Enhanced mantle conductivity from sulfide minerals, southern Sierra Nevada, California

Mihai N. Ducea
Department of Geosciences, University of Arizona, Tucson, Arizona

Stephen K. Park
Institute of Geophysics and Planetary Physics, University of California, Riverside, California

Abstract. Petrographic studies of peridotitic xenoliths entrained in late Quaternary basaltic lavas from beneath the southern Sierra Nevada have revealed the presence of accessory sulfide minerals along grain boundaries and fractures. Equilibration temperatures from the xenoliths are sufficiently high that the molten sulfides coexist with the basaltic melt. Sulfides are extremely conductive relative to the solid matrix or the basaltic melt, so a small fraction can increase the bulk conductivity of the mantle appreciably. Previous estimates of 2-5% partial melt from magnetotelluric measurements can be plausibly reduced to less than 1%. Such low melt percentages have longer residence times in the mantle and are more consistent with the volumetrically minor late Quaternary basin flows and the primitive basalt compositions.

Introduction

An unexpected result of a recent multidisciplinary study of the southern Sierra Nevada (Figure 1) was that anomalously warm mantle is found at depths greater than 35 km [Ducea and Saleeby, 1998]. Xenoliths in Quaternary basaltic lavas are peridotitic for inferred depths greater than 35 km and they equilibrated at temperatures of 1180-1220°C [Ducea and Saleeby, 1998]. Low seismic velocities in the upper mantle [Hot招 et al., 1994] and electrical conductivities of 0.03-0.10 S/m [Park et al., 1996] have led to the suggestion that the asthenosphere is partially molten. Park et al. [1996] proposed that 2-5% partial melt explained the enhanced conductivity. Thus, there are various lines of evidence including outcrops of Holocene basalt [Moore and Dodge, 1980] to support an inference that there is partial melt in an asthenospheric upper mantle at depths of 35-40 km beneath the southern Sierra Nevada and the California Basin and Range.

There are two problems with this simple explanation of partial melt. First, 2-5% partial in a 30 km thick region would generate at least 24 km$^3$ of magma in cross section. Second, this magma would have a residence time of less than 500 ka in a layer 30 km thick with a melt fraction of 2%, based on a grain size of 1 mm and a viscosity of 1 Pas for the basaltic magma [McKenzie, 1985]. Such a short residence time would suggest that there is either significant basaltic underplating (600-1200 m at the base of a crust approximately 35 km thick) or voluminous eruptions.

However, the low seismic velocities (<6.5 km/s) extending to Moho indicate that the eastern Sierra Nevada seismologically defined crust is silicic throughout [Ducea and Saleeby, 1998]. The amount of Quaternary basalt at the surface cannot account for all of this magma. Could the enhanced conductivity be due to phases other than melt?

Examination of the xenoliths in the late Quaternary basaltic lavas reveals accessory opaque phases which we will show are highly conductive sulfides. Sulfides and fluid inclusions found along grain edges lead to a model of a small amount of partial melt containing the sulfides, which would be much more conductive than basaltic melt alone. The models of Waff [1974] are extended to include multiple conductive phases and then used to estimate the amount of partial melt needed in order to explain the observed conductivities.

Accessory Phases in the Xenoliths

Shallow upper mantle xenoliths occur in several Pliocene to Quaternary volcanic centers in the southern Sierra Nevada [Wilshire et al., 1988]. Our samples were taken from the Big Pine Volcanic Field (BPVF) because: the host volcanic rocks are young, the xenoliths are abundant and remarkably fresh, and the BPVF is located in the proximity of the geophysical transect across the Sierra Nevada (Figure 1). The BPVF contains lava flows and cinder cones erupted in the last 0.7 Ma; the youngest magmas in the BPVF are only a few thousand years old [Moore and Dodge, 1980]. Upper mantle xenoliths found in BPVF lavas and cinder cones are predominantly Cr-diopside spinel-peridotites and rare Al-nugite pyroxenites [Wilshire et al., 1988; Ducea and Saleeby, 1996]. The equilibrium pressure of spinel peridotites was estimated to be 1.0-1.5 (±0.4) GPa, and.

![Figure 1](https://example.com/figure1.png)

Figure 1. Locations of southern Sierra Nevada MT transect (white dots with black outlines), central Sierra xenoliths (black squares with white outlines), and Big Pine volcanic field (BP). Inset shows location of Figure 1 in California.
equilibration temperatures range between 1180-1220°C [Ducea and Saleeby, 1996]. A few plagioclase-bearing peridotites have also been found; they equilibrated at 0.9-1.0 GPa. In a pressure-temperature diagram, the BPVF xenoliths fall on an adiabatic-like slope (Figure 2).

Most BPVF xenoliths contain accessory sulfides that were identified using an EDS spectrometer attached to a Cameca scanning electron microscope. The most common sulfide phase is a mono-sulfide solution of Fe, Cu, and Ni (MSS), a typical occurrence in upper mantle xenoliths worldwide. Isolated occurrences of chalcocite, pentlandite and pyrrhotite are probably the result of MSS unmixing at low temperatures [e.g., Andersen, 1987], after the eruption of the host basalts. The sulfide composition was quantitatively assessed using Caltech’s JEOL 733 electron microprobe on four xenolith samples (3 peridotites and 1 pyroxenite) from the BPVF. The concentrations of dissolved oxygen in these sulfides is ~4-7 wt. %. The surface abundances of sulfide in thin section varies from 0.06 to 0.4 vol% in peridotites, and are about half as abundant in pyroxenite xenoliths. The sulfides occur occasionally as primary inclusions in main silicate phases and more commonly as droplets or thin films locally associated with silicate glass and CO2 fluid inclusions along grain boundaries or cross-cutting phases along fractures (Figure 3). Based on the quench textures and association with silicate inclusions, the sulfides appear to have formed as immiscible liquids in the presence of silicate partial melt. The CO2 fluid inclusions suggest that a free vapor phase may have coexisted with the melt phase.

Typical BPVF peridotites have dry solidi in the range 1225-1250°C (Figure 2), based on calculations at 1.0 GPa using the MELTS algorithm [Ghiorso and Sacks, 1995]. The equilibration temperatures measured at 1.0 GPa in xenoliths are typically lower that the sub-BPVF mantle solidi by only a few tens of degrees. The temperatures measured in BPVF xenoliths are consistent with the presence of the asthenosphere at the base of the crust in the eastern Sierra Nevada [Ducea and Saleeby, 1998] and the local onset of partial melting. The thermometry and estimation of peridotite solidi argue that the sub BPVF mantle was close to or above its solidus at the shallowest mantle levels (1.0 GPa) at the time of the eruption of xenolith-bearing volcanic hosts. The temperatures measured in the BPVF peridotites also exceed the solidus of the MSS sulfides at 1 GPa [e.g., Lorand and Conquere, 1983], suggesting that the sulfides observed in xenoliths were probably molten at the time of xenolith entrainment. Andersen et al. [1987] concluded similarly in a study of sulfides from high temperature pyroxenites from various localities including the Southwestern U.S. If the temperatures measured in the BPVF xenoliths reflect the present state of the mantle, then the presence of coexisting sulfide and basaltic melts is expected.

It has long been hypothesized that MSS sulfides form in the shallow mantle as immiscible melts coexisting with silicate melts during peridotite partial melting [e.g., Bishop et al., 1975; Szabo and Bodnar, 1995]. Silicate melts readily escape the residual solid peridotite matrix, but the denser sulfide melt fraction is left behind [Mysen and Popp, 1980]. Sulfides should be molten in hot shallow mantle environments, such as in extended continental regions like the modern Basin and Range. Geothermal gradients in thick lithospheric mantle from stable continental regions are below the MSS solidus (Figure 2).

**Figure 3.** Photomicrograph of sulfides in peridotite xenolith from BPVF. Note how sulfides form equant crystals along silicate grain boundaries and are associated with fluid inclusions.

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**Figure 2.** Equilibration temperatures and pressures of BPVF peridotite xenoliths [modified from Ducea and Saleeby, 1996]. The solidus for mantle-like MSS (Fe,Ni,S) is labeled "MSS" [Lorand and Conquere, 1983]. Dry solidi for BPVF peridotites were computed using the MELTS algorithm [Ghiorso and Sacks, 1995]. These samples were selected because they span the range of modal compositions encountered in the BPVF peridotite xenoliths. The geotherm for a 100 km thick lithosphere ("100 km") is also shown and would shift to the left for thicker lithospheres.

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**Multiple Conducting Phases in the Mantle**

We used conceptual models from Waff [1974] to represent our system with two conductive fluid phases (basalt and sulfide) within a flow path network. Because the sulfide melt has a much smaller volume than the basalt melt and because the melts are likely immiscible, Waff's [1974] composite sphere model with inner spheres of sulfide melt surrounded by outer shells of basalt melt (equivalent to the Hashin-Shtrikman lower bound) was used for the melt. The cubic grain array was used for the melt within a flow path network. The melt contains a large relative basalt proportion (C_b) and a much smaller relative sulfide proportion (C_s),
where \( C_v + C_s = 1 \). With a conductivity \( \sigma_f \) for the sulfide melt and \( \sigma_s \) for the basaltic melt, Waff’s [1974] equation (24) gives the conductivity of the fluid (\( \sigma_f \)):

\[
\sigma_f = \left[ \sigma_f \left( \frac{1}{3} C_s + \frac{2}{3} C_v \sigma_d \right) \right] \left[ 1 + \frac{C_s}{3} \left( \frac{\sigma_s}{\sigma_f} - 1 \right) \right],
\]

Substitution of (1) into Waff’s [1974] equation (33) for the melt conductivity yields the bulk conductivity for the cubic grain array:

\[
\sigma_{eff} = \frac{\sigma_s \sigma_d (1 - \phi)^3}{\sigma_f [1 - (1 - \phi)^3]} + \sigma_f \left[ 1 - (1 - \phi)^3 \right]
\]

If \( \phi \) is the total fractional volume of melt in the rock, then the fractions of basaltic and sulfide melt in the mantle are \( C_v \phi \) and \( C_s \phi \), respectively. Shankland and Waff [1977] show that the conductivity of solid olivine is \( \sigma_s = \sigma_o \exp[(-E_s + PAV)/kT] \) where \( E_s = 22.3 \) S/m, \( E_o = 1.37 \) eV, and \( AV = -0.03 \) eV/kbar. \( T \) is the temperature in \( \text{K} \) for temperatures less than 1500 \( \text{K} \) (1227 \( \text{C} \)). A similar expression predicts the conductivity of basalt melt, but with \( E_s = 18,400 \) S/m, \( E_o = 1.15 \) eV, and \( AV = 0.01 \) eV/kbar. These equations are used to predict the pressure and temperature dependent conductivities of the basalt melt (2.1 S/m) and solid olivine (6 \( \times \) 10\(^{-4} \) - 2.6 \( \times \) 10\(^{-3} \) S/m). Conductivities for solid sulfides range from \( 10^3 \) to \( 10^5 \) [Duba et al., 1994], and we used 10\(^4 \) S/m here. We can predict the effective conductivity of a rock at high pressures and temperatures using (1)-(2) if we know the conductivities of the basaltic melt and the sulfides.

Bulk conductivities inferred from the MT data range from 0.033 to 0.1 S/m, and this range can be used to constrain percentages of sulfides and basaltic melt. Observed sulfide percentages of 0.06-0.4% can be used to determine the possible basaltic melt amounts needed. Less than approximately 0.25% sulfide does not make an appreciable contribution to the bulk conductivity of the mantle (Figure 4). Basaltic melt percentages of at least 1% are still needed to explain the enhanced conductivity beneath the eastern Sierra Nevada. For sulfide concentrations greater than 0.25%, the primary conductivity contribution comes from the sulfide melt, as evidenced by the relative independence of the bulk conductivity contours on the basaltic melt amount (Figure 4). Then, basaltic partial melt percentages of less than 1% and as little as 0.1% are permissible.

**Prediction of sulfide/silicate melt ratios**

For any given silicate melt fraction there will be a concentration of sulfur in the melt; if that value exceeds the \( S \) saturation in melt at shallow upper mantle \( P \) and \( T \) conditions, then the excess sulfur will exsolve as an immiscible liquid and form sulfide liquid [Mysen and Popp, 1980] and sulfide phases upon quenching. The sulfide concentration can be calculated for a type of melting (e.g., batch) as a function of the fraction of partial melt; fraction of sulfur in sulfide (typically 0.3-0.5), concentration of sulfur in peridotite prior to melting (typical mantle values are 200-300 ppm), sulfide silicate melt-solid peridotite partition coefficient (\( K_s \approx 0.1 \)), and the saturation concentration in high-pressure basaltic melts (\( \approx 1500-3000 \) ppm). Ratios of silicate melt/sulfide melt vary between 10-1000 for silicate melt fractions ranging from 0.5-3%. If there has been no silicate melt extraction from the mantle, such small sulfide fractions (0.05-0.003%) cannot explain the high conductivities measured in the eastern Sierra at significantly lower melt fractions than previously estimated. However, if the silicate melt was largely extracted, then a residual melt more concentrated in sulfides would remain. Such a mixture could enhance the conductivity to the values observed beneath the Sierra Nevada.

**Discussion**

Park et al. [1996] calculated that 2-5% partial melt was needed in the upper mantle to raise the conductivity to the observed values. However, accessory sulfide minerals in the mantle may enhance the conductivity appreciably without a substantial volume increase. Basaltic magma percentages of less than 1% are permissible if the concentration of sulfide melt is at least 0.25%. We assume the following to reach that conclusion: the observed xenoliths and sulfide contents are representative of the modern upper mantle (which is sensed by the MT data), the basalt and sulfide melts coexist to form a conducting interconnected fluid, and planar structures containing sulfides and glass inclusions are evidence of extraction paths for partial melt. Basaltic melt percentages of less than 1% are permissible if the sulfide fraction is as high as that observed in the xenoliths. Do these lower values eliminate the problems of basalt volume and residence times cited in the Introduction? Our new estimates of basaltic melt are much more consistent with the petrological evidence of low degree partial melts (~1%) based on the compositions for the late Quaternary basalts. Second, assuming that all other parameters remain the same, minimum residence times of 3 Ma are calculated from McKenzie’s [1985] model of magma extraction. The small amounts of partial melt and longer residence times are more consistent with the geologic evidence of scattered, small-volume basaltic eruptions and primitive magma compositions.
Conclusions

Sulfides are common accessory phases in upper mantle assemblages. Because of the higher density of the sulfide melt compared to that of the silicate melt and solid silicate residue, the sulfide melt phase will remain trapped in the partial melting zone. Temperatures recorded in xenoliths from active extensional environments exceed the MSS solids, so the sulfide component is probably molten in a solid peridotite framework. Based on petrological evidence from xenoliths, we propose that the enhanced mantle conductivity beneath the southern Sierra Nevada is the result of basaltic melt mixed with sulfide melt. Volumetric percentages of these sulfides in late Quaternary xenoliths range from 0.06-0.4%. With the inclusion of these much more conductive sulfides, estimates of basaltic melt below 1% are also much longer, in agreement with the geologic record of Miocene to the Holocene basaltic flows.

If sulfides form an interconnected network in a melt state alone [Gaetani and Grove, 1999] or combined with basaltic melt, then their contribution to the bulk electrical conductivity of the mantle may be appreciable. However, temperatures sufficient to melt the sulfides are likely to be found only in anomalously warm mantle, such as that found in extensional settings. Expected temperatures in lherzolite mantle from stable continental regions are below the MSS solids.

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M.N. Ducea, Department of Geosciences, University of Arizona, Tucson, Arizona 85721 (e-mail: ducea@geo.arizona.edu)

S.K. Park, Institute of Geophysics and Planetary Physics, University of California, Riverside, California 92521 (e-mail: magneto@ucr.cc.ucr.edu)

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