonate must precipitate from the fluid along ascent due to decreasing temperature and pressure. Deep fluids may be self-sealing as it ascends due to the precipitation of silica and carbonate. Judging from the depth distribution of the "S-wave reflectors" (reflectors situate at shallower depths near volcanoes), the depth of precipitation may be more sensitive to ambient temperature than pressure.

<Summary>: In summary, I propose that known features of the "Arima-type brine" may be explained in a coherent manner by considering melt/fluid equilibrium at deep crustal condition. Shallow crustal process (such as precipitation of silica and carbonate) would determine its final chemistry.

キーワード: 有馬型塩水, 低周波地震, S波散乱体, 松代群発地震, 地殻流体循環

Keywords: Arima type brine, low frequency earthquake, S-wave reflector, Matsushiro earthquake swarm, geofluid circulation

いわき内陸地震に関連する熱水の成因について Genesis of thermal water related to Iwaki-Nairiku earthquake

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2011年4月11日、福島県いわき市直下の深さ約6kmを震源としたM7.0の福島県浜通りの地震(いわき内陸地震)が発生した。いわき内陸地震に伴い、いわき市を中心として少なくとも3カ所で新たに温泉水が噴出した。地下水変化については、湧出量の増加や水位の上昇は、井戸沢および湯ノ岳断層の東側で生じ、湧出量の減少や水位の低下は断層の西側で生じており、これらの地下水変化はいわき内陸地震時の地殻歪変化による水位変化に起因すると考えられる。温泉水の噴出は2013年1月現在も引き続き生じており、一部場所においては湧出量も減少していない。このような事例は今までに報告がない。また、いわき市およびその周辺は、東北日本の前弧側の非火山地域であるにもかかわらず水温80℃の温泉水が存在し、その熱源、起源などは不明である。

本研究では、湧出が続く原因や温泉水の起源を解明するため、温泉の噴出や水位上昇に関連した地下水・温泉水の同位体・化学分析を行った。いわき市は過去に炭鉱開発が行われ、開発時に地下坑道で湧出する温泉水の分析データが豊富にある。今回湧出した最も高温の温泉水は、これらの坑内温泉水やいわき湯本の温泉水と特徴が一致しNaCl成分に富む。このNaClを含む高温の熱水成分は、その温度からより深い場所(花崗岩)から上昇していると考えられるが、南北系の正断層群から湧出する点が特徴である。

福島県浜通り地域から北茨城地域のNaCl型温泉水の分析結果から、以下の特徴がわかった。

1) 水の安定同位体比とCl濃度の関係から、NaCl型温泉水の端成分は、海水に由来した変質水である。Cl濃度は、6000-20000mg/L程度の範囲にあり、いわき市の湧出に関連するNaCl型温泉水の端成分のCl濃度(約6000mg/L)は低い。

2) 放射性塩素同位体比($^{36}\text{Cl}/\text{Cl}$)の結果から、この地域の塩水の年代は数10万年から100年以上(放射平衡値を示す)となり非常に古い。

以上より、花崗岩を通して上昇していると考えられる高温の塩水は、海水に由来するものの非常に古く、Cl濃度は、非常に大きなバリエーションを持つことがわかる。このような塩水は、油田鹹水に見られる特徴と一致する。すなわち、海水に加え、粘土鉱物などの含水鉱物の脱水作用などが関連した塩水である。この塩水の起源として、

1) いわき沖にある天然ガスを含む常磐沖堆積盆の地層水

2) 前弧側で沈み込むスラブの間隙水が放出・上昇した水などが考えられる。

キーワード: 熱水, いわき内陸地震, 成因, 化学的特徴, 同位体比

Keywords: Thermal water, Chemical, Isotopic, Iwaki, Earthquake

日本沈み込み帯のP波異方性トモグラフィー Mapping seismic anisotropy and heterogeneity of Japan subduction zone

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We determined P and S wave tomography and 3-D P-wave anisotropic structure under the Northeast Japan arc from the Japan Trench to the back-arc area under the Japan Sea using a large number of P and S wave arrival times from local shallow and deep earthquakes recorded by the dense local seismic networks. Arrival times from many suboceanic earthquakes relocated with sP depth phases enable us to determine the 3-D structures under the Pacific Ocean and Japan Sea, which expand the study region from the land area to the whole arc from the Japan Trench to the Japan Sea with a width of more than 500 km. Our results show strong heterogeneities on the top of the subducting Pacific slab under the Pacific Ocean and most large thrust earthquakes occurred in the high-velocity (high-V) areas where the Pacific slab and the overriding plate are strongly coupled. Low-velocity (low-V) zones are imaged in the mantle wedge with significant along-arc variations under the volcanic front. The mantle-wedge low-V zones extend westward under the Japan Sea and are connected with the subducting Pacific slab at depths of 150-200 km under the back-arc. The results indicate that the H₂O and fluids brought downward by the subducting Pacific slab are released into the mantle wedge by dehydration and are subsequently transported to the surface by the upwelling flow in the mantle wedge. Significant P-wave anisotropic anomalies are revealed under the Honshu arc. The predominant fast-velocity direction (FVD) is E-W in the mantle wedge while it is N-S in the subducting Pacific slab. The anisotropy in the mantle wedge is the result of deformation caused by the subduction of the Pacific plate and the induced mantle wedge convection, while the special pattern in the middle of the mantle wedge argues for the 3-D mantle flow or the specific alignment of the olivine in partially molten mantle. The N-S (trench-parallel) FVD in the subducting Pacific slab represents either the original fossil anisotropy when the Pacific plate forms or the trench-parallel crystal and shaped preferred orientation in the subducting slab due to the slab bending.

We also performed a detailed 3-D P-wave anisotropic tomography of the crust and upper mantle beneath Southwest Japan using P-wave arrival times from local earthquakes. The Philippine Sea (PHS) slab is imaged clearly as a high-V anomaly which exhibits considerable lateral variations. Significant low-V anomalies are revealed above and below the PHS slab. The low-V anomalies above the PHS slab may reflect the upwelling flow in the mantle wedge and the PHS slab dehydration, and they form the source zone of the arc volcanoes in SW Japan. The low-V zones under the PHS slab may reflect the upwelling flow in the big mantle wedge above the Pacific slab. The anisotropy in the crust and upper mantle is complex. In Kyushu, the P-wave FVD is generally trench-normal in the mantle wedge under the back-arc, which is consistent with the corner flow driven by the PHS slab subduction. The FVD is trench-parallel in the subducting PHS slab under Kyushu.

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キーワード: 地震波トモグラフィー, P波異方性, 沈み込み帯, 太平洋スラブ, フィリピン海スラブ, スラブ脱水

Keywords: seismic tomography, P-wave anisotropy, subduction zone, Pacific slab, Philippine Sea slab, slab dehydration

長周期MT観測による東北地方沈み込み帯3次元上部マントル電気伝導度構造 A three-dimensional electrical conductivity model in the subduction zone of Tohoku district, northeastern Japan

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We acquired magnetotelluric (MT) data at 65 sites in Tohoku district, northeastern Japan for the aim of three-dimensional (3-D) electrical conductivity distribution in the wedge mantle. Typical observation duration were three months at each site, and MT response functions from 10 to 20000 s in period have successfully collected with fine quality. The site location was arranged with ca. 20 km distance. We integrated the MT data observed on the seafloor in Japan Sea using the ocean bottom electromagneters (OBEM) (Toh et al., 2006) into these inland data, and estimated a conductivity model.

The MT phase response functions at some sites show over 90 degrees over 5000 s period and suggest that 3-D conductivity distribution beneath those sites. The distribution of phase tensor ellipses (Caldwell et al., 2004) shows more clearly the degree of lateral heterogeneity or dimensionality. The phase tensor ellipses of the sites in Akita and Iwate Prefectures have major axes aligned with NW direction. The direction is almost parallel to the Pacific plate motion. On the other hand, the major axes around Naruko and Kitakami river have random directions and the ellipticity of the phase tensor ellipses are very large (over 10).

We carried out the 3-D inversion using WSINV3DMT code (Siripuaraporn et al., 2005) and gave a prior model composed of subducting slab (10^{-4} S/m) and seafloor bathymetry. The plate boundary information by Kita et al. (2010), Nakajima et al. (2009) and Nakajima and Hasegawa (2006) was used. Before inverting the observation data, simple checker board resolution tests were performed to estimate a resolution. We tested the three models composed of cubes with the same size (60, 40 and 20 km) and 1 S/m conductivity in the wedge mantle of 0.01 S/m. Each cube with 40 and 60 km on side was imaged using the synthetic data, while the adjacent cubes sticking together were imaged in the model composed of cubes with 20 km on side. Furthermore, any cubes beneath no observation site were not imaged at all using the synthetic data. The east-west profile (across the Japan Arc) of the obtained model shows that conductive region appears from 20 km to just above the subducting slab beneath Tohoku backbone range. That basic images are well consisted with the seismic tomographic model (Nakajima et al., 2001), provided that conductive and low velocity zone should corresponds with each other. Obtained the final 3-D model, our final destination is to estimate the mantle geotherm and fluid distributions in the wedge mantle using seismic tomographic and electrical conductivity images.

キーワード: 電気伝導度, 沈み込み帯, MT 法

Keywords: electrical conductivity, subduction zone, magnetotellurics

Hydration-dehydration processes in active subduction zones, and their geophysical signature

Hydration-dehydration processes in active subduction zones, and their geophysical signature

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Seismological and magneto-telluric methods are potential tools for imaging fluid circulation when combined with petrophysical models. Recent measurements of the physical properties of rocks, in particular serpentinites, have permitted to refine hydration of the mantle and fluid circulation in the mantle wedge from geophysical data.

In the slab lithospheric mantle, serpentinization caused by bending at the trench is limited to a few kilometers below the oceanic crust (<5 km). Double Wadati-Benioff zones, 20-30 km below the crust, are explained by deformation of dry peridotites, not by serpentine dehydration. It reduces the required amount of water stored in solid phases in the slab (Reynard et al., 2010).

In the cold (<700C) fore-arc mantle wedge above the subducting slab, serpentinization is caused by the release of large amounts of hydrous fluids in the cold mantle above the dehydrating subducted plate. Low seismic velocities in the wedge give a time-integrated estimate of hydration and serpentinization. Serpentinization reaches 50-100% in hot subduction, while it is below 10% in cold subduction (Bezacier et al., 2010; Reynard, 2012).

Electromagnetic profiles of the mantle wedge reveal high electrical-conductivity bodies. In hot areas of the mantle wedge (> 700C), water released by dehydration of the slab induces melting of the mantle under volcanic arcs, explaining the observed high conductivities. In the cold melt-free wedge (< 700C), high conductivities in electromagnetic profiles provide "instantaneous" images of fluid circulation because the measured electrical conductivity of serpentine is below 0.1 mS/m (Reynard et al., 2011). A small fraction (ca. 1% in volume) of connective high-salinity fluids accounts for the highest observed conductivities. Low-salinity fluids (< 0.1 m) released by slab dehydration evolve towards high-salinity (> 1 m) fluids during progressive serpentinization in the wedge. These fluids can mix with arc magmas at depths and account for high-chlorine melt inclusions in arc lavas.

High electrical conductivities up to 1 S/m in the hydrated wedge of the hot subductions (Ryukyu, Kyushu, Cascadia) reflect high fluid concentration, while low to moderate (< 0.01 S/m) conductivities in the cold subductions (N-E Japan, Bolivia) reflect low fluid flow. This is consistent with the seismic observations of extensive shallow serpentinization in hot subduction zones, while serpentinization is sluggish in cold subduction zones.

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キーワード: subduction, fluids, serpentine, seismic velocity, electrical conductivity

Keywords: subduction, fluids, serpentine, seismic velocity, electrical conductivity

火山岩から推定される日本列島下マンツルの物理化学的状态 Mantle physico-chemical conditions beneath the Japan arcs constrained by chemical composition of volcanic rocks

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Chemical compositions of arc magmas in subduction zones are thought to reflect several processes, such as fluid contribution derived from subducting slabs, mantle melting, and crystallization and fractionation at crustal level. By using isotopic systematics, the amount and origin of slab-derived fluids beneath the Japan arcs have been quantified with a fairly good accuracy, which give a "Geochemical Map" regarding the distribution of slab-derived fluid, as well as melting P-T condition, in the mantle wedge [1,2]. In this study, we try to construct "Geochemical Map" regarding the mantle physico-chemical condition beneath the Japan arcs, based on such approaches.

Considering the amount of slab-derived fluid and its origin, we forward estimated the chemical compositions of slab-derived fluid, fluid-added mantle and subsequently generated magma. Then we can inversely evaluate the melting condition by optimizing the prediction with the observed magma compositions. In this model, there are several uncertainties involved in this estimation, such as compositional range of subducting materials, partition coefficients among melt-water-solid, which have been considered to evaluate the fitting accuracy [2].

As a result, we have obtained the melting conditions (melting degree; proportion of sp- and gt-lherzolites) together with fluid contribution, all of which have been quantified with uncertainties. For instance, in the mantle wedge beneath central Japan, relatively low degrees of dominantly garnet-lherzolite (plus minor spinel-lherzolite) melting at near-solidus has been identified [2]. These calculations suggest that the melting conditions can be inferred with a fairly good resolution (melting degree ~ 5 %; proportion of sp- and gt-lhs. ~ 10 %), especially when coupled with fluid contribution determined independently by isotopic systematics. Based on this modeling, we discuss the mantle condition beneath Japan arcs and its global implications.

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キーワード: マントル, 沈み込み, スラブ, 流体, 火山, 温度
Keywords: mantle, subduction, slab, fluid, volcano, temperature

圧力と塩濃度を関数にした高 Mg 安山岩と水流体の間の元素分配 Elemental partitioning between high Mg andesite and aqueous fluids as functions of pressure and salinity

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1. Introduction

Silicate melts and aqueous fluids are major fluids in subduction zones. Elemental partition among minerals and these fluids is a key to understand the elemental transfer from subducting slab to mantle wedge [1-3]. Partition between minerals and melts is relatively well known, while partition between aqueous fluids and melts remains to be investigated.

2. Experimental

Synchrotron radiation X-ray fluorescence analysis is conducted to know elemental distribution between aqueous fluids and high magnesian andesite melt under high-temperature and high-pressure (HTHP) conditions. We put Cs, Ba, La, Sm, Gd, Ho, and Yb-doped high-Mg andesite with water or a saline solution (2.5 mol NaCl and 2.5 mol KCl per 1 kg water) in a metal tube + single-crystal-diamond lids and brought it under HPHT conditions. We achieved HTHP conditions with SPEED 1500 Kawai-type large-volume press installed at BL04B1, SPring-8, Japan. Incident X-ray is a white beam with energy ranging from 20 keV to 150 keV. During heating at a given pressure, synchrotron X-ray radiography technique allows us to observe a melt globule surrounded by aqueous fluids through the diamond windows [4, 1]. SR-XRF spectra are collected from the melt globule and the aqueous fluid using an SSD detector placed with 6 degrees to incident X-rays.

3. Results

A series of experiments has been carried out at pressures of 0.5, 1, 1.5, 2 and 2.2 GPa. The spectra show characteristic X-ray peaks of the doped elements superimposed on a continuous X-ray background. At 1 GPa, no characteristic X-ray peak from any doped element is observed in Cl-free fluids and all the doped elements are partitioned into melts. At 1.5 GPa and greater pressures, only Cs is found in Cl-free fluids, with one exception of small X-ray peak of Ba at 2 GPa. In contrast, X-ray peaks of Cs and Ba are observed in saline solutions at 1 GPa. In addition to Cs and Ba, a small peak of La is also found in the saline solutions at 1.5 GPa and greater pressures. The other elements (Sm, Gd, Ho, Yb) are found only in melts at all conditions.

4. Discussion

NaCl and KCl in aqueous fluids have large effects on elemental partition between melts and fluids as Keppler suggested [5]. He measured distribution coefficients between saline solution and andesitic melt based on quenched experiments and reported D Ba and D La at 0.3, 1, 1.5 and 2 GPa. The present observation is qualitatively consistent with reported values in his measurement [5]. Elliott and his colleagues suggested two slab-derived components: a melt component and a fluid component in order to explain trace element characteristics of basalts and basaltic andesites in the Mariana arc [6]. Both components are characterized by enrichment of alkali and alkali earth elements. The fluid component shows rare earth element abundances relatively similar to MORB, while the melt component shows more light rare earth element rich pattern (Figure 3 in [6]). Such features can be consistent with a Cl-rich aqueous fluid and a melt that can be formed through a separation of a slab-derived supercritical fluid during its migration to the surface [1-3]. If this is the case, the melt should be characterized by less abundance of alkali elements and more abundance of alkali earth and rare earth elements than the aqueous fluid. The aqueous fluid and melt components suggested as slab-derived components in the Mariana arc show features consistent with a Cl-rich aqueous fluid and a melt formed through a separation of a slab-derived supercritical fluid [1]. In order to address this hypothesis, more data sets of elemental partition under HTHP conditions are required. Chemical fractionation of slab-derived supercritical fluids may play an important role in subduction zone magmatism.

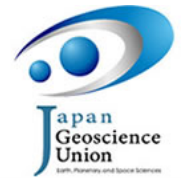
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SIT06-12

会場:104

時間:5月22日 12:00-12:15

[4] Mibe et al. (2004) GCA

[5] Kepler (1996) Nature

[6] Elliott, et al. (1997) JGR

キーワード: メルト, H₂O, 高温度高圧力, 蛍光 X 線, 放射光 X 線, マグマ

Keywords: melt, H₂O, high temperature and high pressure, XRF, synchrotron X-ray, magma

沈み込み帯過程におけるLiとB元素濃度と同位体比 Behaviors of Li and B and their isotope ratios in subduction zone processes: Perspectives from a geochemical forward mod

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$7\text{Li}/6\text{Li}$ and $11\text{B}/10\text{B}$ stable isotope ratios have been used as tracers of slab derived fluids in the arc magmas. Temperature dependent isotopic fractionation releases heavier fluids from the subducted slab, hence leaves lighter residual solids in the slab. As slab fluid dehydration undergoes in the prograde metamorphism with increasing pressure and temperature, fractionation profiles of these isotopes from the slab is not simple. Moreover, release of Li and B from the slab is controlled by varying mineral assemblages in the prograde metamorphism so that adding further complexities in the element behaviors thus isotopic fractionation. Several works have dealt with the models in elemental behaviors of Li and B and their isotopes for slab dehydration. However, entire dehydration profiles of the subducted slab sediment and altered oceanic crust have not yet been studied. Moreover, interactions between slab fluids and overriding mantle peridotite form arc magmas and are also the factor that alters element abundances of Li and B and their isotopic ratios found in the arc magmas. This work examines the elemental and isotopic behaviors of Li and B and $7\text{Li}/6\text{Li}$ and $11\text{B}/10\text{B}$ in the slab and released fluids under prograde metamorphism and reactions between the released slab fluids and mantle to form arc magmas. A geochemical forward mode Arc Basalt Simulator ver.3 modified from Kimura (2012) (EarthChem Library <http://www.earthchem.org/library>) was used for the modeling and results presented in comparison to the reported values from arc magmas. The model calculations reasonably reproduced across arc variations of the Li and B isotope ratios found in the arc magmas. Calculated fluid compositions would also be useful in predicting the non-volcanic slab-derived fluid compositions potentially observed in the fore arc settings.

キーワード: リチウム, ホウ素, 同位体, 沈み込み帯, 島弧マグマ
Keywords: Li, B, isotopes, subduction zone, arc magma

伊豆小笠原弧における希ガスとハロゲンのリサイクル Noble gas and halogen recycling at the Izu-Ogasawara subduction zone

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Recent findings of subducted halogens and noble gases with seawater and sedimentary pore-fluid signatures in exhumed mantle wedge peridotites and eclogites from the Sanbagawa-metamorphic belt, southwest Japan [1,2], as well as seawater-derived heavy noble gases (argon, krypton, and xenon) in the convecting mantle [3], challenge a popular concept that the water flux into the mantle wedge is controlled only by hydrous minerals in altered oceanic crust and sediment (e.g., [4]). Serpentinized lithosphere of subducting oceanic plate would transport noble gas and halogens acquired from pore-water in the overlying sediment [1,2,5]. To verify whether and how such subduction fluids modify the composition of the mantle beneath subduction zones, we determined noble gas and halogen compositions of olivines in arc lavas of the northern Izu-Ogasawara subduction zone and IODP sediments and basalts recovered from northwestern margin of the Pacific plate.

MORB-like ³He/⁴He and halogen ratios of the Izu arc olivines indicate insignificant contribution to the mantle wedge of radiogenic ⁴He and pore fluid-like halogens both observed in the subduction fluids in the Sanbagawa samples exhumed from a depth ranging from 30 to 100 km [1,2]. On the other hand, systematically higher contribution of atmospheric argon in volcanic front lavas than in rear-arc lavas of the Izu-Ogasawara subduction zone suggests progressive decrease in flux of subducted argon from the slab according with distance from the Izu-Ogasawara Trench. Distinct halogen and heavy noble gas elemental ratios of altered oceanic basalts indicate their minor contributions to the Izu arc magma and the Sanbagawa subduction fluids. On the contrary, high I/Cl ratios of oceanic sediments well explain elevated I/Cl ratios of the Sanbagawa subduction fluids compared to sedimentary pore fluids [1].

The significantly smaller contributions of subducted noble gas and halogen in the Izu-Ogasawara arc than those in the Sanbagawa belt may result from a difference in P-T condition of the subducted slabs. A hotter mantle wedge than those of mature subduction zones is proposed for the Sanbagawa subduction system [6], in contrast the Pacific slab subducting in the Izu-Ogasawara subduction zone is relatively cold and would therefore lose relatively little water at equivalent depths to other slabs [7]. This implies a relatively small amount of the pore water subduction fluids would be released from the Pacific slab at a sub-arc depth (150-200 km) resulting in further subduction to great depths in the mantle.

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キーワード: 希ガス, ハロゲン, 沈み込み, 伊豆小笠原弧, 間隙水

Keywords: noble gas, halogen, subduction zone, Izu-Ogasawara arc, pore fluid

マントルウェッジにおけるかんらん岩の加水反応速度に関する実験的研究 Experimental study on the hydration rates of peridotites in the mantle wedge condition

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Although hydration of mantle wedge is a key process in understanding the nature of magmatism in subduction zones, the hydration rate of peridotites has been poorly constrained. Two extreme cases can be considered in terms of equilibration degree between the fluid and rocks. The first is the equilibrium case, in which the hydration rate is fast and H₂O is fixed as hydrous minerals as soon as the fluid is supplied. The other is the disequilibrium case, in which the fluid ascends without hydrating solid matrices. Based on a numerical model, Iwamori (1998) showed that distribution of H₂O in subduction zones is significantly affected by the extent to which the fluid-rock interaction proceeds. The hydration rate of mantle rocks is thus a primary parameter in the control of H₂O transport in subduction zones. In order to obtain the hydration rates of peridotites under mantle wedge conditions, we have conducted hydration experiments using a piston-cylinder apparatus at 580 degC and 1.3 GPa for 4-20 days. Starting materials were prepared from the crushed powder (75-125 micrometer in diameter) of a San Carlos lherzolite xenoliths. The starting materials were put in Ag capsules with 15 wt% distilled water.

In the experimental condition, antigorite (high-T serpentine) is expected to be the stable serpentine phase (Ulmer and Trommsdorff, 1995). We found with Raman spectroscopy, however, that the synthesized serpentine mineral was not antigorite but lizardite (low-T serpentine), which is consistent with its platy shape. The high Al₂O₃ content (6-9 wt%) in the serpentine mineral probably stabilized Al-lizardite to higher temperature (Caruso and Chernosky, 1979). The degree of reactions was obtained by measuring the area fractions of relict minerals on BSE images of polished surfaces of the run charges. The degree of reaction basically followed an interface controlled rate law. The migration velocity of reaction front, *G*, was estimated to be 1.23 - 3.18 micrometers per day.

By using these values and the estimated range of porous flow velocities, we obtained the nondimensional time for local chemical equilibration. It is inferred that the mostly complete hydration reaction can be established in the porous flow. This result indicates that slab-derived water should be fixed quickly in the convecting mantle wedge mainly as serpentine and carried down to ca. 150 km, i.e., the stability limit of antigorite or aluminous lizardite.

キーワード: マントルウェッジ, 水流体, 加水反応, 蛇紋岩
Keywords: mantle wedge, aqueous fluid, hydration, serpentinite

Evidence for multi-stage infiltration of aqueous fluids in a block-emplaced serpentinite along the San Andreas Fault

Evidence for multi-stage infiltration of aqueous fluids in a block-emplaced serpentinite along the San Andreas Fault

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A structural and petrological study of a tectonically-emplaced serpentinite sliver along the San Andreas Fault in California was initiated with the aim of understanding the geological history and emplacement mechanisms of such bodies that are common in the California Coast Ranges and along the San Andreas diffuse plate boundary. This particular serpentinite melange in Redwood City, California is largely composed of cm- to m-scale tectonite blocks that reflect the internal deformation and complex history of interaction with geofluids during peridotite alteration and ascent from the mantle. These tectonite blocks commonly exhibit a core-and-mantle internal structure that indicates that tectonic blocks have not come to mineralogical equilibrium. Innermost core structure often consists of partially-serpentinized OI/OPx/Cpx peridotite rimmed by layers of greater degrees of serpentinization. These tectonite blocks are typically rimmed with green sheared lizardite indicating that high fluid pressure was present during the last stage of emplacement. We also observed chrysotile filled reticulate arrays of vein fillings that often cross cut the sheared lizardite. We discuss these and other observations in the context of the tectonic and fluid environments of the San Andreas Fault System that originated during Tertiary plate reorganization from subduction to continental transform tectonics.

キーワード: serpentinite, mantle, vein filling, hydrothermal alteration, San Andreas Fault, metamorphism

Keywords: serpentinite, mantle, vein filling, hydrothermal alteration, San Andreas Fault, metamorphism

沈み込み帯深部で発生する脱水流体と地震性破壊 Dehydrated fluid and seismic deformation in deep subduction zone

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Dehydrated fluid in deep subduction zone causes various geological phenomena such as earthquake, and arc volcanism. 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. Recent petrological researchs have revealed that both blueschist and lawsonite eclogite are stable in the same pressure and temperature condition because chemical variation including water content creates both lawsonite-amphibole eclogite and lawsonite eclogite in different portion of subducted crust. Partial melting would occurred in eclogite in deep subduction zone if warm slab is subducted. In descending slab, the eclogite would reach wet solidus defined as phengite-, through zoisite-, and amphibole-decomposition reactions with increasing temperatures. The lower plane of the double seismic zone, is considered to be related to dehydration reaction in the slab. Metamorphic olivine has been described in vein from serpentinite mylonite. The vein was created by dehydration reaction to decompose antigorite under shear deformation. In the cold slab beneath Tohoku arc, the reaction has a negative slope in P-T space and forms olivine+orthopyroxene+fluid. In the warm slab beneath SW Japan, the reaction has a positive slope in P-T space and forms olivine+talc+fluid. The above these dehydration reactions are well-described in the serpentinite from high P/T metamorphic belt from Spain, and Italy, respectively.

キーワード: 沈み込み帯, 青色片岩, ローソン石エクロジイト, 脱水流体, 地震断層, 変成かんらん石

Keywords: Subduction zone, Blueschist, Lawsonite eclogite, Dehydrated fluid, Earthquake faulting, Metamorphic olivine

高温高圧におけるアノ-サイトの弾性異常 Elastic anomaly of anorthite at high temperature and high pressure

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To understand the elastic properties of subducted crustal minerals at P-T conditions of crust and upper mantle, we performed in situ measurement of the elastic wave velocities of anorthite at temperatures up to 1373 K at less than 2.0 GPa and up to 273 K at 2.0-7.0 GPa. A fine grained polycrystalline anorthite was synthesised by using gas pressure apparatus installed at magma factory in Tokyo Tech. The experiments were performed using the SPEED-1500 apparatus installed on beam line BL04B1 at Spring-8. Pressure was generated by eight 26 mm tungsten carbide anvils with 11 mm truncated edge length. A Co-doped semi-sintered MgO octahedron with an 18 mm edge length was used as a pressure medium. The sample was enclosed in a BN sleeve container, and was placed in the central part (hot spot) of the furnace. Platinum foils (2.5 μm in thickness) were inserted at the both side of the sample for determination of sample length by using X-ray radiographic imaging techniques. An Al₂O₃ rod (5.3 mm in length and 2.0 mm in diameter) was used as buffer rod which transmit ultrasonic wave to the sample. Temperature was measured by a W97Re3-W75Re25 thermocouple. MgO was used as a pressure marker, and it was mixed with BN to prevent grain growth at high temperatures. The ultrasonic signals were generated and received by 10 degree Y-cut LiNbO₃ transducer of 50 μm in thickness and 3.2 mm in diameter. We used the ultrasonic wave of the frequencies 30-60 MHz with 3-5 cycles. Diffracted X-ray from the sample was measured simultaneously with the measurement of elastic wave velocities. A solid-state detector connected to a multi-channel analyzer combined with incident white X-ray beam was used for data collection. The X-ray diffractions were collected at a fixed 2 theta angle (= 2.961 degree).

In this study, we found temperature induced elastic anomaly. That is increase of elastic velocities and elastic moduli with increasing temperature in the range of 500-900 K at pressure of ~1 GPa. Based on the phase relation, it considered that this elastic anomaly is occurred in the high-temperature I(-1) phase stability field. Here we suggest a hypothesis that the tilting behavior of corner shared TO₄ tetrahedra in three dimensional frameworks causes the elastic anomaly of anorthite at higher temperature more than 500 K. In general, elasticity of solid materials depends on the bond length of atoms; the materials are hardened with decrease of bond length. Noritake et al (unpublished data) found that T-O-T angle increases and bond length of Si-O decreases with increasing temperature for high temperature I(-1) structure, although that is constant for low temperature structure (= P(-1)). This structure changes reasonably explains that the elastic wave velocities of anorthite increase with increasing temperature in the range of 500-900 K. Above 900 K, effect of the thermal expansion may reveal the reduction of elastic constants.

We also found pressure induced elastic anomaly. Elastic wave velocities of anorthite have a negative correlation with density at pressure more than 4.0 GPa. We consider that the pressure induced elastic anomaly is also caused by the tilting of TO₄ tetrahedra. Plagioclase feldspars are one of most abundant minerals of subducted crustal rocks on the Earth. Plagioclase may survive in subducted slab at higher pressure as a metastable phase if the temperature of the slab is low. Therefore we consider that plagioclase feldspar might be one of the causes for low velocity anomaly of slab.

Keywords: plagioclase, anorthite, elastic wave velocity, elastic anomaly, subducted slab, crust

Rheological behaviors of subducting oceanic crust: Implications from experimentally deformed blueschists

Rheological behaviors of subducting oceanic crust: Implications from experimentally deformed blueschists

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Investigations on deformation mechanism of blueschist can be helpful for delineating rheological behaviors of subducting oceanic crust. We deformed natural blueschists under pure and simple shear regimes using Griggs-type solid-medium apparatus and conducted fabric analyses of rock-forming minerals. Mechanical data of pure shear experiments display larger increase of yield stress at low confining pressure (0.5 to 1 GPa) rather than that at high confining pressure (1 to 2 GPa), implying that pressure-sensitive creep at low pressure (0.5?1 GPa) shifts to pressure-insensitive creep at high pressure (1?2 GPa). Microstructures of glaucophane and lawsonite deformed at simple shear experiments suggest that brittle fracturing are dominant at 1 GPa, but plastic flow of constitute minerals become important at 2.5 GPa. In addition, EBSD data indicate angle between slip plane and shear direction corresponding to angle of strain marker at 1 GPa and to angle of strain ellipsoid at 1.5?2.5 GPa. Our experimental data indicate, therefore, that deformations of glaucophane and lawsonite in the subducting oceanic crust are mostly controlled by brittle deformation at 1 GPa and ductile deformation at higher confining pressure (1.5?2.5 GPa); consequently, brittle-ductile transition zone likely occurs at ~1.0?1.5 GPa in our experimental conditions.

キーワード: Blueschist, Glaucophane, Lawsonite, Griggs-type solid-medium apparatus, oceanic crust
Keywords: Blueschist, Glaucophane, Lawsonite, Griggs-type solid-medium apparatus, oceanic crust

東北日本弧プレート境界および前弧間の比抵抗不均質

Electrical resistivity heterogeneity between the trench and fore-arc area in NE Japan arc

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We discussed 2-D resistivity distributions around the rupture zone of the 2011 Tohoku earthquake (M9.0) along latitude 38 degrees north and 39 degrees north in order to clarify structural properties and fluid distribution. Magnetotelluric (MT) impedances were obtained mainly in the ocean using ocean bottom electro-magnetometers (OBEMs). Long period land MT data also obtained near the coastline. Based on these data, we carried out 2-D resistivity inversion after the evaluation of 3-D bathymetric effect. The inverted resistivity model in the survey line of latitude 38 degrees entirely consists of conductive surface layer (< 3 ohm-m) and subsequent resistive area (> 1000 ohm-m). The thickness of surface conductor is a few km at landside of trench axis. On the other hand, the conductor distributes from surface to about 10 km deep in the Pacific plate and thus seems to correspond to the oceanic crust. The oceanic crust conductor can be recognized after the subduction, however, is disappeared at the about 20 west of the trench axis. It implies fluid dehydration from fluid rich oceanic crust soon after the subduction. In the presentation, resistivity distribution in the cross section along latitude 39 degrees will be discussed.

キーワード: 地殻流体, 比抵抗構造, 海底電位差磁力計, 東北日本弧, 2011年東北沖地震, 日本海溝

Keywords: Geofluid, electrical resistivity structure, OBEM, NE Japan arc, 2011 Tohoku-oki earthquake, Japan Trench

東北地方下に沈み込む海洋性地殻のP波速度構造

P-wave velocity structure in the subducting crust of the Pacific plate beneath northeast Japan

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It is considered that the low-velocity oceanic crust exists at the uppermost part of the oceanic lithosphere. Water produced by dehydration reactions of hydrous minerals is considered to weaken the strength of faults by increasing pore-fluid pressure and facilitate seismic activity in the oceanic crust. Therefore, it is important to reveal the spatial variation in seismic velocity to understand where fluids are trapped and where dehydration reactions occur in the oceanic crust. However, it is generally difficult to obtain the detailed velocity variation in the oceanic crust, because the direct P- and S-waves from intraslab earthquakes tend to propagate in a short distance in the crust.

It is known that P-to-S converted phases at the plate interface are often observed in seismograms of intraslab earthquakes. Matsuzawa et al. (1986) examined arrival times and amplitudes of PS-converted phases, and suggested the existence of a low-velocity layer at the top of the slab down to a depth of at least 150 km. Here, we follow the strategy of Matsuzawa et al. (1986), and estimate the spatial variation in P-wave velocity in the oceanic crust beneath northeastern (NE) Japan using arrival times of PS-converted waves.

At first, we identified PS-converted waves in seismograms of intraslab earthquakes and obtained 2,798 arrival times of PS converted waves from 305 earthquakes. Before estimating P-wave velocity structure in the oceanic crust, we applied tomographic inversion method of Zhao et al. (1992) to arrival-time data of the direct P and S waves, and estimated 3D seismic velocity structures beneath the entire region of NE Japan. We then relocated earthquakes with the obtained 3D velocity model and determined P-wave velocity in the oceanic crust using arrival-time data of PS-converted waves.

The obtained results show that P-wave velocity in the oceanic crust varies across the arc, with V_p of 6.5-7.5 km/s in the fore arc and 7.5-8.5 km/s in the back arc. P-wave velocity at depths of < 100 km is much lower than the values derived from MORB model beneath NE Japan (Hacker et al., 2003), suggesting the existence of aqueous fluids in the oceanic crust. High seismic activity at depths of 70-90 km (Kita et al., 2006) is located in areas of abundant aqueous fluids. The enhanced pore-fluid pressures and the resultant reduced effective normal stress weaken the strength of the faults sufficiently to bring the system into the brittle regime. Fluid-related embrittlement is probably working for the genesis of crustal earthquakes. Another important observation to be noticed here is that the observed P-wave velocity is almost consistent with the prediction of MORB model at depths of >100 km. This suggests that aqueous fluids in the crust should be released to surroundings at depth of ~100 km, and the fluids thus liberated may contribute to metamorphic reactions in the overlying mantle wedge.

キーワード: PS 変換波, 海洋性地殻, 太平洋スラブ

Keywords: PS converted wave, oceanic crust, Pacific slab

オーストラリア下マントル遷移層の3次元電気伝導度構造 3-D electrical conductivity structure in the mid mantle beneath Australia region

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The 3-D electrical conductivity in the mid and most upper lower mantle beneath Australia was elucidated by inverting C response data at 8 observatories in Australia. We just used data obtained by Semenov and Kuvshinov (2012) estimating by using very long time series up to 51 years maximum. The period range used in this study is between 4 and 100 days by removing data with shorter period to avoid contamination of some irregular source effects such as auroral effects. By using this data under the assumption that the source is external dipole field in geomagnetic coordinate, the 3-D conductivity map beneath Australia is inverted.

To invert data, we used the 3-D inverse code developed by Koyama (2002), in which integral equation method with modified IDM pre-conditioner is applied for forward calculation and the misfit function is minimized by quasi-Newton iterative method. By conducting a hundred of numerical tests, we found that the conductivity in the depth between 510-900 km is well resolved.

Mainly we detected a highly conductive body in the mid-mantle beneath eastern Australia, which is almost 1.0 S/m. This might indicate the existence of fluid and/or melt in the mid-mantle.

キーワード: 電気伝導度, マントル遷移層, オーストラリア, インバージョン, C レスポンス
Keywords: electrical conductivity, mid mantle, Australia, inversion, C response

ケイ酸塩メルトへの二酸化炭素の溶解機構
Dissolution mechanisms of CO₂ in silicate melts

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See English abstract.

キーワード: ケイ酸塩メルト, 二酸化炭素, メルト構造, 溶解メカニズム, 核磁気分光法, ラマン分光法

Keywords: silicate melt, carbon dioxide, melt structure, dissolution mechanism, NMR spectroscopy, Raman spectroscopy

日本各地の温泉水のホウ素同位体組成の高精度迅速分析 B isotopic variation of spring water in Japan

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Boron has two stable isotopes ¹⁰B and ¹¹B with abundance of 18.98% and 81.02%, respectively. Natural isotopic variation of ¹¹B/¹⁰B among geological samples is from -30 permil to +60 permil as delta-¹¹B values, which is defined as relative deviations from an isotopic reference material (NIST-SRM 951) in parts per 1000. Boron isotope ratio is a powerful tracer in the fields of geochemistry, biochemistry, and environmental chemistry to trace the origin of materials.

Here B isotope ratios of spring water samples were precisely determined by ICP-MS with a multiple collector array. About 70 samples were selected among those collected from the whole area of Japan. Boron was extracted from the water samples of less than 1mL, and anion and cation ion-exchange chromatography was applied to separate B from matrix elements. Boron amount required was about 50 ng, and procedural B blank was typically around 100 pg.

Resultant delta-¹¹B values had a very wide range from +40 permil to almost -10 permil. There was a decreasing tendency of delta-¹¹B values from fore-arc to back-arc of Japan Island, which was consistent with the previously reported trend of delta-¹¹B values observed in volcanic arc rocks. These results indicate that some kind of spring water has a B isotopic signature of fluids derived from continuous dehydration reaction within the slab, though interaction with granitic rocks during upwelling should be evaluated.

キーワード: ホウ素同位体, 同位体比, ICP 質量分析法
Keywords: Boron isotope, isotope ratio, ICP-MS

岩内岳超塩基性岩体にみられる鉱物組織の連続変化と蛇紋岩化反応の進行 Progress of serpentinization reactions and successive changes of mineralogical textures in Iwanai-dake ultramafic body

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We investigated successive change of serpentine textures accompanied with progress of serpentinization observed in serpentinized harzburgite and dunite samples from Iwanai-dake ultramafic body, Hokkaido, Japan. The change of serpentine textures shows serpentinization processes of harzburgite are different from dunite. Serpentine mesh texture of serpentinized harzburgite has two kinds of mesh rim types; type A rim is mixture of serpentine (Mg#97) and brucite (Mg#75), and type B rim consists of only serpentine (Mg#93). Type B rims are always accompanied with brucite-magnetite veins. The formation of type B rims and brucite-magnetite veins are observed concurrently with serpentinization of orthopyroxene. These observations suggest that two-stage reactions occurred during the serpentinization processes of harzburgite, and magnetite was formed by the later-stage reactions, which were triggered by supply of silica component from serpentinization of orthopyroxene. This is consistent with the higher magnetic susceptibility in moderately and highly serpentinized harzburgite than in less serpentinized ones. In case of serpentinized dunite, type A rim was dominantly observed and the amount of magnetite doesn't increase with the progress of serpentinization. These observations suggest that silica supply is a trigger of the later-stage serpentinization reactions, in which magnetite and hydrogen are generated.

キーワード: 蛇紋岩, 蛇紋岩化, 鉱物組織, 初磁化率, 含水量, 磁鉄鉱

Keywords: serpentinite, serpentinization, mineralogical texture, magnetic susceptibility, water content, magnetite

Electrical conductivity measurement of albite-quartz-water system under high P/T conditions

Electrical conductivity measurement of albite-quartz-water system under high P/T conditions

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Magnetotelluric surveys have revealed that the high conductivity anomalies exist in the middle to lower crust. Electrical conductivity (EC) of dry crustal rocks are much lower than the high conductivity anomalies, suggesting the existence of conductive material in the crustal rocks that are stable only with the middle to lower crustal conditions. Aqueous fluids seem to be most likely candidate to explain the high conductivity anomalies. Quartz-water system has been investigated recently, but it cannot account for the high conductivity anomalies. Therefore, other ionic species, such as Na^+ , in addition to silica phases dissolved in fluid is required to increase conductivity. In this study, albite was introduced to add the ionic species in the fluids. The electrical conductivities of albite-water and albite-quartz-water systems have been measured using an impedance analyzer at 1 GPa and 400-1100 K. Albite-water samples with water contents of 0.5, 1, 5, 9.3 wt.% were prepared by natural albite powder and mixture of $1\text{Na}_2\text{SiO}_3$, 5SiO_2 and $2\text{Al}(\text{OH})_3$ (mole ratio) in designed ratios. Albite-quartz-water samples with water contents of 0.34, 1.2, 5.6, 10 wt.% were prepared by natural albite powder and silicic acid ($\text{SiO}_2 \cdot 0.5\text{H}_2\text{O}$) in designed ratios. EC and temperature relationship of all the other samples cannot be expressed by the Arrhenian formula except for the sample with 0.34 wt.% water content. The electrical conductivity of these samples decreased from highest designed temperature (e.g., 1000 K) during cooling, but the temperature dependence was getting weaker and weaker. EC, however, increased upon further cooling from 800 K until around 500 K. Then temperature dependence of EC was negligible. The tendency of EC changes with temperature indicates the concentration of electrical charge carrier changes with temperature assuming the charge carrier series will not change. The thermal dynamic calibration shows the total electric charge carriers (including H^+ , OH^- , Na^+ , AlO_2^- and HSiO_3^-) solved in water decreases with decreasing temperature from 908 to 773 K and then increases with decreasing temperature down to 573 K. The experimental result can be well explicated by the theoretical calibration. EC of the albite-quartz-water or albite-water systems are much higher than that of quartz-water system. We can well explain the high conductive anomalies in the crust even the temperatures are lower than the normal geotherm by dissolved albite in fluids.

キーワード: electrical conductivity, albite, quartz, water, fluids, high pressure

Keywords: electrical conductivity, albite, quartz, water, fluids, high pressure

様々な場における蛇紋岩化と酸化還元 Serpentinization and redox in various geologic environments

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In this study, serpentinization and simultaneous redox reactions in various geologic environments are described from a petrologic viewpoint with thermodynamic calculations for minerals and fluids. Serpentinization occurs at where geofluid and ultramafic rock interact. Sites of serpentinization spatially and temporally range and have physical, chemical, and biologic implications for the Earth's process.

Serpentinization in the present seafloor and deeper part of the oceanic plate is an entrance of water to deep mantle via subduction zone. Serpentinite has been found from the Mars surface suggesting that the existence of water and hydrothermal system in the early stage of the Mars history. It is known that the serpentinization of ultramafic rock simultaneously produces hydrogen by reduction of H₂O during the serpentinization. Hydrogen is one of the key elements to control the metabolism of the ecosystem, therefore the importance of serpentinization in biologic process has also been raised. Forearc mantle wedge is also the site of serpentinization in the present Earth.

Regarding the various site of serpentinization described above, phase diagrams for serpentinite in the model system CaO-MgO-FeO-Al₂O₃-SiO₂-O-H are calculated using internally consistent thermodynamic-dataset for the rock forming minerals and fluid. Using the diagrams, we discuss how the serpentinization and redox reactions depend on temperature, pressure, and bulk composition of the host rock and effect to redox of the geofluids.

キーワード: 蛇紋岩, 状態図, 酸化還元反応, 蛇紋岩化

Keywords: serpentinite, phase diagram, redox reaction, serpentinization

沈み込み帯での流体の数値計算：グローバルな同位体異常への示唆 Numerical simulation of subduction zone fluid processes: implications for global compositional anomaly

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Aqueous fluids released from subducting slabs are thought to transport incompatible elements from the slabs to the overlying wedge mantle, which consequently concentrates the incompatible elements in an arc magmas, and causes elemental differentiation.

Element transportation by slab-derived fluids has an important role on global material differentiation; however this process is not constrained well due to its complexity such as dehydration reaction, fluid migration, fluid-solid reaction, and melting. In this study, we try to induce the transportation and reaction of trace element during these complex processes in the solid-melt-water system. Based on numerical simulation with generation and migration of water by the relevant phase relationships, we construct numerical model for solid-fluid-melt flow beneath the NE Japan arc in order to estimate the influence of subduction process on chemical compositions of the each constituent phases.

As a result, we have successfully estimated trace element distributions in the solid, melt, and aqueous fluid and their migration in subduction zones. For instance, melts is distributed 80km~150km above the Wadati-Benioff Zone, which is consistent with volcanic distribution in NE Japan. Based on the obtained elemental mapping over the subduction zone, we have also found a high Rb/Sr and Th/Pb layer above the subducting slab along the bottom of the mantle wedge. This layer subducts to the deeper mantle, which may contribute to a source region with high $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios deep in the mantle: if they are accumulated, e.g., beneath a supercontinent associated with focused subduction towards it, such a source region can explain Dupal anomaly (Hart, 1984) or "Mantle Eastern Hemisphere" (Iwamori and Nakamura, 2012), in which the mantle-derived basalts show isotopic anomaly over the region.

キーワード: 沈み込み, 数値計算, 微量元素, 同位体異常, 物質循環, スラブ
Keywords: subduction, simulation, trace element, isotopic anomaly, material recycling, slab

蛇紋岩の脱水反応によるスラブマンントルの酸化作用 Oxidation of slab mantle due to dehydration of serpentinite

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The oxygen fugacity in subduction zones controls the speciation of C-O-H-bearing fluids and phase equilibria in metamorphic processes. It is therefore important to quantify the oxidation states in the Earth's interior. This study used X-ray absorption near edge structure (XANES) spectroscopy to investigate changes in redox state that accompany the dehydration of serpentinite. A run product (Atg02) of our previous deformation experiment (Shimizu et al., 2011) was used for the analysis.

The starting material of the experiment was dark-green natural serpentinite (from Oeyama, Kyoto Prefecture, Japan) consisting mainly of antigorite and accessory wustite. A cylindrical sample of serpentinite (diameter 10 mm, height 15 mm) was enclosed in Ni and Ag sheets, and was set in confining mediums of talc and pyrophyllite. High-pressure and high-temperature deformation experiments were conducted with a piston-cylinder type apparatus. The confining pressure was kept at 800 MPa during the experiments. A graphite furnace was used to heat the sample to 700°C. After the constant strain-rate experiment, the color of the sample had changed to pink or red, and forsterite and talc had grown in the antigorite matrix. Small particles of hematite were identified in the matrix by optical microscope and micro-Raman spectroscopy.

The oxidation state of the serpentinite before and after the experiments was investigated by the Fe-K edge XANES spectra acquired at BL9A, Photon Factory, KEK (Tsukuba, Japan), using Fe standards of FeS₂, fayalite, magnetite (Fe₃O₄), FeO, *a*-FeOOH, and *a*-Fe₂O₃. Following Wilke et al. (2001), the ratio $X(\text{Fe}^{3+}) = \text{Fe}^{3+}/(\text{Fe}^{2+} + \text{Fe}^{3+})$ was calculated from the Fe-K pre-edge centroid positions. The results show that $X(\text{Fe}^{3+})$ increased from 7% of the original sample to 23% in the reacted sample. It is probable that the oxidation state of the sample was buffered by a large amount of free water liberated by the following dehydration reaction: antigorite => forsterite + talc + H₂O.

The mechanical data of the antigorite-serpentinite showed drastic dehydration weakening. This result supports the hypothesis that intermediate-depth earthquakes in subduction slabs are triggered by the dehydration instability of serpentinite. If this hypothesis holds true, then the subducting slab mantle must be largely serpentinitized.

In general, the oxygen fugacity of peridotites is equilibrated near the fayalite-magnetite-quartz (FMQ) buffer at the top of the upper mantle, and decreases with increasing depth (Frost and McCammon, 2008). However, if large parts of the slab mantle are serpentinitized and if free water is released by the breaking down of antigorite, the reaction front of antigorite would be highly oxidized. The redox states in the subducting oceanic crust and the wedge mantle would be also influenced by water supplied from the slab mantle.

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キーワード: 蛇紋石, 脱水反応, 酸化還元状態, X線吸収端近傍構造 (XANES), 高温高圧実験, 沈み込み帯

Keywords: serpentine, dehydration reaction, redox state, X-ray absorption near-edge structure (XANES), high-PT experiment, subduction zone

Naに富む白雲母の組成改変から読み取った三波川変成帯上昇期の流体流入 Exhumation stage fluid migration recorded in Na-rich phengite in Sanbagawa metamorphic rocks

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天然に産する変成岩は多くの場合、昇圧・減圧（岩体上昇）過程に於いて複数段階の流体活動の影響を受けている為、天然試料を用いて深部流体の研究を行う場合、それぞれの流体の活動時期の特定が必要となる。

本研究では、エクロジヤイト相の変成作用（550～650°C, 1.5～2.0 GPa: Endo et al., 2009）を被った四国中央部別子地域五良津岩体より採取した、堆積岩に由来する変成岩（IR04）を研究対象とした。IR04は主として角閃石、白雲母、ザクロ石からなり、少量の緑泥石などを含む。Yoshida and Hirajima (2012)ではIR04の主片理と平行に存在する石英脈から、昇圧期、昇圧期ないし変成ピーク時前後、及び岩体上昇期にトラップされたと考えられる三段階の流体包有物を報告している。

IR04の母岩試料中の含水鉱物である白雲母は変形部や粒界に沿って組成改変を受けている。この組成改変部は劈開と高角に斜行する方向に発達していることが多い。組成改変部は白雲母同士の粒界にも見られるため、後退変成に伴う隣接鉱物間での元素分配による組成改変によるものではないと考えられる。未改変のコア部はNaに富み（Na-rich core）、 $Na/(Na+K)=XNa=0.16-0.20$ 程度の組成をしているのに対して、改変部（Na-poor rim）では $XNa<0.04$ とNaに乏しい組成を持つ。また、 XNa の減少に伴って、 $Mg\# (=Mg/(Mg+Fe))$ がコアの $Mg\#=0.68-0.72$ からリムの $Mg\#=0.62-0.68$ 程度へと減少する。

この組成改変部の形成タイミングを推定するために、Perple_X (Connolly, 2005)を用いて、岩体がピーク変成条件650°C / 2GPaから400°C / 0.3 GPaまで上昇してくる過程で、系の含水量に対して安定な相と白雲母の組成がどのように変化するかのモデル計算を行った（Composition-P(T) pseudosection）。計算結果から、白雲母の $Mg\#$ は温度圧力の変化に対しては鈍感であるが、系の含水量の増加と共に減少することがわかった。また XNa については系の含水量によらず減温と共に減少していく傾向が得られた。組成改変部で起きている化学反応に関与している物質の有効なバルク組成が、本試料の全岩化学組成によって近似できるものと仮定すると、試料の組成改変部で見られた、 XNa の減少（0.2 < 0.04）、及び $Mg\#$ の減少（0.7 > 0.62）の変化は、450°C以下の条件での系の含水量の増加により説明できることが判った。また、白雲母の組成改変部が組成のギャップを持って存在していることから、450°C以下までの減温減圧は水が不飽和な状態で進行し、その後、系の含水量の増加が生じたと考えられる。石英脈中の流体包有物の捕獲時期と比較すると、この含水量の増加を引き起こした流体は上記の流体である可能性が高い。

上記試料と同様の組成改変を呈する泥質変成岩2試料が、IR04の採取地点から3km程度離れた、五良津岩体の北側近傍地域の、黒雲母帯（それぞれの最高変成条件：IR27 = 600°C / 1.0GPa, IR28 = 550°C / 0.8GPa）からも見いだされた。別子地域の三波川変成帯黒雲母帯の岩石は、地下25～30km付近で五良津岩体と接合し、共に上昇してきたと考えられている。今回推定された流体流入の温度圧力条件（<450°C）は岩体接合以降の温度圧力を示す条件であり、上記の流体流入は三波川変成帯の上昇過程において、五良津岩体近傍で広域的に起こった現象であることが示唆される。

キーワード: 三波川変成帯, 後退変成流体, シュードセクション, 水岩石相互作用

Keywords: Sanbagawa metamorphic belt, retrograde fluid, pseudosection, fluid-rock interaction

S-wave attenuation structure around the western part of Nankai subduction zone S-wave attenuation structure around the western part of Nankai subduction zone

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Seismic imaging of lithospheric structure is crucially important to investigate spatial distribution of geofluid and its role in dynamics of the Earth's interior. Even though V_p and V_s structures are widely imaged in various regions in the world, these structures cannot explain complex and broadened seismic waves at higher frequency ($>1\text{Hz}$). Such complex wave trains can be described by considering wave scattering and attenuation due to random inhomogeneities and inelasticity of the medium [e.g., Sato & Fehler, 1992]. It can be expected that medium containing fluid-filled cracks is one of the possible causes of S-wave scattering and attenuation. Therefore, medium inhomogeneities and inelasticity are also important to elucidate geofluid distribution. In Nankai subduction zone, we have estimated the 3D distribution of random inhomogeneities [Takahashi et al. submitted to JGR]. This study estimated the spatial distribution of $1/Q$ of S-wave around the western part of the Nankai trough. In Kyushu and Shikoku regions, most of the medium shows weak attenuation ($1/Q < 1/1500$ at 8-16Hz). Volcanic area in Kyushu region shows strong attenuation ($1/Q = 1/600 \sim 1/300$ at 8-16Hz). Beneath west Shikoku, slightly strong attenuation ($1/Q=1/1000 \sim 1/800$ at 8-16Hz) are imaged at 20-40km depth. This anomaly is approximately located in or above the non-volcanic tremor zones [e.g., Obara et al. 2010]. If we compare the random inhomogeneities and $1/Q$, there are clear differences of medium properties in volcanic area and tremor zone. This difference suggests that random inhomogeneities and attenuation may reflect fluid properties (magma or aqueous fluid) or amounts of geofluid in medium.

キーワード: 南海トラフ, ランダム媒質, 散乱, 減衰

Keywords: Nankai trough, random media, scattering, attenuation

マントル最下層における沈み込みスラブの影響 Interaction of sinking slabs of the lowermost mantle

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Mantle plumes that rise from the lowermost mantle generate the most hotspots. The lowermost mantle has complex seismic structure that consist long-wavelength seismic low- and high-velocity anomalies. These seismic anomalies are anticipated to correspond with respectively. In addition, the margins of Large Low Shear Velocity Provinces (LLSVPs) under the African and Pacific areas are related to hotspots, and have a sharp seismic discontinuity. In this study, we investigate roles of post-perovskite (PPV) phase transition and compositional stratification in the generation of observed heterogeneity of the lowermost mantle and the upwelling plume. We construct a 2-D integrated model of the mantle convection with a sinking slab.

The PPV phase covers over the whole area of the CMB when the compositional layering is not introduced. In the models with high-density stratification, the structure of the lowermost mantle and the plume generation change significantly. The sinking slab pushes the high-density layer so that the high-density layer is piled up in the outside of the subduction area. This is more distinct in the case with lower density contrast of the chemical layering. The PPV phases in the high-density layer distribute very locally. On the other hand, the PPV phase is stably maintained beneath the subduction zone. The top of the phase boundary reaches about 300 km above the CMB. The PPV phase boundary becomes vertical at the location where the slab contacts with the high-density layer. This is expected to form the steep seismic discontinuity at the margin of the LLSVPs.

The slab also produces disturbances of thermal boundary layer, which causes the plume generation. The plumes grow more rapidly in the case with the PPV phase than that without it. Although the high temperature anomaly is generated at the margin of the high-density layer, the upwelling plume is not generated because the slab climbs up above high-density layer. Thicker pile of the chemical layer with the lower density contrast used in our study may be required to generate plumes at the margin of LLSVPs.

Keywords: plume, slab, high-density layer, LLSVPs, post-perovskite phase transition