

Thermal diffusivity of olivine single-crystals and polycrystalline aggregates at ambient conditions—a comparison

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[1] Heat transfer is a key process for the mantle dynamics. However, analysis of experimental data on thermal transport properties of upper mantle materials highlights a large scatter of absolute values of thermal diffusivity. In particular, conduction of heat in single crystals is systematically higher than in polycrystalline samples. Here we present new thermal diffusivity measurements on San Carlos olivine single crystals and mantle rocks at 300K. Measured components of the olivine thermal diffusivity tensor along the [100], [010], and [001] directions are 2.73, 1.70, and 2.49 mm² s⁻¹, respectively. Measurements of thermal diffusivity of peridotites as a function of structural orientation show absolute values and anisotropy in good agreement with those predicted by petrophysical models based on the crystal preferred orientation of olivine and the above thermal diffusivity tensor. This suggests that the upper mantle thermal diffusivity is up to 50% higher than indicated by previous measurements on mantle rocks. **INDEX TERMS:** 5112 Physical Properties of Rocks: Microstructure; 5134 Physical Properties of Rocks: Thermal properties; 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; 8130 Tectonophysics: Heat generation and transport. **Citation:** Gibert, B., F. R. Schilling, A. Tommasi, and D. Mainprice, Thermal diffusivity of olivine single-crystals and polycrystalline aggregates at ambient conditions—a comparison, *Geophys. Res. Lett.*, 30(22), 2172, doi:10.1029/2003GL018459, 2003.

1. Introduction

[2] Thermal diffusivity is the key parameter that controls the temperature distribution as a function of time and, indirectly, through the temperature dependence of density and rheology, the deformation patterns in the mantle. In particular, recent studies have shown the effect of a variable thermal conductivity on convection [Dubuffet *et al.*, 1999] and subduction dynamics [Hauk *et al.*, 1999]. Although thermal transport properties of upper mantle materials have been extensively studied at high pressure and high temperature [e.g., Hofmeister, 1999; Katsura, 1995; Shankland *et*

al., 1979], some important aspects of these properties, like the scale transfer from single crystal properties to rock properties, are still poorly constrained. Indeed, measured thermal diffusivities of upper mantle rocks are 30% lower than the thermal diffusivities predicted by petrophysical models that average the single crystal tensor as function of the crystals orientation distribution [Gibert *et al.*, 2003; Tommasi *et al.*, 2001]. Two assumptions may explain this discrepancy. On one hand, physical parameters controlling heat diffusion in single crystal and polycrystalline scales may differ. Grain boundaries, as well as intracrystalline defaults or microcracks may hinder thermal transfer at the polycrystal scale, due to interactions of phonons with these imperfections [Klemens, 1958]. However, these interactions are expected to be dominant at very low temperature ($\ll 300\text{K}$), but negligible at higher temperatures where phonon-phonon interactions predominate. On the other hand, different methods and experimental setups were used to determine thermal transport properties of single crystals and polycrystalline aggregates: The discrepancy between single-crystal and rock thermal diffusivities may be due to an experimental bias.

[3] In order to test these hypotheses, we measured, using the same transient technique, the thermal diffusivity tensor of olivine single-crystals and polycrystalline aggregates at ambient conditions. Seven olivine single crystals, three natural dunites, one lherzolite, and one synthetic dunite were studied. For the natural rocks, the crystal preferred orientation (CPO) of olivine was measured and thermal diffusivities predicted on the basis of the measured olivine single-crystal tensor and lattice preferred orientations are compared to the measured thermal diffusivities.

2. Experimental Set-Up

[4] We use a transient technique that allows thermal diffusivity measurements of both single-crystals and relatively large rock samples ($>1\text{ cm}^3$) in different directions [Höfer and Schilling, 2002; Schilling, 1999]. The method does not require any specific sample shape, only two parallel well-polished plane faces. A filament close to the front surface produces a heat signal, which is recorded by a first thermocouple located between the filament and the

Table 1. Olivine Thermal Diffusivity Tensor at 300K (in mm²/s) Obtained in the Present Study (Values Under Brackets Indicate 2 σ Uncertainties in the Last Digit) and Previous Measurements at Ambient Conditions (1) [Chai *et al.*, 1996]; (2) [Kobayashi, 1974]; (3) [Kanamori *et al.*, 1968]; (4) [Beck *et al.*, 1978]-Non Oriented Crystals

ref.	This study	(1)	(2)	(3)	(4)
method	transient	PTGS	Angstrom	Angstrom	Hot wire (273K)
Fo content	91%	89%	91.6%	82%	90%
[100]	2.73(04)	2.16	2.18	–	
[010]	1.70(12)	1.25	1.07	–	Sc1: 2.12
[001]	2.49(14)	1.87	1.71	1.85	Sc 2: 3.56

front surface of the sample, without contact to either the filament or the sample. A second thermocouple situated on the rear part of the sample registers the resulting temperature equilibration in the sample. The thermal diffusivity of the sample is evaluated from the temperature-time evolution recorded at the two thermocouples using a one-dimensional finite difference scheme, which allows consideration of heat losses by radiation from the sample surfaces [Schilling, 1999]. The ballistic (direct and absorbed) heat transfer is also modeled as an additional signal on the rear thermocouple. Since temperature derivatives of thermal diffusivity of olivine are high at ambient conditions, low energy signals were used in order to have a weak elevation of the sample temperature (<5K). The resulting internal precision of the apparatus depends on the sample length and on the thermal diffusivity of the measured crystals; an error of 3–5% is expected at ambient conditions [Schilling, 1999] and it increases when the sample length decreases. The external precision is about 5% [Schilling, 1999]. Extensive calibration of the apparatus was performed using standard glass and quartz samples [Höfer and Schilling, 2002].

3. Results

3.1. Single Crystals

[5] Seven San Carlos olivine single crystals (Fo90) were oriented by the Laue backscattering technique at the IKZ Institute, Berlin. They are green-colored and free of cracks and inclusions. Six crystals were cut in order to obtain a platelet geometry with two faces polished plan-parallel; these faces are either normal to the [100], to the [010], or to the [001] crystallographic axes. The length of the measured heat diffusion path varies from 4.5 to 9.1 mm, and the cross section has a rectangular shape of about 1 cm² or more. These geometries are chosen to minimize heat losses at the lateral sides of the sample. In addition, a cubic sample of 8 mm was cut in order to measure the complete thermal diffusivity tensor on one single crystal. Results

obtained on the different samples display a good reproducibility of the measurements in a given direction (Table 1). Reproducibility is particularly good for the [100] direction (standard deviation <3%) where large crystals were used (7.4 to 9.1mm), suggesting that experimental uncertainties due to heat losses on lateral sides are not significant. The lower reproducibility in the [010] and [001] direction (standard deviation >3%) may be explained by the smaller samples used in these measurements (from 4.5 to 8 mm).

3.2. Rocks

[6] Four naturally-deformed mantle rocks have been selected for petrophysical modeling and laboratory measurements of thermal diffusivity (Table 2). Thermal diffusivity was also measured in a synthetic dunite sintered from crushed San Carlos olivine in a Paterson press at 300 MPa and 1200°C for 12 hours. Crystal preferred orientation (CPO) of olivine was measured by the Electron-Back Scattered Diffraction (EBSD) technique in a JEOL 5600 Scanning Electron Microscope. Measured CPO in the alpine samples (Figure 1) are typical of peridotites deformed under high-temperature, low-stress conditions (>1000°C). 00BA1 displays a strong concentration of olivine [100] axes sub-parallel to the lineation (X-direction, density > 8 multiple of uniform distribution) and a girdle distribution of [010] and [001] axis in the plane perpendicular to the lineation, with a maximum of [010] normal to the foliation. [001] maxima, usually weaker than the [100] and [010] ones, are normal to the lineation in the foliation plane (Y-direction). This CPO pattern suggests a dominant activation of the high-temperature (010)[100] and (001)[100] slip systems. The dunites 00VS24 and 00VS11 show an olivine CPO with an orthorhombic symmetry, characterized by equivalent concentrations (maximum density \cong 5 m. u. d.) of the [100], [010] and [001] axes in the X, Z and Y direction, respectively. This CPO pattern is characteristic of single activation of the olivine high-temperature easy-glide system: (010)[100]. The Oman dunite has a weak and inhomogeneous olivine CPO. The synthetic dunite has a random fabric.

[7] The thermal diffusivity at the sample scale is calculated using the olivine thermal diffusivity tensor determined above and the measured olivine CPO [Mainprice and Humbert, 1994]. For each grain of a mineral phase, the thermal diffusivity matrix D_{kl} in the crystal co-ordinates is rotated into the sample co-ordinates using the rotation matrix g_{ij} .

$$D_{ij}(g) = g_{ik} \cdot g_{jl} \cdot D_{kl} \quad (1)$$

The thermal diffusivity of the polycrystal is then calculated by averaging the individual orientation measurements,

Table 2. Peridotite Samples: Origin, Modal Composition, Microstructure, Density, and Mean Forsterite Content of Olivine

Sample	Location	Modal composition	Microstructure	Density (g. cm ⁻³)	Fo content (%)
00BA1	Baldissero, Alps	75% olivine, 18% enstatite, 5% diopside	HT porphyroclastic: Porphyroclasts >1 mm	3.38	90.2
00VS24	Val Sesia, Alps	>98% olivine, spinels	Recrystallised grains <0.5 mm	3.39	90.5
00VS11	Val Sesia, Alps	>98% olivine, spinels	Equigranular; Static recrystallisation, uniform grain size of 2–3 mm	3.43	84.2
OMAN	Oman ophiolite	>95% olivine, enstatite, spinels	LT porphyroclastic: Porphyroclasts (<0.3 mm) in a fine grained matrix (0.02 mm)	3.36	91.0
SYN1	Hot pressed sample	100% olivine	Fine grained, undeformed (0.015 to 0.025 mm)	3.34	91.0

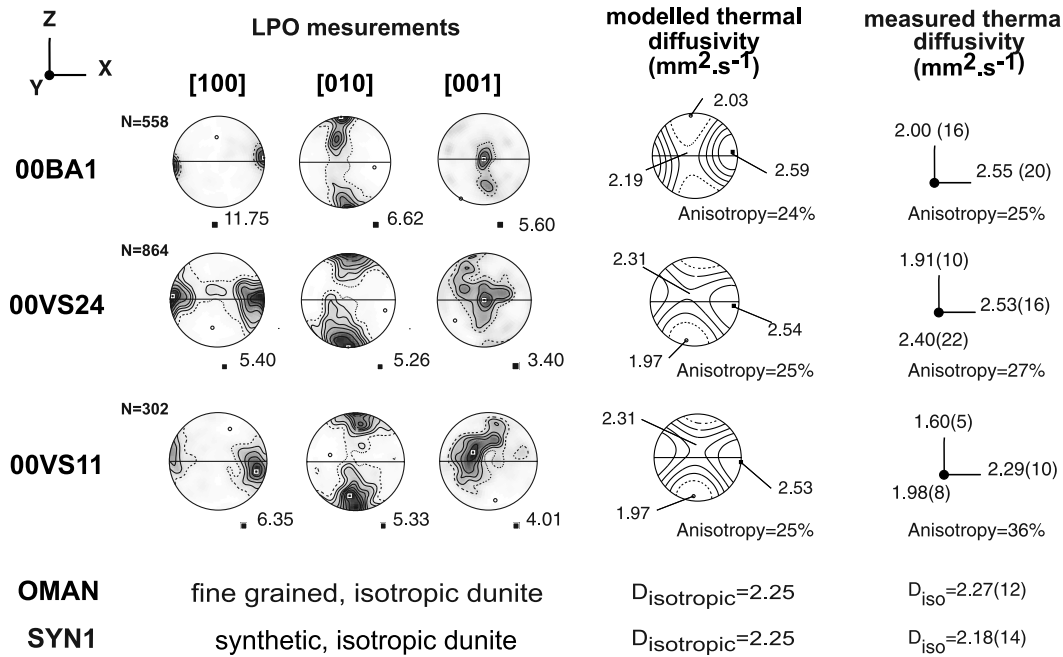


Figure 1. Olivine CPO, modelled and measured thermal diffusivity in naturally deformed peridotites. Lower hemisphere, stereographic projections. Full lines mark the foliation (XY plane) and the lineation (X direction) is horizontal. In the CPO stereoplots, N represents the number of measured grains, contours intervals are at 0.5 multiples of a uniform distribution, and inverse-log shading varies from white (minimum density) to black (maximum density indicated by the solid square). Thermal diffusivity plots are contoured at $0.1 \text{ mm}^2 \cdot \text{s}^{-1}$ intervals. Anisotropy is defined by $(D_{\text{max}} - D_{\text{min}}) / D_{\text{mean}}$ in %. Values under brackets indicate 2σ uncertainties for the measured diffusivities.

where $v(g)$ is the volume fraction of the grain in the direction g :

$$\begin{aligned} \langle D_{ij} \rangle_{\text{Voigt}} &= \sum D_{ij}(g) \cdot v(g) \text{ or} \\ \langle D_{ij} \rangle_{\text{Reuss}} &= \left(\sum (D_{ij}(g))^{-1} \cdot v(g) \right)^{-1} \end{aligned} \quad (2)$$

In the present models, we assume that the olivine volume fraction in the rock is 1, neglecting the pyroxenes and spinels. Thermal diffusivities are calculated as the arithmetic mean of the Reuss and Voigt bounds (VRH average).

[8] These petrophysical models (Figure 1) show that development of an olivine CPO leads to a strong anisotropy of thermal diffusivity. Thermal diffusivity is maximum parallel to the olivine [100] axes concentration, i.e., parallel to the lineation direction, and minimum parallel to the olivine [010] axes concentration, i.e., perpendicular to the foliation plane. However, this model does not consider the effects of grain boundaries, microcracks, or crystalline imperfections on heat transfer. To investigate these effects, we measured the thermal diffusivity of these samples at ambient conditions.

[9] Cylinders of 12 mm in diameter and 10–15 mm length were drilled for measurements in the X , Y , and Z structural directions of each sample. Due to their weak or random olivine CPO, cores of the Oman and synthetic dunites were not oriented. For each direction, 2 to 5 cylinders were cut in order to test the reproducibility and the representativity of the measurements (Figure 1). The low standard deviations suggest a good reproducibility of the measurements and a good representativity of the core sample. In particular, deviations obtained for the Oman dunite are within the range of the internal error of the

apparatus. In spite of its very large grain size, 00VS11 also shows a consistent behavior from core to core. A large anisotropy (about 25%) of thermal diffusivity is observed for 00BA1 and 00VS24. For 00VS11, a still larger anisotropy (36%) is observed and its absolute values are lower by 10% to 15% relatively to the other samples.

4. Discussion

[10] The present thermal diffusivity measurements in olivine single-crystals (Table 1) show that heat transport in olivine is more effective in the [100] direction and less effective in the [010] direction, in good agreement with previous determinations [Chai *et al.*, 1996; Kobayashi, 1974]. Anisotropy of thermal diffusivity is lower than Kobayashi [1974] data, but it is in good agreement with more recent measurements by Chai *et al.* [1996]. However, the present absolute values of thermal diffusivity are about 30% higher than these data. This discrepancy may be explained by a more effective contact between the rear thermocouple and the crystal and by a better control of the ambient temperature in our experiments. Indeed, in the modified Angstrom method [Kanamori *et al.*, 1969], large temperature excitations are used and a silver coating material insures the contact between the samples and the thermocouple, leading to a thermal resistance. Calibration of the modified Angstrom method on quartz and silica glass shows that the resulting errors are expected to be about 10 to 20% [Kanamori *et al.*, 1968; Kobayashi, 1974]. The present thermal diffusivities are also higher than those obtained by the Picosecond Transient Grating Spectroscopy method [Chai *et al.*, 1996; Zaugg *et al.*, 1992]. This non-

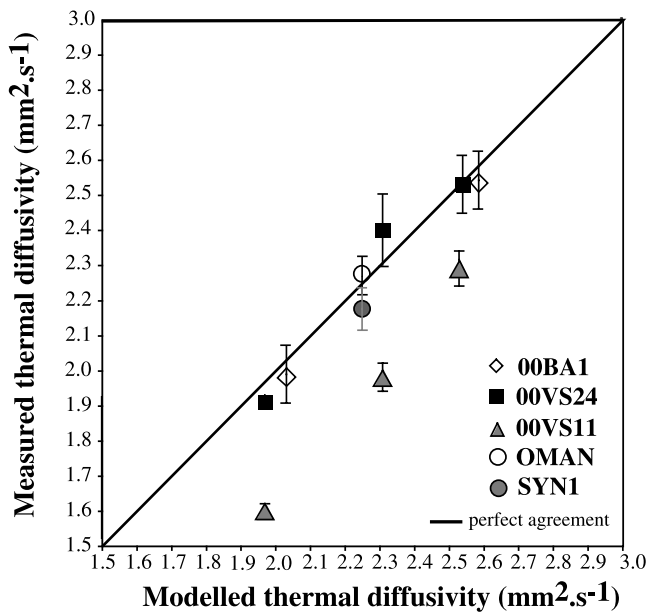


Figure 2. Comparison between measured and modelled thermal properties in naturally deformed peridotites.

conventional method for thermal diffusivity measurements does not suffer from the same problems as the modified Angstrom method, because of the use of a laser-induced thermal grating as a thermal excitation and the absence of thermocouple as sensors. Part of this discrepancy as well as the lower diffusivity measured along the [001] axis by Kanamori *et al.* [1968] may be due to the higher iron content of their single crystals. Accuracy of the PTGS method was tested through measurements of the thermal diffusivity of water at high temperature and pressure [Abramson *et al.*, 2001], but calibration on standard materials like silica glasses or quartz is not available. An inter-laboratory comparison using the same materials is necessary to further investigate the discrepancy between the two methods. Finally, extrapolation of thermal diffusivity measurements on two non-oriented single crystals at 273K by Beck *et al.* [1978] to 300K gives values in the same range than the present data.

[11] Comparison between petrophysical models and direct measurements on rock samples shows that heat transport properties at the aggregate scale and at the single-crystal scale are well correlated (Figures 1 and 2) in both absolute values and anisotropy. For the Oman and synthetic isotropic dunites, the difference is within the error bar of the measurement method (<3–5%). This agreement shows that microcracks and intracrystalline defaults do not hinder thermal diffusion or modify its anisotropy. Moreover, concordance in average thermal diffusivities in samples displaying a wide range of grain sizes (0.01 to 2 mm) also implies that grain size and grain boundaries have no effect on thermal diffusivity at ambient conditions. Presence of pyroxenes (about 25%), whose thermal diffusivity absolute values are expected to be lower than the olivine ones [Chai *et al.*, 1996], neither hinders heat transport at ambient conditions in the lherzolite 00BA1 (difference <5%) nor modifies its anisotropy. Finally, modeled thermal diffusivities in OOV511 are systematically higher than the mea-

sured ones (difference >15%). This discrepancy may be due to the higher iron content of olivine in this sample (Fo84) relatively to the San Carlos olivine crystals (Fo90) [Horai, 1971].

[12] The similarity between thermal diffusivities measured at the crystal and rock scales suggests that, even at ambient conditions, interaction of phonons with the lattice imperfections or grain boundaries is negligible compared to phonon-phonon interactions. Thus thermal diffusivity of these low-porosity rocks is dominated by the crystals intrinsic properties and by their orientation. In consequence, petrophysical models based on the olivine crystal thermal diffusivity tensor and CPO provide a good approximation of the 3-dimensional phononic thermal transport of mantle rocks at ambient conditions. Since phonon-phonon interactions increase with increasing temperature, agreement between single crystal and rock phononic heat transport is expected to be preserved at high temperature.

[13] Finally, the present thermal diffusivity data are higher by more than 50% than the values obtained in previous studies on olivine polycrystals at ambient conditions [e.g., Gibert *et al.*, 2003]. Most of these studies use transient methods in radial geometries, which are submitted to experimental uncertainties, like the exact position of the thermocouple, or to problems in boundary conditions, that may lead to systematic experimental errors. Based on our evaluation of the accuracy of the present method as well as on its extensive calibration with standards, we suggest that the present measurements provide more realistic values of thermal diffusivity of mantle materials at ambient conditions. Extrapolation to upper mantle conditions, using previously defined temperature and pressure dependencies [e.g., Gibert *et al.*, 2003; Katsura, 1995], suggests that upper mantle thermal diffusivity may be up to 50% higher than traditionally used values.

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