Estimation of electrical anisotropy in the oceanic upper mantle from seafloor magnetotelluric array data

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Electrical anisotropy in the oceanic upper mantle could provide important clues on mantle structure and dynamics if it is confirmed from observational data. Seafloor magnetotelluric (MT) data are useful to estimate electrical anisotropy in the oceanic upper mantle, but should be carefully treated partly because maximum anisotropic signal may not be so large (half an order of magnitude in electrical conductivity) and there is always trade-off between intrinsic anisotropic effects and effects of a large-scale lateral heterogeneity including bathymetric variations and coast effects. One promising method to estimate electrical anisotropy from seafloor MT array data is first to obtain a 1-D isotropic model through iterative correction for bathymetric distortion, and then to estimate anisotropy as deviations from the 1-D isotropic model. We first investigate the performance of this method through a series of synthetic modeling using plausible 1-D anisotropic models for the Normal Oceanic Mantle project area in the northwestern Pacific. The synthetic modeling includes forward modeling using the 1-D anisotropic models with and without bathymetry and inversion with iterative bathymetric correction to data produced from the 1-D anisotropic models underlying a 3-D real bathymetry. After the synthetic test, we apply the method to an observational array data obtained during the Normal Oceanic Mantle project in the northwestern Pacific. We will show and discuss results of the application in the presentation.

Layered seismic anisotropic structure of the subducting asthenosphere in the Cocos subduction zone

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Previous studies of the seismic anisotropy in the subslab mantle of the Cocos subduction zone show that the fast directions are in general parallel (~30 degrees) to the absolute plate motion (APM). Such APM-parallel pattern can be interpreted as the a-axis of olivine being aligned by the shear stress associated with the moving plate.To better understand the relationship between anisotropy and mantle flow, we collected S waves from the Cocos slab recorded by the stations located on the Pacific plate. Our results show that fast directions predominantly align at N65E, or 30 degrees clockwise from the direction of the APM, and that the delay time of our source-side anisotropy is much larger than previously reported. We also found that both of the splitting parameters have $\pi/2$ periodicity. We model the periodic distribution using 2 layer anisotropic structure with E-type olivine fabric, for which the fast direction remains the same at all incident angles to satisfy the basic assumption of the 2 layer modeling. The best-fit model shows that the upper and lower layers are characterized by a fast direction of 30 and 65 degrees, respectively, with delay time ratio about 1:2~3. The upper layer immediately entrained by the slab is "normal" descending and the lower layer is oblique in subduction. The mechanism behind this double layer subduction of the asthenosphere is under investigation.

Keywords: Subslab anisotopy, Cocos subduction zone, asthenosphere

Radial anisotropy as "bodywave-surface wave discrepancy"

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The lithosphere-asthenosphere system (LAS), especially beneath the ocean, is known to have pronounced radial anisotropy (transverse isotropy with vertical symmetry axis, VTI), but its physical origin is not well understood. Radial anisotropy in the mantle has been often associated with "Rayleigh/Love wave discrepancy", but it could be also due to other factors. Recently, Kawakatsu et al. (2015) and Kawakatsu (2016a,b) have introduced a new fifth parameter in VTI system that describes the incidence angle dependence of bodywaves. Rayleigh wave dispersion has a strong sensitivity to this parameter (Kawakatsu, 2016b), and thus it can also affect the strength of radial anisotropy.

Song and Kawakatsu (2012) has demonstrated how bodywaves that enter the LAS with different incident angles can be used to constrain asthenospheric anisotropy. Also the reflection/conversion efficiency at the G-discontinuity depends on the fifth parameter in a peculiar way. Thus bodywaves can provide additional information about radial anisotropy of the LAS, and it is possible to view radial anisotropy as "bodywave-surface wave discrepancy" through the new parameter, \eta_k. Lateral change of the strong asthenospheric anisotropy may be due to this effect.

Constraints on mantle flow in the oceanic upper mantle from a high-resolution estimate of seismic velocities in the central Pacific

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Observations of seismic anisotropy in ocean basins are important for constraining deformation and melting processes in the upper mantle. The NoMelt OBS array was deployed on relatively pristine, 70-Ma seafloor in the central Pacific with the aim of constraining upper-mantle circulation and the evolution of the lithosphere-asthenosphere system. Azimuthal variations in Rayleigh-wave velocity suggest strong anisotropic fabric both in the lithosphere and deep in the asthenosphere, with the asthenospheric flow driven by either small-scale convection or large-scale lateral pressure-gradients, and little deformation related to plate motion. To further evaluate these mechanisms, we combine Love waves derived from high-frequency ambient noise (5-10 s period) and earthquakes (20-100 s period) with body-wave travel times to further constrain fabric and flow in the oceanic mantle. High-frequency Love waves require positive radial anisotropy (Vsh > Vsv) and azimuthal anisotropy with a strong 4-theta azimuthal signal in the upper 30 km of the mantle, consistent with the high-resolution Rayleigh-wave anisotropy, but inconsistent with estimates from global models. Forward modeling of multi-mode Love waves traversing the array from three strong earthquake sources suggests that the positive radial anisotropy (Vsh > Vsv) extends through the asthenosphere. Taken together, the Love- and Rayleigh-wave anisotropy suggests that olivine fabric can explain the anisotropic signature of the lithosphere-asthenosphere system, and melt or other exotic mechanisms are not required. To further evaluate the processes producing asthenospheric fabric, we measure teleseismic P- and S-wave multi-channel delay times to constrain lateral velocity variations beneath the array. Finite-frequency sensitivity kernels provide the mapping of the delay times to velocity variations in the asthenosphere. We will specifically test for the presence of lateral velocity variations within the asthenosphere that are consistent with small-scale convection. At minimum, we will place bounds on the maximum plausible temperature variations allowed by the data. Taken together, the surface- and body-wave modeling will provide a unique, high-resolution picture of seismic structure and mantle flow within the oceanic lithosphere-asthenosphere system.

Keywords: asthenosphere, seismic anisotropy, mantle flow

Waveform modeling of BBOBS data for old oceanic lithosphere-asthenosphere system

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Analysis for a base of lithosphere, at nearly 100 km depth, is still difficult because of a lack in observation data which contain a pure information for the lithosphere-asthenosphere system (LAS). Recent developments in seafloor in-situ observation and waveform analysis enable to determine more detailed structure of the LAS. In this study, we modeled broadband seismic waveforms of outer-rise earthquakes occurring after the Tohoku earthquake around the Japan trench that are observed by 5 broad-band ocean bottom seismometers(BBOBSs) at the northwest pacific seafloor; the traveling paths of these seismic waves are entirely within the old (~130Ma) ocean LAS, and can be used to constrain the average 1-D velocity structure under ’ normal ocean’ . Because the observation data contain much short-period noise, the waveforms need to be applied appropriate bandpass filters: periods 6-100s for P wave, 33-100s for Rayleigh wave, and many octave-range filters for Love wave. We compared observed and synthetics waveforms, and then adjusted our model. Very preliminary analysis indicated that (1) crust is 3% faster in P wave or 0.5 km thinner than the PA5 model (Gaherty et al., 1999), (2) LID is 20km thicker or 2% slower than PA5, but (3) the model has still strong trade-off between crust thickness and crust velocity, and between LID thickness and LID velocity. As a result, the depth of lithosphere-asthenosphere boundary (LAB) or G-discontinuity is not constrained uniquely. Further analysis for multiply bounced S-waves (e.g., ScS, SS, SSS) should constrain more detailed structure for the depth.

Super-weak asthenosphere in light of plate motions and azimuthal anisotropy

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Plate motions and azimuthal seismic anisotropy from surface waves are consistent with a strong, oceanic lithosphere that is predominantly dragged by slabs, and weakened upon subduction. Plates are underlain and sustained by a moderately weak asthenosphere, as expected from the temperature and pressure dependence of olivine viscosity for the upper mantle. However, recent observations from active source seismology, magneto-tellurics, body wave anisotropy, and postseismic surface deformation can be interpreted to imply the existence of a very weak channel of low viscosity material, potentially decoupling plates, not unlike a plume-fed asthenosphere scenario in several ways. Here, I explore the implications of such a decoupling channel for plate driving forces as well as observations of seismic anisotropy. The thickness and viscosity reduction of the channel are expected to trade off with each other, and plate motions are sensitive to the lateral extent of this super-weak asthenosphere. While there is some ambiguity of plate motion metrics with the strength of slabs, seismic anisotropy is expected to be sensitive to how shear is localized with depth. The overall good fit of azimuthal anisotropy patterns to flow model predictions brakes down for a number of the more extreme lateral and depth-dependent viscosity scenarios. This may imply that weakening mechanisms may not apply globally under plates, but are rather limited to isolated regions, perhaps associated with melt-rich pockets that have limited connectivity.

Keywords: asthenosphere, plate motions, azimuthal anisotropy

Significance of sediment reverberations on receiver functions of broadband OBS data

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We attempted to estimate the depth of the lithosphere-asthenosphere boundary (LAB) and velocity contrast at LAB with a receiver function (RF) analysis of waveform data observed by a broadband ocean bottom seismometer (BBOBS) installed in the northwest Pacific Ocean under the OHP project. Beneath the station (WPAC), thickness and several physical properties of the sediment layer were revealed from a boring core (Kanazawa *et al.*, 2001, *Proceedings of the Ocean Drilling Program, Initial Reports*). The oceanic crustal structure was precisely estimated by a seismic experiment (Shinohara *et al.*, 2008, *PEPI*). Using waveform data observed at the bottom of a borehole just beneath WPAC, depth of the LAB and S-wave velocity contrast at LAB were estimated to be 82 km and 7.2%, respectively (Kawakatsu *et al.*, 2009, *Science*; Kumar *et al.*, 2011, *JGR*).

We calculated P-wave RFs (PRFs) and S-wave RFs (SRFs) from teleseismic waveforms, and obtained averaged PRF and SRF. To calculate RFs, a Gaussian low pass filter, $G(\omega)=\exp(-(\omega/2\alpha)^2)$, was applied. We obtained four pairs of PRF and SRF with different values of α, 0.25, 0.5, 1.0, and 2.0. We synthesized PRF and SRF using the known structural parameters revealed from the studies shown above. However, the synthetic PRF and SRF cannot explain the observed ones. The synthetic PRF has several peaks caused by reverberation of S-wave in the sediment layer with larger amplitudes than the observed one. Amplitude of the first peak of the synthetic SRF is much larger than that of the observed one.

We showed that the observed PRF can be explained when we assume attenuation and velocity gradient of S-wave in the sediment layer in addition to the known parameters. Although the observed SRF cannot be explained even if we assume them, we showed that they can be explained when we calculate an SRF from synthetic waveforms added with large noise. Velocity gradient and attenuation of S-wave in the sediment layer and noise are necessary to be taken into account for explaining RFs obtained from BBOBSs.

The observed waveforms would contain noise that largely changes amplitude of SRF, and it is difficult to constrain subsurface structure from SRFs. Only from PRF, we searched structural parameters from the ocean bottom to the asthenosphere, where attenuation and velocity gradient in the sediment layer were contained. The depth of LAB and S-wave velocity contrast at LAB are constrained to be 73-129 km and 6-25%, respectively. Thick sediments beneath WPAC (377 m; Kanazawa *et al.*, 2001) would make the analysis difficult. New BBOBSs have been developed to reduce noise (*e.g.* BBOBS-NX: Shiobara *et al.*, 2013, *IEEE J. Ocean Engineering*). At other stations, where the condition is better, the parameters might be constrained better.

Keywords: receiver function, oceanic sediments, broadband ocean bottom seismometer

The impact of temporal stress variations, dynamic disequilibrium, and asthenospheric channels on the initiation of plate tectonics

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We use 3-D numerical experiments and 1-D thermal history models to study the impact of dynamic thermal disequilibrium, asthenospheric channels, and large temporal variations of normal and shear stresses on the initiation of plate tectonics. Previous models that explored plate tectonics initiation from a steady state, single plate mode of convection concluded that normal stresses govern the initiation of plate tectonics. Using 3-D spherical shell mantle convection models in an episodic regime allows us to explore larger temporal stress variations than can be addressed by considering plate failure from a steady state stagnant lid configuration. The episodic models show that an increase in convective mantle shear stress at the lithospheric base initiates plate failure. In this out-of-equilibrium and strongly time-dependent stress scenario, the onset of lithospheric overturn events cannot be explained by boundary layer thickening and normal stresses alone.

Moreover, we empirically find that the period increases with a decrease in “channel number MN”, which we define as MN=$\mathrm{eta}_A/(d_A)^3$ (here eta_A is the non-dimensional channel viscosity and d_A the ratio between channel thickness and mantle depth). Therefore, decreasing values of MN move the system toward stagnant lid convection.

At this stage, our results indicate that a decreasing channel number is associated with lower basal shear stress on the plate above, and in that sense, our results are consistent with the idea that basal shear stress, asthenospheric channels, the temporal variation of stresses, and dynamic disequilibrium are critical for initiating plate tectonics.

References. Stamenkovic, V., Höink, T., Lenardic, T. (2016) JGR Planets, 121, 1–20, doi:10.1002/2016JE004994.

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Keywords: Plate tectonics, Asthenosphere, Stresses, Non Equilibrium, Mantle Convection

Diffusion creep of fine-grained olivine aggregates : Chemical and melt effects

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Since olivine is the major constituent mineral of the earth's upper mantle, flow properties of the upper mantle are often estimated based on flow laws of olivine aggregate which are determined by high-temperature creep experiments. In particular the viscosity of asthenospheric mantle plays a key role on plate tectonics because it decouples solid plates above and convective upper mantle below. Recently, the presence of a small amount of melt at the oceanic mantle asthenosphere has been suggested by some studies on seismic wave, electrical conductivity, and geochemistry (Hawley et al. 2016, Naif et al. 2013, Hirschmann 2010).

The effect of melt on rheology of olivine aggregates at dry conditions, however, has not been understood well yet. Deformation experiments on olivine aggregates synthesized from naturally derived mantle rocks (we refer naturally-derived olivine hereafter) showed that 4% melt-doped samples had a factor of 3 lower viscosity than undoped samples indicating a relatively small melt effect (Hirth and Kohlstedt 1995). Experiments on olivine aggregates synthesized from reagents using sol-gel methods (hereafter we call Sol-gel olivine) showed that the 4% melt-doped samples had a factor of 50 lower viscosity compared to non-doped samples indicating a very large melt effect. These previous studies have difficulties in determination of precise melt effect, 0.5 to 1 vol. % melt was observed even in non-doped naturally-derived samples presumably due to impurities (Hirth and Kohlstedt 1995). The change in viscosity due to adding of melt phase in sol-gel olivine can be due to the effect of impurities at grain boundaries which is known to have a large effect on the strength of polycrystalline oxide (e.g. Yoshida et al. 1997).

In this study, we synthesized olivine aggregates with and without impurities (CaO and Al_2O_3) by using a new technique and conducted high-temperature creep experiment on such synthesized olivine aggregates to investigate effects of chemical composition and presence of the melt phase on the creep properties of olivine aggregates.

The aggregates were prepared by applying vacuum sintering to nano-sized olivine powder synthesized from highly pure and fine-grained (<100 nm) raw powders (Koizumi et al 2010). Olivine aggregates with and without dopants of <1 wt% Al_2O_3, CaO, were prepared. Deformation tests on these samples showed that non-doped samples were deformed by grain boundary diffusion creep mechanism with no major difference in strength between non-doped and impurity-doped samples at temperatures below solidus of impurity-doped samples, while a reduction of a factor of 6 in viscosity was observed in impurity-doped samples with 0.05 vol. % melt at temperatures above solidus. FTIR analysis showed that both synthesized and deformed samples were dry. The strength of the non-doped samples was essentially identical to the aggregates by Faul and Jackson (2007), thus the difference in strength between previous studies can be explained solely by melt effect on olivine rheology.

Keywords: diffusion creep, olivine aggregates, chemical effect, melt effect, rheology

Water sensitivity of the rheology and seismic properties of upper-mantle olivine

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Hydrous, but water-undersaturated, conditions for the fabrication and mechanical testing of synthetic olivine polycrystals have been achieved within internally heated gas-medium high-pressure apparatus. Enclosure of specimens within a Pt capsule rather than the usual Ni-Fe sleeve results in significantly more oxidising conditions and a relatively high water fugacity. Exposure of Ti-doped olivine to these conditions results in the creation and preservation of an extended defect involving Ti/Mg substitution, charge balanced by double protonation of a neighbouring Si vacancy. Fully synthetic solution-gelation derived Fo_{90} olivine, doped with 660-1940 atom ppm Ti/Si, was hot-pressed and then deformed in Pt capsules at 300 MPa confining pressure and temperatures of 1200–1350°C. Due to the enhanced grain growth under hydrous conditions, the samples were at least three times more coarse-grained than their dry counterparts and deformed by power-law creep at differential stresses as low as a few tens of MPa. The data define an essentially linear relationship between strain rate and the concentration of chemically bound hydroxyl, inferred from the intensity of infrared absorption bands at 3572 and 3525 cm^{-1} diagnostic of the Ti-hydroxyl defect. The observed rheology is broadly consistent with the hydrous rheology previously determined for olivine under water-buffered, and therefore saturated conditions. However, in contrast with previous interpretations, we conclude that extrinsic defects (involving the Ti impurity) in olivine play the dominant role in water weakening of the Earth’s upper mantle (Faul et al., *EPSL*, 2016). Concerning seismic properties, similarly prepared Ti-doped olivine polycrystals, have been sleeved in Pt for mechanical testing in torsional forced oscillation under water-undersaturated conditions. The observed mechanical behavior is of the high-temperature background type involving monotonically decreasing shear modulus and increasing dissipation with increasing oscillation period and increasing temperature. The modulus dispersion and dissipation, thus measured under water-undersaturated conditions, are markedly stronger than for a similarly prepared specimen, tested dry within an Ni-Fe sleeve under more reducing conditions. The contrasting seismic properties of the hydrous and dry specimens suggest an important role for the chemical environment (changes of f_{O2} and f_{H2O}) in the viscoelastic relaxation responsible for reduced seismic wave speeds and attenuation in the Earth’s asthenosphere (Cline et al., *Nature Geoscience*, submitted).

Keywords: olivine rheology, water weakening, seismic wave dispersion and attenuation

Temperature dependency of the electrical grain boundary transport in forsterite aggregates

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The grain-size-dependency on the electrical conductivity of fine-grained forsterite aggregate was found and attributed to grain boundary diffusion of charge carriers as a main conduction mechanism in the aggregate (ten Grotenhuis et al., 2004). Such result indicates that the electrical conductivity measurement can be used to detect physicochemical changes of grain boundaries with changing temperature and bulk chemistry. We conducted impedance measurements on forsterite aggregates with different grain sizes and secondary phases (e.g., forsterite + enstatite and forsterite + diopside) under a gradual change in temperature in order to obtain temperature (*T*) and grain size (*d*) dependency of the electrical conductivity (*s*).

Synthetic samples of forsterite + enstatite (solidus temperature T_m = 1557 C) and forsterite + diopside system (T_m ˜ 1350 C) were prepared from the powders of $Mg(OH)_2$, SiO_2 and $CaCO_3$ (50 nm). Impedance measurements were carried out every 2 ˜ 5 minutes during annealing at the highest temperature (1300 ˜ 1400 C) for 50 hours and during subsequent gradual cooling down to 1000 C.

Impedance measurements of both forsterite + enstatite and forsterite + diopside during their annealing show grain-size-dependency of their electrical conductivities as $s \propto 1/d$, indicating that the electrical conduction mechanisms are grain boundary transport of the charge carriers in both aggregates.

Impedance measurement during the cooling of forsterite + enstatite shows Arrhenius type of temperature dependency of electrical conductivity which changes with temperature ranges such as the dependency well described by activation energy of 240 kJ/mol at 1000 ˜ 1150 C, 290 kJ/mol at 1150 ˜ 1350 C and 320 kJ/mol at 1350 ˜ 1400 C. Forsterite + diopside exhibits stronger temperature dependency than a simple Arrhenius type dependency providing apparent activation energy ranging from 180 kJ/mol to 1000 kJ/mol at temperature from 1000 C to 1350 C (= sample solidus). We will discuss such temperature dependencies based on structural and/or chemical changes of grain boundaries in these systems.

Keywords: Electrical conductivity, Grain boundary, Grain size dependence

Thermal & petrological structure of lithospheric mantle deciphered from xenoliths from Ichinomegata, NE Japan.

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Mantle xenoliths are important sources of information on thermal and petrological structure of lithospheric mantle and its temporal variation. Extraction of such information from xenoliths in arc settings is critical to understand evolution of wedge mantle. However, our knowledge on arc lithosphere is limited because of lack of reliable geobarometers for plagioclase- and spinel-peridotites. We have conducted geothermobarometry on carefully selected pairs of minerals and their chemical compositions, and successfully gained reasonable pressure estimates. This allows us to construct reliable thermal and petrological structure and its temporal variation of the mantle beneath NE Japan arc.

Ichinomegata volcano is a latest Pleistocene maar in Oga peninsula, NE Japan. Peridotite xenoliths occur as inclusion in basaltic to dacitic pyroclastic rocks (Katsui et al. 1979). The MOHO depth beneath Ichinomegata is estimated as 28 km (Zhao et al. 1992), and the depth of lithosphere-asthenosphere boundary (LAB) was estimated to be close to that of Japan Sea (ca. 60 km; Zheng et al. 2011). Eight lherzolite and one wehrlite samples were examined. Three samples contained plagioclase and/or pyroxene-spinel symplectite after plagioclase (Takahashi, 1986), and six samples were spinel-peridotite. They are also grouped into two types: equigranular samples with etching pits on void surfaces indicating a fluid phase, and porphyroclastic samples with interstitial glass suggesting a melt phase.

We analyzed chemical zonings of orthopyroxene and clinopyroxene using EPMA to pinpoint compositional pairs where equilibrium conditions are preserved. Four patterns of the chemical zonings of Ca, Al, and Cr due to temperature (T) changes are distinguished. They indicated 1) simple and gradual T decrease, 2) gradual T decrease followed by rapid and weak T increase, 3) gradual T decrease followed by rapid and strong T increase, 4) faint T increase. The prograde zonings observed in (3) are referred “preheating” in Takahashi (1980). On the basis of the zoning patterns and consideration on diffusional time scale, the most appropriate pairs of chemical compositions and minerals preserving pressure and temperature information just before xenolith extraction were identified for geothermobarometry.

The essential strategy in the choice of geothermobarometers is based on the fact that Al and Cr effects on geothermobarometries are very difficult to evaluate which is actually included in several thermobarometers (e.g. Lindsley 1983; Tayler 1998; Nimis and Taylor 2000; Putirka 2008). This is because response of the solubility of Al and Cr in pyroxene to pressure and temperature changes is different for plagioclase, spinel, and garnet peridotites (Gasparik 2003). We thus used T_{BKN} and $T_{Ca\text{-}in\text{-}Opx}$ (Brey and Köhler 1990), since the effects of Al and Cr contents are less important.

The estimated pressure ranges from 0.7 to 1.6 GPa, which correspond to a depth range from 28 to 54 km (± 6 km), and the estimated temperature ranges from 831 to 1084 ˚C (± 9 ˚C). The pressure values are well within the range of lithosphere, and the temperature values are consistent with those of previous studies (e.g. Takahashi 1980; Takahashi 1986; Abe and Arai 2005).

According to the pressure estimate, we can construct thermal and petrologic structure beneath Ichinomegata. Samples derived from the deeper level (1.1-1.6 GPa) were “preheated” (up to 1016-1084 ˚C), and samples from the shallower depth (0.7-0.9 GPa) stayed at low temperature (832-905 ˚C) without such “preheating”. Systematic depth variations of various features of the xenoliths are identified: the change of Al-phases from plagioclase to spinel, the change of interstitial phases from fluid to melt, and change of microstructure from equigranular to porphyroclastic textures. The consistent depth dependent transitions might correspond to those expected in the thermal and rheological boundary

layers near LAB controlled by wet-solidus.

Keywords: wedge upper mantle, thermal structure, rheological structure