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Constraints on seismic velocity anomalies beneath the Siberian craton from xenoliths and petrophysics

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Abstract

High seismic Vp velocity anomalies (8.7–9.0km s^{-1}) have long been known about in regions of the uppermost mantle of the Siberian craton, often in association with kimberlite fields. Laboratory measurement of seismic properties of five xenoliths, three peridotites and two eclogites, from the Udachnaya kimberlite under confining pressures up to 600 MPa were extrapolated to uppermost mantle P–T conditions of 1500 MPa and 500 °C, however none of the velocities are high enough to explain the observations. Eclogites or peridotites are commonly considered to be the source of anomalous high velocities. We prefer a peridotitic source to an eclogitic source due to the unusual chemistry and regional uniformity of eclogitic garnets required, maximum velocity limitations on laboratory measurements of seismic properties of natural eclogites, and purported abundance of eclogites in the lithosphere. Alternatively, a highly depleted peridotite, such as dunite or harzburgite, can produce velocities high enough to match observations. Olivine petrofabrics in most peridotites, including the three peridotites used in this study, are great enough to produce the observed high velocities provided olivine petrofabrics are continuous enough and correctly oriented to be seismically detectable and the modal proportion of olivine is high. There have been suggestions by other authors that the Siberian upper mantle is highly depleted and that a lithosphere-scale shear zone exists, which may have acted to organize fabrics into segments large enough for detection. Anomalously high Vp–Vs velocity ratios of greater than 1.8 are expected parallel to the olivine [100] maxima required to be present in a high-velocity olivine-dominated upper mantle. Vp–Vs velocity ratios can serve as a means of inferring large-scale anisotropy when limited seismic data are available, as in Siberia. © 2006 Elsevier B.V. All rights reserved.

Keywords: Lithospheric mantle; Seismic anisotropy; Peridotite; Eclogite; Siberia; Petrofabric

1. Introduction

Investigations of the Siberian craton by the former Soviet Union in the late 1970s and early 1980s with long-range reversed seismic refraction profiles revealed anomalously high uppermost-mantle P-wave velocities, some approaching 9.0 km/s (Yegorkin and Pavlenkova, 1981; Fuchs and Vinnik, 1982; Egorkin and Chernyshov, 1983; Pavlenkova et al., 1996; Suvorov et al.,

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1999; Suvorov et al., 2006). Recent seismic tomographic inversion of data from the KRATON profile has confirmed these interpretations of very high velocity (Nielsen et al., 1999). The highest velocities are located just below the seismic Moho in distinct high velocity "blocks" (Pavlenkova et al., 1996, Suvorov et al., 2006), often associated with kimberlite groups. In a comparison of the seismic data with other geophysical data including gravity and magnetics, Pavlenkova et al. (1996) demonstrate that potential field anomalies do not correlate with the high velocities and Fuchs (1979, 1983) concludes that the anomalous velocities are most likely due to velocity anisotropy in upper mantle peridotites.

The exact nature of this anisotropy remains unclear. More detailed deep seismic sounding data collected over the past few decades in the Yakutia province of the Siberian Platform (Suvorov et al., 1999; Suvorov et al., 2006) and teleseismic data collected across the platform (Oreshin et al., 2002) have improved the data set, but as yet have been unable to clearly explain the observations. Oreshin et al. (2002) argue that the seismic anomalies are undoubtedly due to anisotropy, but the anisotropy is likely not simple. Anisotropy in the upper-most cratonic mantle is most probably controlled by fabrics originating from ancient tectonic processes and is not representative of anisotropy in the asthenospheric mantle as detected by SKS splitting (e.g., Vinnik et al., 1992; Saruwatari et al., 2001; Christensen et al., 2001).

Suvorov et al. (2006) present interpretations of seismic refraction data along two perpendicular profiles that cross close to the Mirnyi kimberlite field. They demonstrate the existence of extremely high Pn velocity (>8.7 km/s) in the sub-Moho mantle along most of one of the profiles and along parts of the other profile. However, the geometry does not allow determination of the cause of these high velocities, i.e. whether or not they are caused by anisotropy, because of abrupt changes between the high velocity of 8.7 km/s and the "normal" velocity of 8.1 km/s. Given that teleseismic shear wave fast polarizations are not parallel in orientation with high P-wave velocities from deep refraction data, it is clear that there are differences in anisotropy with depth, perhaps due to a change in olivine slip systems (Li et al., 2003; Mainprice et al., 2005). Deeper anisotropy must be controlling shear wave splitting and is rather consistent across the craton, where refraction studies indicate an irregular velocity structure in the shallower portion of the upper-most mantle.

Anisotropy is likely the causes of both shear wave splitting and high refraction velocities beneath the Siberian craton. We have taken two approaches to better understand the nature of this anisotropy. First, xenoliths of deep origin from the Udachnaya kimberlite field, located in central Siberia, were analyzed for both laboratory-measured seismic velocities and olivine lattice preferred orientation. Second, published data from samples of the upper-most mantle from other regions in the world combined with single-crystal elastic data have been used to constrain possible origins of the anomalously high P-wave velocities present in the upper-most mantle of Siberia.

2. Geologic setting and sample description

The Siberian craton (Fig. 1) comprises the stable core of the Asian continent, with an area of approximately 4×10^9 km^2. Riphean–Phanerozoic sediments with an average thickness of 4 km overlie the basement (Rosen, 2003). The basement can broadly be divided into two lithologies: granulite–gneiss and granite–greenstone. Phanerozoic fold belts surround the craton, as is the case with many continental shields worldwide.

The Siberian craton was brought together in its current configuration in the period from about 1.9 to 1.8 Ga. This involved the amalgamation of several previously independent "super terranes" each composed of many smaller terranes of widely varying age, between 3.5 and 2.5 Ga (Rosen, 2003; references therein). The outline of the major super terranes (Fig. 1) has mainly been determined geophysically since the contacts are often concealed beneath sedimentary and/or glacial cover. The Udachnaya kimberlite pipe, denoted by a star in Fig. 1, is contained in the Daldyn kimberlite field, located in the Anabar province of the shield. In addition to the Daldyn field, there are a number of other kimberlite fields within a few hundred kilometers including the Mirny, Alakit, and Mun (Rosen, 2003).

It has been argued that kimberlites preferentially exploit pre-existing structural weaknesses to reach the surface (White et al., 1995; Vearncombe and Vearncombe, 2002). Many of the kimberlites of the Siberian craton occur along the suture zones of the terranes and super terranes, especially in places where these sutures intersect with other smaller scale structural elements. These fault zones, many of which have recognizable thrust components, are usually large, crustal or perhaps lithospheric scale structures (Griffin et al., 1999; Poudjom Djomani et al., 2003).

We have selected five xenolith samples from the Udachnaya kimberlite for study. Three of these rocks are peridotites; two being sheared garnet lherzolites (samples UV04 and UV05) and one a coarse grained

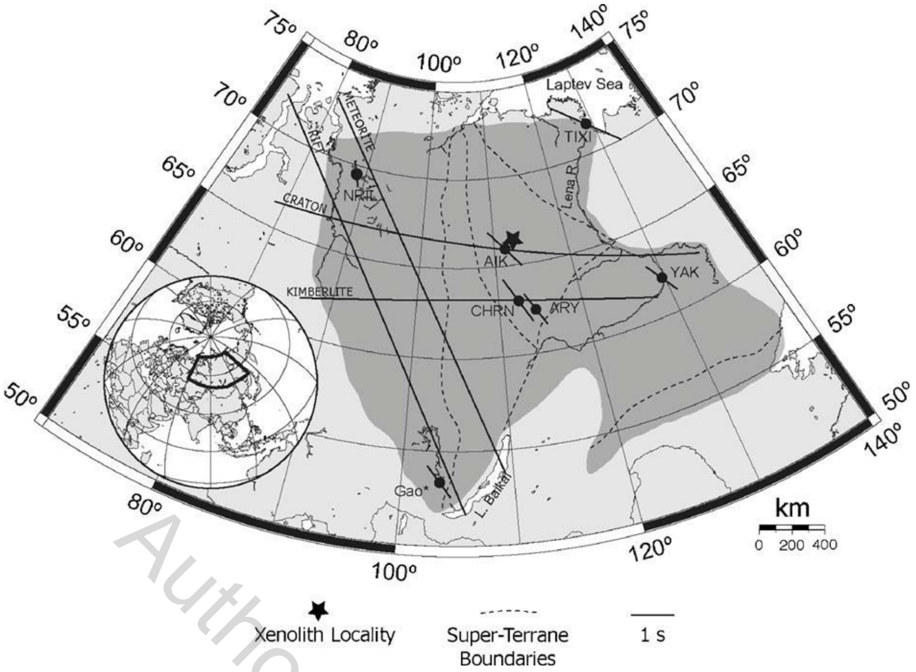


Fig. 1. A map of NE Asia. Shaded region is the Siberian craton, which is divided into super-terranes (dashed lines). Circles are the broadband seismic stations of Oreshin et al. (2002), with shear wave splitting shown by short lines proportional to delay time and parallel to fast polarization azimuth. Long lines are the long-range seismic profiles completed by the former Soviets. Gao* is a combination several shear wave splitting measurements from Gao et al. (1997). The Udachnaya kimberlite pipe, denoted by a star, is contained in the Daldyn kimberlite field, located in the Anabar province of the shield. In addition to the Daldyn field, there are a number of other kimberlite fields within a few hundred kilometers including the Mirny, Alakit, and Mun (Rosen, 2003).

garnet harzburgite (sample UV03). The sheared lherzolites (Fig. 2a) have a mosaic porphyroclastic texture (Mercier and Nicolas, 1975), with garnets, orthopyroxene, and rarely olivine forming the porphyroclasts. The harzburgite has a mosaic equigranular texture (Fig. 2b), with many olivine grains showing kink banding and signs of intracrystalline deformation. The remaining two rocks are eclogites, one of which is strongly sheared (sample UV01), the other being coarse grained (sample UV02). Both eclogites display slight retrogression in the form of kelyphite rims on garnet. The sheared eclogite contains approximately 30% garnet and 70% clinopyroxene, while the coarse eclogite is more garnet-rich, containing approximately 60% garnet and 40% clinopyroxene.

The Udachnaya kimberlite was emplaced during Late Paleozoic time, approximately 360 Ma (Kinny et al., 1997). There have been no major tectonic events within the Siberian craton involving plate collisions since this time, which would strongly modify the fabrics and associated anisotropy (Silver and Chan, 1991). In the following analyses, it is assumed that the xenolith grain fabrics from the Udachnaya kimberlite field are representative of the modern upper mantle in the region.

3. Seismic properties

There are two petrophysical data sets commonly used for interpreting mantle anisotropy: (1) calculated anisotropies and seismic velocities based on mineral lattice preferred orientation data, mineral elastic constants and their temperature and pressure derivatives (e.g., Crosson, 1971; Christensen and Lundquist, 1982; Mainprice and Silver, 1993), and (2) measured seismic velocities from high pressure laboratory experiments (e.g., Birch, 1960; Christensen, 1966; Kern, 1993; Kern et al., 1996).

3.1. Olivine petrofabrics

Olivine lattice preferred orientations were measured on the three peridotites with a five axis universal stage using the methods described by Emmons (1943). For each rock 100 olivine grain orientations were measured on a grid encompassing a broad area of the thin section. Velocity surfaces were calculated using software provided by Mainprice (1990). Since fabric information was not available for other phases, these calculations assume a pure olivine rock and do not account for other phases. Fabric data and velocity calculations are shown in Fig. 3.

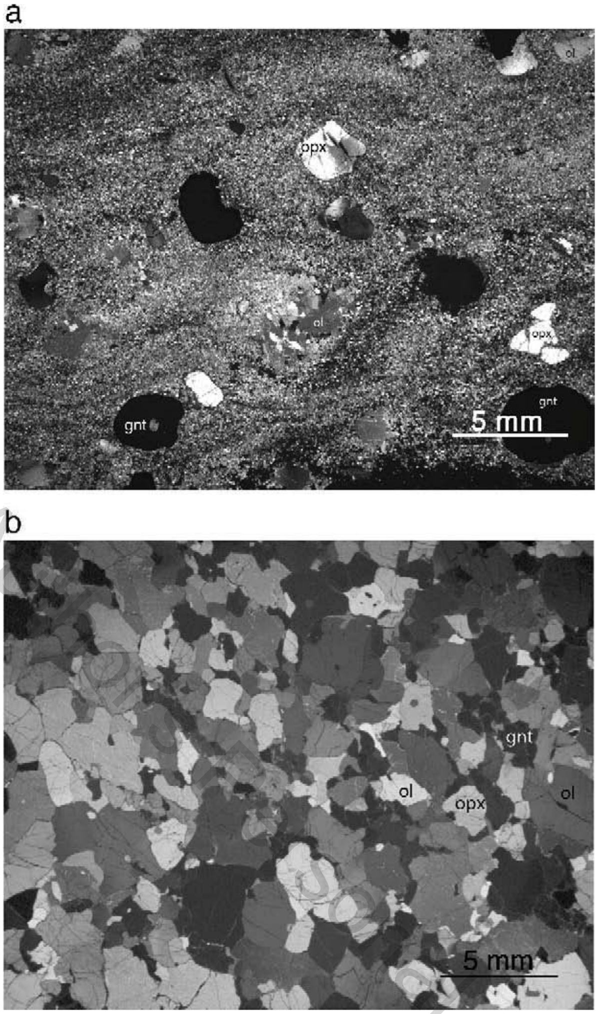


Fig. 2. Photomicrographs of sample UV04, sheared garnet lherzolite (a) and sample UV03, coarse-grained garnet harzburgite (b). ol =olivine, opx=orthropyroxene, and gnt =garnet.

Orthopyroxene is the next most abundant phase in these rocks, however, orthopyroxene fabrics have different elastic symmetry than olivine fabrics (Christensen and Lundquist, 1982), and so reduce or “dilute” bulk seismic anisotropy (Ben Ismail and Mainprice, 1998). Compared to olivine and orthopyroxene, clinopyroxene displays much weaker fabrics (Mauler et al., 2000; Bascou et al., 2001), again resulting in lower anisotropy as well as lower maximum seismic velocities. Garnets are almost elastically isotropic and so reduce the total rock anisotropy, but, depending on chemical composition, may actually increase maximum seismic velocities (Babuska et al., 1978).

We are interested in finding the maximum compressional wave velocity attainable from these rocks. The peridotites contain approximately 75% olivine, and as discussed above, olivine will control the anisotropy of olivine-rich rocks. Therefore, we expect to be able to locate the direction of maximum compressional wave velocity in each peridotite sample with a reasonable amount of accuracy using the fabric data from olivine alone.

3.2. High pressure laboratory experiments

All five samples were cored for seismic velocity measurements at elevated confining pressures using the ultrasonic pulse transmission method (Birch, 1960; Christensen, 1985). Two cores were taken from each of the three peridotites. Using the fabric data (Fig. 3)asa guide, one core was taken parallel to the calculated maximum compressional wave velocity and the other parallel to the direction calculated to have the greatest

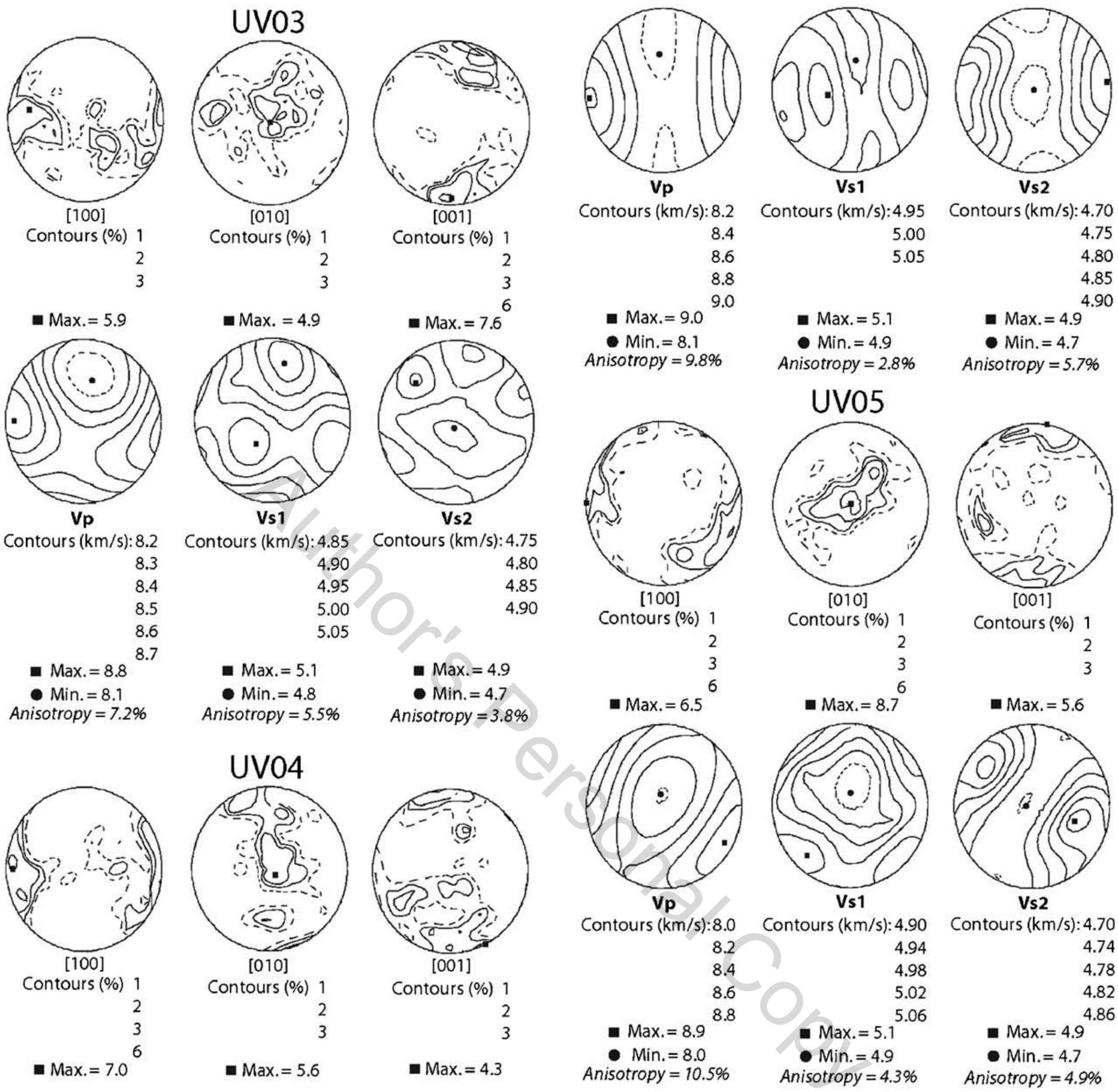


Fig. 3. Olivine petrofabrics and seismic velocity calculations for the Udachnaya peridotites. The results are shown on six equal-area nets with lower hemisphere projections. The first three are Schmitt contoured density plots of the crystallographic axes of olivine. The following three are plots of compressional wave velocity and the velocity of both the fast (Vs1) and slow (Vs2) shear waves. In each case, foliation is in the plane of the paper. The velocities have been computed at room temperature and pressure.

shear wave splitting. Three orthogonal cores were taken from the eclogite samples for velocity measurements. The sheared eclogite contains a strong foliation and lineation, so cores were aligned with respect to these fabric elements. The coarse eclogite has no macroscopic fabric. Velocity data are given in Table 1. The results from a single high-pressure experiment on sample UV04 (sheared garnet lherzolite) are shown in Fig. 4, displaying the rapid increase in velocity due to the closing of microcracks with increasing pressure, which is followed by a change to an approximately linear relationship of velocity with confining pressure. All measurements were made at room temperature and confining pressures up to 600 MPa. Velocities up to pressures of 1500 MPa were extrapolated using the least squares method (Wepfer and Christensen, 1991), however this method may overestimate actual velocities at 1500 MPa by a small amount if microcracks are not

Table 1 Measured velocities (km s^{-1}) of Udachnaya xenoliths at various confining pressures and room temperature

			Density (kg/m^3)	Confining pressure (MPa)					
				20	50	100	200	400	600
UV01-A-Vp	Sheared eclogite	Normal to foliation	3222	7.001	7.215	7.341	7.393	7.471	7.518
UV01-B-Vp		Par. foliation, perp. lineation	3307	7.075	7.589	7.663	7.719	7.776	7.809
UV01-B-VsA		Par. foliation, perp. lineation	3307	3.657	3.843	3.984	4.089	4.164	4.206
UV01-C-Vp		Par. foliation, par. lineation	3255	7.359	7.431	7.522	7.643	7.759	7.802
UV02-A-Vp	Eclogite	No macroscopic fabric	3459	8.066	8.092	8.121	8.160	8.213	8.252
UV02-A-Vs			3459	4.409	4.502	4.550	4.578	4.603	4.617
UV02-B-Vp			3433	7.905	7.969	8.001	8.042	8.084	8.108
UV02-C-Vp			3415	7.513	7.843	7.899	7.945	7.991	8.018
UV03-VpMax-Vp	Coarse garnet harzburgite	Par. calculated max Vp	3282	8.156	8.224	8.263	8.298	8.344	8.381
UV03-dVsMax-Vs1		Par. max Vs splitting	3274	4.575	4.716	4.761	4.792	4.823	4.841
UV03-dVsMax-Vs2			3274	4.560	4.592	4.616	4.640	4.664	4.679
UV04-VpMax-Vp	Sheared garnet lherzolite	Par. calculated max Vp	3285	7.975	8.284	8.383	8.475	8.567	8.622
UV04-dVsMax-Vs1		Par. max Vs Splitting	3300	4.542	4.587	4.632	4.683	4.730	4.749
UV04-dVsMax-Vs2			3300	4.310	4.374	4.425	4.478	4.525	4.551
UV05-VpMax-Vp	Sheared garnet lherzolite	Par. calculated max Vp	3342	7.860	7.992	8.093	8.197	8.301	8.364
UV05-dVsMax-Vs1		Par. max Vs splitting	3293	4.080	4.550	4.610	4.652	4.696	4.723
UV05-dVsMax-Vs2			3293	4.270	4.345	4.403	4.462	4.522	4.558

completely closed, which is possible considering the exhumation history of these xenoliths.

The measured velocities are lower than the calculated velocities from lattice preferred orientations for the peridotites due to the simplifications of modal mineralogy implicit in the calculations. The measured maximum velocities are 0.32 to 0.46 km/s lower than calculated velocities at expected temperature and pressure conditions for Siberia. Similar observations have been reported for fresh mantle peridotites from California (Soedjatmiko and Christensen, 2000). One of the eclogite samples (UV02) has velocities comparable to the peridotite samples, but the other sample (UV01) is much lower, probably due to the prevalence of interstitial alteration products.

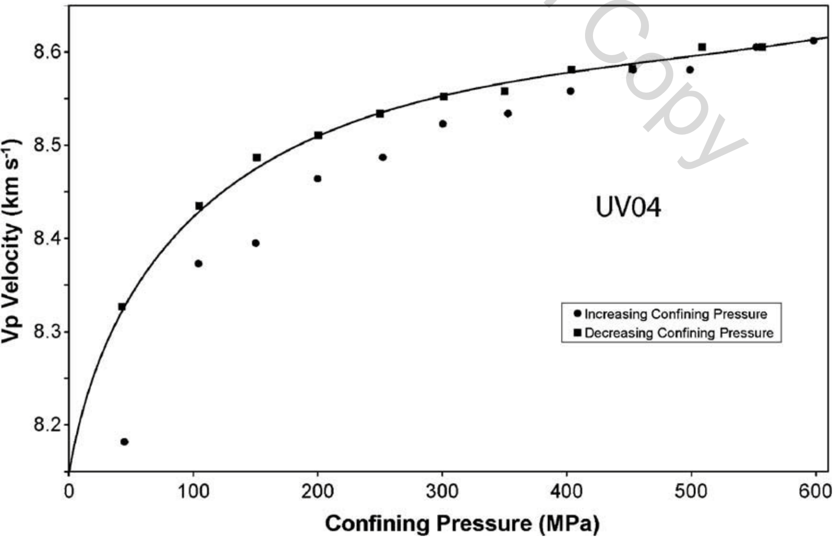
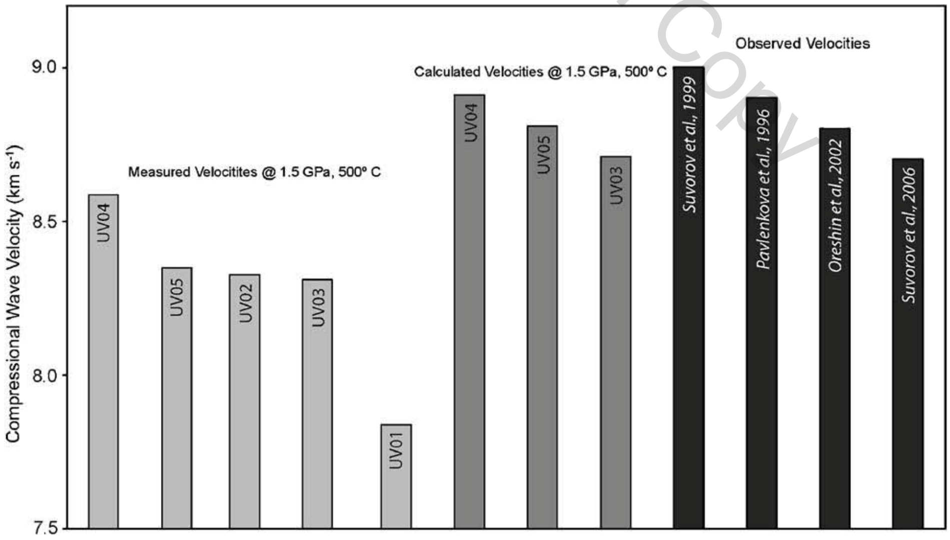


Fig. 4. Compressional wave velocity versus increasing and decreasing confining pressure for sample UV04. Velocities increase rapidly with increasing confining pressure as microcracks are closed. A least squares best-fit line is displayed through decreasing confining pressure points (see text for discussion). Some hysteresis is observed due to some microcracks staying closed as pressure is reduced.

4. Seismic observations below the Siberian craton

Shear-wave splitting parameters are relatively consistent across the Siberian Platform, including the three temporary broadband stations CHRN, ARY, and AIK of Oreshin et al. (2002) nearest the site of origin for the xenoliths used in this study (Fig. 1). This suggests that the anisotropy responsible for these observations is consistent throughout the region. SKS wave fast polarization directions do not parallel the available fast P-wave azimuths suggesting that the anisotropy changes with depth. It is generally thought that velocity anisotropy of teleseismic waves such as SKS is due to anisotropy present in approximately the upper 400 km of the earth (Vinnik et al., 1992; Saruwatari et al., 2001; Christensen et al., 2001), although recent experimental work has questioned the relative contribution and symmetry of anisotropy with respect to depth (Mainprice et al., 2005; Li et al., 2003). Analysis by Oreshin et al. (2002) of the P-wave refraction data from four long-range profiles (Fig. 1) implies that variations in the P-wave travel times for depths less than about 150 km are non-systematic, suggesting strong lateral heterogeneity and/or anisotropy. These findings are supported by the complicated velocity fields observed by Suvorov et al. (1999, 2006) with shorter epicentral distance arrays, which sample the shallow regions of the mantle compared to the longer arrays used by Oreshin et al. (2002) and Nielsen et al. (2002). At epicentral distances between 1400 and 2000 km, variations in first arrivals are systematic, indicating coherent anisotropy parameters below depths of 150–200 km (see also Thybo and Perchuc, 1997).



At this time it is not clear what the orientation or nature of anisotropy is in the region above 150 km depth. The interpretation of newly digitized vintage seismic data from around the Mirnyi kimberlite is unfortunately not conclusive regarding the issue of anisotropy (Suvorov et al., 2006). This problem will benefit from additional seismic experiments.

5. Discussion

Fig. 5 shows a comparison of measured and calculated velocities from the Udachnaya xenoliths with observed velocities from the Siberian craton. Laboratory measurements were made at room temperature, and temperature effects are known to reduce seismic velocities (Christensen, 1979; Kern et al., 1996). The group on the left is the maximum measured compressional wave velocities for each sample at confining pressures of 1500 MPa, which has been corrected to a temperature of 500 °C using thermal derivatives listed by Wang et al. (2005b).This pressure and temperature is a conservative estimate of Moho conditions in Siberia, using a 40 mW/m^2 conductive model geotherm (Pollack and Chapman, 1977; Griffin et al., 1996). The second group are calculated velocities from petrofabric data on the peridotites, again at 1500 MPa confining pressure and 500 °C. The last column of Fig. 5 shows some high velocity observations reported for the Siberian craton (Pavlenkova et al., 1996; Suvorov et al., 1999; Oreshin et al., 2002; Suvorov et al., 2006). Including thermal effects, it is clear that even the maximum measured velocity in these samples cannot account for the observations of high P-wave velocities in the Siberian upper mantle.

Fig. 5. Compressional wave velocities for the Udachnaya xenoliths at elevated pressures and temperatures and observations of compressional wave velocities in Siberia from several authors. Calculated velocities assume a pure olivine rock. Sample velocities have been adjusted for P–T conditions of 1500 MPa and 500 °C, using derivatives from Christensen (1989) and Wang et al. (2005b).

5.1. Peridotites and eclogites

There are two lithologies commonly considered to cause high-velocity anomalies in the upper mantle: olivine rich peridotite with a strong crystallographic orientation (e.g., Musacchio et al., 2004)orUHP eclogite of crustal origin (e.g., Wang et al., 2005a,b). We prefer a peridotitic source for the high velocities based on the following arguments:

(1) Of the upper mantle rock-forming minerals orthopyroxene, clinopyroxene, garnet, and olivine, olivine displays the highest seismic velocity (9.87 km/s) for one crystallographic direction (Kumazawa and Anderson, 1969; Kumazawa, 1969; Wang and Simmons, 1974; Christensen, 1989; Bhagat et al., 1992). Deformation experiments on (e.g., Carter and Ave'Lallemant, 1970) and observation of (e.g., Nicolas and Christensen, 1987; Ben Ismail and Mainprice, 1998) natural peridotites show that olivine displays the highest fabric strength and controls bulk seismic wave velocities of peridotites. Eclogites display much weaker fabrics and anisotropy (Bascou et al., 2001; Mauler et al., 2000; Ji et al., 2003; Wang et al., 2005a,b), however bulk seismic velocities can remain high if the modal fraction of garnet is high. Garnets show a range of compressional wave velocities based on composition (Babuska et al., 1978; Christensen, 1989). Most relevant to eclogites is the pyrope–almandine series. End-member pyrope has compressional wave velocities of 9.13 km/s, while almandine is much lower at 8.42 km/s under ambient conditions. Eclogitic garnets display highly variable magnesium number (100 × Mg / (Mg + Fe)), from just over 80 to less than 30 (Schulze, 2003). Therefore, producing seismically observable anomalously high velocities would require a body of eclogite to posses both a high modal proportion of garnet and a high magnesium number, continuously in a large volume. Alternatively, mantle peridotites vary much less in major-element composition and need only have consistent fabric orientation over a large area, which have been observed in continental massifs (Christensen, 1971, 2002, 2004).

(2) Laboratory measurements of compressional wave velocities in eclogites are not high enough to explain the observations in Siberia, while there are reports in the literature of peridotites with velocities high enough to account for the observations (Christensen, 1966; Christensen and Ramananantoandro, 1971). There have been many observations of seismic velocities in eclogite at elevated pressures and temperatures from multiple sources, such as Norway, the Czech Republic, and Dabieshan (e.g., Christensen, 1974; Kern et al., 1999; Kern et al., 2002; Zhao et al., 2001). Recent work by Wang et al. (2005a) in the Dabie–Sulu orogenic belt contains the highest reported velocities for eclogite. They propose the relation $Vp = 8.42 + (1.41 \times 10^{-4} P) - (1.348 \times 10^{-4} T)$ for the highest velocity, “Type-1” eclogites, where Vp is in km/s, P is in MPa, and T is in °C. If we assume conditions of 1500 MPa and 500 °C just below the Moho in Siberia, the resulting velocity is 8.56 km/s, which is not high enough to explain the observations.

(3) Eclogite is likely a volumetrically insignificant component of the upper mantle, particularly in cratonic areas, which have been well sampled by kimberlites. Statistical counting studies of xenoliths from kimberlites are absent from the literature, however, Sobolev (1990) estimates mantle xenoliths from the Udachnaya pipe as 60% high-T garnet peridotites, 15% low-T garnet peridotites, 11% spinel peridotites, 4% eclogites, 3% pyroxenites, 3% dunites, and 4% other. Xenolith suites from some pipes, such as Roberts Victor in South Africa, are reported to be nearly entirely composed of eclogite, however the xenocryst suite from the same kimberlite is dominated by garnets of peridotitic origin indicating a bias toward preservation of eclogite xenoliths during emplacement and subsequent weathering (Schulze, 1989). Shulze goes on to state that this is true of many famous eclogite xenolith localities (e.g., Bobbejaan, Zagadochnaya, Orapa) based on analysis of garnet concentrates, and considering xenoliths and xenocrysts in kimberlites as a whole, concludes that the upper 200 km of the mantle is no more than one percent eclogitic by volume.

We suggest the most likely candidate for the source of these high velocities is a highly depleted and common mantle rock such as dunite or harzburgite. There are some occurrences of dunite xenoliths from Udachnaya, but as Boyd et al. (1997) point out, the dunites are very friable and may be a more significant upper mantle rock type than xenolith proportions would indicate. Also, from a study of garnet xenocrysts in heavy-mineral concentrate from Siberia, Griffin et al. (2005) give indirect evidence of a depleted upper mantle based on the minimum depth of garnet xenocryst origin and the depth of the garnet–spinel transition.

There are reports in the literature of laboratory measurements of seismic velocity of dunites exceeding 9.0 km/s at 1000 MPa and room temperature (Christensen, 1966; Christensen and Ramananantoandro, 1971; Christensen, 1971). After temperature effects are taken into account for these samples, they provide velocities high enough to account for the observations in Siberia. Additionally, calculated maximum compressional wave velocities from olivine petrofabrics are high enough to explain most of the observed velocities. As discussed earlier, these calculations represent a maximum velocity for our samples due to simplifications in modal mineralogy as well as temperature effects (Kern et al., 1996; Soedjatmiko and Christensen, 2000), however, as we are considering the observed seismic velocities in the mantle to be due to anisotropy of dunites, these fabrics can still be useful as an indicator of the deformation history and fabric strength of peridotites in the Siberian upper mantle.

Since we only have three peridotite samples, it is necessary to look at a broader sample of peridotite fabrics, such as those of Mainprice and Silver (1993), Ji et al. (1994), Kern et al. (1996),and Christensen et al. (2001).In each of these studies, the individual olivine grain fabrics are of similar or greater intensity than the fabrics reported here. Seismic velocity calculations by Mainprice and Silver (1993), Ji et al. (1994),and Kern et al. (1996), however, are significantly lower than would be required in Siberia due to the fact that in their samples and calculations they have included appropriate modal proportions of pyroxene and garnet/spinel, which reduce anisotropy and bulk seismic velocity. Ben Ismail and Mainprice (1998) argue that peridotites acquire significant anisotropy at relatively low fabric strength and that fabric pattern and geodynamic environment only have a small effect on overall seismic properties. If seismic properties of peridotites in the upper mantle are essentially independent of geodynamic environment and fabric symmetry, and observations of olivine fabrics in natural samples are all of similar intensities, then the maximum observable seismic velocities depend mainly on sample modal abundances and the continuity of fabric over broad areas.

While highly depleted rocks such as dunites produce high seismic velocities at relatively modest lattice preferred orientation strengths, it is unusual that fabrics would be continuous over a sufficiently large area to be detectable by seismic refraction methods. As discussed by Christensen (2002, 2004), crystallographic fabric tends to vary slightly over relatively small areas. This implies that single samples may not be representative of the overall anisotropy of a larger region. Therefore, in Siberia we might expect there to be either (1) modest fabric strength continuous over a large area or (2) strong fabric, organized into less continuous segments or volumes, as is commonly observed in upper mantle massifs elsewhere in the world. As discussed by Ben Ismail and Mainprice (1998),only relatively modest fabric strength is required to produce significant anisotropy, however, some agent or event is required to impart a coherent fabric pattern over a seismically observable region of the upper mantle. A study of elastic thickness of the Siberian lithosphere by Poudjom Djomani et al. (2003) revealed a zone of anomalous weakness in association with kimberlites in an otherwise strong lithosphere. They have attributed this weakness to a lithospheric scale shear zone, which may be a source of broad, uniform alignment.

5.2. Vp–Vs ratios

Vp–Vs velocity ratios for the refracted phases in the upper mantle provide a means of detecting this anisotropy. Vp/Vs for a randomly oriented aggregate of single crystal olivine (Fo_{93}) using the Voigt–Reuss–Hill average is 1.723 (Kumazawa and Anderson, 1969) under ambient conditions. If we consider Vp/Vs along individual crystallographic axes for olivine single crystals using the velocity of the fast shear wave parallel to that axis, the ratio has a range varying from 2.023, parallel to [100], to 1.581, parallel to [010]. For rocks with non-perfect lattice alignment, the range is much lower, but Vp/Vs is still anomalously high parallel to maximum a-axes concentrations and smaller in other directions.

In order to observe the very high P-wave velocities present in the Siberian upper mantle, there must be nearly horizontal olivine a-axis concentrations. If we measure Vp/Vs parallel to the a-axes concentration, we should observe anomalously high values corresponding to some amount of divergence from the Voigt–Reuss–Hill average. This divergence is summarized in Fig. 6. Real dunites do not behave like either the isotropic Voigt– Reuss–Hill average for olivine, or olivine single crystals, but must show a behavior between these two extremes if the fabric has orthorhombic symmetry. Increasing lattice preferred orientation results in the rock body behaving more like a single crystal and less like an aggregate with random crystallographic orientation (i.e. the Voigt– Reuss–Hill average). Since there is little difference in shear wave velocity parallel to the olivine a-axis, Vp/Vs is virtually the same for either shear wave polarization.

Average Vp/Vs values for eclogite are 1.785 ± 0.044 (Christensen, 1996). Eclogites show low anisotropy (<5%), so their Vp/Vs values are relatively constant

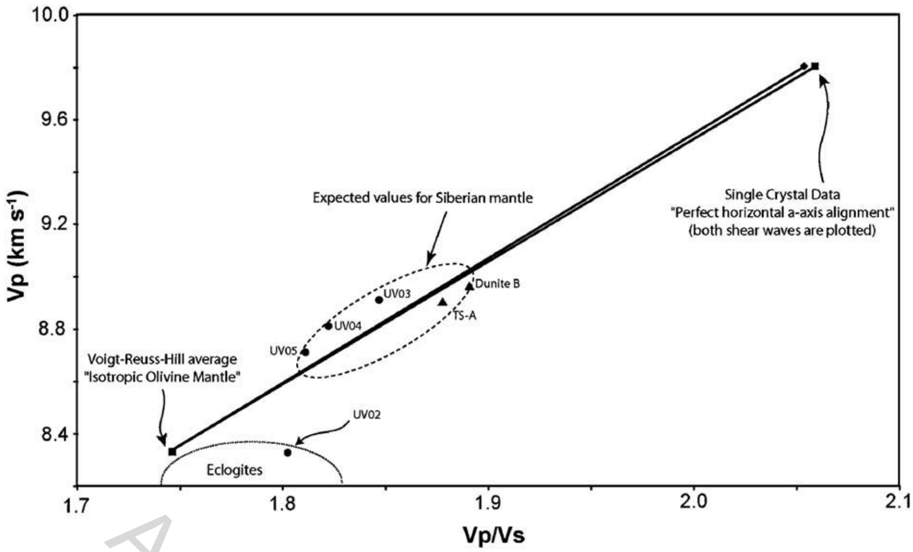


Fig. 6. Vp/Vs versus compressional wave velocity parallel to olivine [100] for increasing crystallographic orientation. The lines represent the gradient between isotropic olivine aggregate and an olivine single crystal. Real Vp and Vp/Vs values must lie somewhere in between, as shown. The separation between the lines is shear-wave anisotropy parallel to olivine [100]. Data points "TS-A" and "Dunite B" are from Christensen (1966) and Christensen and Ramananantoandro (1971), respectively. Samples UV03, UV04, and UV05 are plotted based on velocities from calculations, and sample UV02 is based off of high-pressure experimental data. The eclogite field is from average eclogite data (± σ)of Christensen (1996). All velocities have been adjusted for conditions of 1500 MPa and 500 °C.

with direction. Ranges in values among eclogites are primarily due to different proportions of constituent minerals, secondary alteration, or weak preferred orientation of clinopyroxene. Dunites, however, are almost pure olivine and almost always show lattice-preferred orientations. Since olivine is a highly anisotropic mineral, there can be a much larger range in Vp/Vs for dunites than for other rock types. The range depends on the directions of the Vp/Vs measurements, and the deformation history of the rock. There is not enough data including orientation and deformation history to give a statistically meaningful range, however, we know that there could be a range from the minimum (1.581) to the maximum (2.023). Using observations parallel to the direction of anomalously high P-wave velocity in Siberia, Vp/Vs values versus Vp (Fig. 6) should plot very near the lines and away from the eclogite field. The direct application of this exercise to the Siberian upper mantle requires the measurements of P-wave and S-wave velocities along the same ray paths through the Siberian upper mantle.

6. Summary and conclusions

Seismic refraction surveys across the Siberian craton reveal anomalously high P-wave velocities within the Yakutian kimberlite province and neighbouring regions immediately below the seismic Moho. Measurements of SKS splitting at various points around the Siberian craton (Oreshin et al., 2002) demonstrate a consistent pattern of splitting parameters that is not parallel with the often incoherent pattern of anomalous P-wave velocities. High-pressure seismic experiments were conducted on two eclogite and three peridotite xenoliths from the Udachnaya kimberlite to measure compressional wave velocities. In addition, olivine petrofabric analysis was carried out on the peridotites to identify any anomalies that might indicate a source of unusually high seismic wave speeds. Using these data in combination with data from other rocks and single-crystal experiments, we have arrived at the following conclusions:

(1) The measured velocities from the five xenoliths are not sufficiently large to explain the anomalously high P-wave velocities observed in places on the Siberian craton, especially taking thermal effects on velocity into account.

(2) Eclogite is most likely not the cause of the high velocities because a) no experiments have demonstrated high enough velocities under the same conditions as field observations, b) changing the chemistry of eclogite to increase velocities is not tenable on large scales, and c) there is not enough

eclogite in the cratonic lithosphere to become seismically important.

(3) Dunite is the only common rock type with sufficiently high P-wave velocities to match those observed in the shallow mantle. Laboratory experiments on dunites with moderate crystallographic preferred orientation from other locations, and calculations for dunitic rocks with similar fabric strengths to those observed from Siberia lead to velocities comparable to the observed high velocities, even after corrections for temperature. It is possible that dunite forms a larger component of the cratonic upper mantle than previously thought.

(4) Olivine with favorably oriented horizontal a-axes has sufficiently high velocity to explain the observations. This can potentially be proven by measuring Vp/Vs values in the field, which should show anomalously high values parallel to high P-wave velocities, much higher than average values for other upper mantle rock types.

(5) A lithospheric scale regional shear zone in Siberia, such as the one proposed by Poudjom Djomani et al. (2003), may have influenced the fabrics, making for the unique high velocities observed in Siberia.

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