Foundering lithosphere imaged with magnetotelluric data beneath Yosemite National Park, California

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ABSTRACT

A magnetotelluric profile consisting of 14 sites and spanning 240 km from the San Joaquin Valley to the Nevada border was installed across the central Sierra Nevada, through Yosemite National Park, in an effort to constrain the northward extent of lithospheric removal beneath the range. Broadband and long-period instruments from the EMSOC (Electromagnetic Studies of the Continents) consortium were used to record data with periods ranging from 0.01 to 20,000 s, allowing the conductivity structure beneath the Sierra to be imaged to a depth of 120 km.

Two-dimensional models reveal that the batholith’s resistive root extends to a depth of just 30 km beneath the eastern Sierra and 45 km beneath the western Sierra. The batholith is separated by a thin conductive zone that coincides with the Moho from a resistive mantle structure at depths of ~55 km. We propose that this resistive structure is residual root. Deeper, a broad conductive feature dipping eastward at depths of 65–100 km below the range is upwelling asthenosphere containing <1% melt that originates from the extensional tectonic regime of the Basin and Range to the east.

INTRODUCTION

Magnetotelluric (MT) and seismic studies of the southern Sierra Nevada (California and Nevada, USA; Fig. 1) revealed the absence of a thick crustal root beneath the high Sierra (Wernicke et al., 1996). Fliedner et al. (1996), using seismic refraction, mapped the Moho as varying between 30 and 35 km depth, consistent with the findings in Park et al. (1996), who imaged the conductive mantle asthenosphere at depths as shallow as 35 km. Xenoliths from Pliocene volcanic flows dated as 3.5 Ma are predominantly peridotitic and marked by the absence of lower crustal eclogite (garnet pyroxenite). However, garnet pyroxenite is present in xenoliths that equilibrated at a depth of 70 km and were found in Miocene volcanic flows dated as 11 Ma (Ducea and Saleeby, 1998). Ducea and Saleeby (1998) inferred, from the loss of garnet pyroxenites and the increase in temperatures estimated from geothermometry at 3.5 Ma, that the lithosphere beneath the Sierra Nevada batholith was replaced by asthenosphere between 11 Ma and 3.5 Ma.

The removal mechanism responsible for lithospheric foundering is poorly understood and the fairly recent loss of lithosphere beneath the southern Sierra Nevada could indicate that the phenomenon is still occurring elsewhere in the range. Given that seismic studies (Fliedner et al., 1996) showed that the root thickened to the north, we shifted our investigation of the Sierra Nevada’s deep structure to a profile through the central Sierra Nevada, specifically, through Yosemite National Park.

MT METHOD AND DATA

A 240-km-long MT profile extended from the San Joaquin Valley to the Nevada border; across the Sierra Nevada through Yosemite National Park (Fig. 1); 14 stations were recorded with colocated short-period (0.001–300 s) MT-24 and long-period (30–10,000 s) NIMS (Narod Intelligent Magnetotelluric Systems) instruments.

The MT method relies on natural electromagnetic signals in the Earth (Vozoff, 1991). Horizontal electric fields induced by the Earth’s naturally occurring oscillatory magnetic field are measured at the Earth’s surface with 100 m long dipoles (essentially a digital voltmeter with long wire leads). Horizontal and vertical magnetic fields are measured with induction coils to record both source and secondary induced fields. Data are acquired at two sites simultaneously in order to use a process called remote referencing to separate noise from signal. We used the Larsen et al (1996) robust processing technique to do this analysis.

MT transfer functions are computed in the frequency domain between observed electric and magnetic fields, but period (the inverse of frequency) is conventionally used for data presentation and modeling (Vozoff, 1991). A complex, frequency-dependent, 2 × 2 impedance tensor (Z) relates horizontal vector electric fields (Ex, Ey) to horizontal vector magnetic fields (Hx, Hy). Such a tensor has two principal axes that are usually orthogonal. Theoretical analysis shows that if fields are measured over two-dimensional (2-D) structures, the tensor may be decomposed into two orthogonal, independent modes through rotation to a direction either parallel or perpendicular to strike. The transverse magnetic (TM) mode couples E perpendicular to strike (Ey), H parallel to strike (Hx), and a vertical magnetic field (Hz). This mode has a principal axis that is perpendicular to strike. The transverse electric (TE) mode couples Ex, Hy, and Hz, and has a principal axis that is parallel to strike. Conventionally, tensors are rotated to a principal direction that maximizes the amplitudes of these two modes and minimizes coupling terms between them. There is still a 90° ambiguity in the rotation because Zxz (=Ex/Hy) could be larger than Zyx (=Ey/Hx), or vice versa.

We found in this study that the directions of principal axes were generally aligned either parallel or perpendicular to the geologic strike of the major features in California (Figs. 1 and 2). Rose diagrams for tensor rotations at periods longer than 30 s (Fig. 2) show that one of the two principal directions at each site is approximately parallel to the regional geologic strike. In some cases, this is the direction of Zxy and in others it is Zyx. Each rose diagram shows directions for several sites that are in the same geologic province (San Joaquin Valley, western foothills metamorphic rocks, batholith, Basin and Range). The principal axes rotate gradually from N30W in the San Joaquin Valley and western Sierra Nevada to due north in the central Sierra and Basin and Range (Fig. 2). This is similar to the regional variation seen in the SSCD (Southern Sierra Continental Dynamics) MT line that Park et al. (1996) attributed to the...
change in structural orientation from N30W in California to due north in the Basin and Range.

In addition to the MT impedance tensor, we can compute a magnetic transfer function that relates vertical and horizontal magnetic fields for a given frequency. The direction of greatest coherence between the vertical and horizontal field is represented by a set of induction arrows for each site in the profile (Fig. 2). An induction arrow of unit length means that the vertical induced magnetic field has a strength comparable to that of the horizontal field. Typically, induction arrows have lengths of <1. The induction arrows in our analysis follow the convention that real components point away from good conductors (Wiese, 1962). If the structure of the Sierra Nevada were perfectly 2-D, then induction arrows would be aligned perpendicular to geologic strike and real components would point away from good conductors. Such behavior is seen at the western end of the profile, where the effects of the conductive Pacific Ocean are seen at periods of 1000 s and longer (Fig. 2). However, the real components of the induction arrows in the Sierras and western Basin and Range are pointing southward, suggesting electrical conductors to the north (Fig. 2).

While the most thorough analysis of MT data would involve 3-D inversion, studies usually use 2-D inversion because field behavior from 3-D bodies is often sufficiently similar to that from 2-D structures (Wannamaker, 1999). In this study, there are three reasons why 2-D modeling is appropriate. First, the principal axes of the impedance tensors are aligned either parallel or perpendicular to overall geologic strike. Second, induction arrows are small and ones at the western sites are perpendicular to geologic strike. This means that the effect of conductors north of the profile will not dominate the MT responses at the eastern sites. Last, the overall geologic structure is ~2-D in the vicinity of the profile. An added advantage of 2-D inversion is that it is fast, allowing many more models to be run. As shown herein, running many models is important to assessing the reliability of features in the preferred electrical cross section.

One complication in using 2-D modeling is that tensors and transfer functions need to be rotated to a common strike. We used N10W as an average between sites on the west and on the east of our profile. Both impedance tensors and magnetic transfer functions were rotated to this common direction, and then modes had to be identified. The Zxy component was chosen as the TE mode because that is the mode used by the rotation as the first principal axis. The TM mode was the Zyx component.

The impedance and magnetic transfer functions are complex, so they have both magnitude and phase. We convert the impedance magnitude into an apparent resistivity, which would be the true resistivity if the structure were homogeneous. Each impedance tensor results in two apparent resistivities and two phases because it has two principal axes (Zxy and Zyx). These were plotted against the period in a sounding curve, and the sounding curves from each site were compiled to produce pseudo sections of apparent resistivity and phase (Fig. 3). A pseudo section shows the distribution of apparent resistivities or phases versus spatial location and period. Because longer periods penetrate deeper into the Earth, the lower portions of pseudo sections image deeper structure than do the upper portions (Fig. 3).

While a pseudo section is a qualitative view of the resistivity structure with increasing depth toward the bottom, simple conversion to a true depth section is not possible because the depth of penetration of the electromagnetic wave depends on both the period and the average resistivity of the material it passes through. A period of 1 s at site 201 penetrates ~3 km while the same period at site 205 penetrates over 70 km, e.g., penetration depth = \( \sqrt{[\text{apparent resistivity}] \times \text{(period)} \} \). In addition, MT fields are sensitive to lateral variations as well as vertical ones. In Park et al. (1991), it was shown that fields at periods longer than 20 s in the Sierra Nevada were affected by the electrical conductivity of the Pacific Ocean and the structure in between. A rise in apparent resistivity with increasing period may be due to a more resistive layer or a conductor off to one side. For these reasons, qualitative discussion of pseudo sections is appropriate, but inversion of data is required to produce a depth section of electrical resistivity.

Both the TE and TM apparent resistivity sections have higher resistivities at periods <10 s for stations across the Sierran batholith, a result consistent with the high resistivity of unfractured granitic rock (Fig. 3). Conductive sediments to the west in the San Joaquin Valley are responsible for the low resistivities at intermediate periods (0.1–10 s), and the volcanic terrain in the western Basin and Range is responsible for intermediate resistivities in both the TE and TM pseudo sections (Fig. 3). Both sections show a distinctive decrease in resistivity at periods longer than 10 s, suggesting increased conductivity of the lower crust and upper mantle across the entire section. Complex structure is indicated in several portions of the profile. For example, site 201 has multiple increases and
decreases of apparent resistivity (Fig. 3). While
it may be tempting to interpret this as alternat-
ing conductive and resistive layers, the values
at periods longer than 3 s may be the result of
sensing the resistive Sierran batholith and its
underlying structure.

MT MODELING

An initial model for the 2-D inversion is
needed, and our strategy was to pick one that
is layered so that any lateral contrasts seen in the
output have been added by the inversion. A 1-D
layered structure determined for a single repre-
sentative or average sounding curve was chosen
as a basis for the starting model for the inver-
sion. The model consisted of a 65 row × 81 col-
umn grid, with 24 rows devoted to topography
and widths of adjacent columns varying by no
more than a factor of 1.5. The first 18 km were
set to 100 ohm-m followed by 10,000 ohm-m
from 18 km to 40 km. A layer from 40 km to
210 km had a resistivity of 100 ohm-m, and the
half-space below that was set to 10 ohm-m.
The Pacific Ocean was included in the model
to the west of the profile as a 0.3 ohm-m band
from 0 to 5 km depth. Prior work in California
(Park et al., 1991; Mackie et al., 1996) showed
that electromagnetic induction in the conductive
water of the Pacific Ocean affects MT fields as
far inland as the western Basin and Range, mak-
ing the ocean a necessary feature in any model
of California.

All of the TE and TM apparent resistivity and
phase data and magnetic transfer functions would
ideally be used to generate the model; how-
ever, some data were missing and others were
of poor quality. The black dots on the pseudo-
sections in Figure 3 show the data included in
the inversion (8–12 points per decade of period).
In addition, data types can be weighted differ-
ently. While we attempted initially to weight all
data equally, these converged with unacceptably
high misfits. We finally downweighted the TE
mode apparent resistivity sufficiently to achieve
acceptable models; this can be justified because
TE mode apparent resistivity is particularly
sensitive to truncation of 2-D bodies along
strike. Previous work (e.g., Wannamaker, 1999)
has shown that use of the TM mode data, the
induction arrows, and the TE phase results in a
good 2-D approximation to 3-D structure. Error
floors of 5% for TM apparent resistivity, TM
phase, and TE phase were used while the error
floor for TE apparent resistivity was 10,000%.
Components of the induction arrows aligned
along the profile had error floors of 0.03.

Figure 2. Location map for magnetotelluric (MT) survey. In topographic map, white denotes elevations above 2500 m, dark gray sym-
bolizes elevations between 1500 and 2500 m, and light gray is for elevations <1500 m. The profile extends from station 201 to station 216 (not
all are numbered). CA-NV—the California-Nevada border; B—Bishop; M—Modesto; ML—Mono Lake (light blue); YNP—Yosemite
National Park (outlined in yellow). SR49, SR99, and SR120 are state routes. Brown lines are geologic contacts from Figure 1. Geologic units
labeled in the Sierra Nevada: Mmm—Mesozoic metamorphic rocks; Pmm—Paleozoic (mostly metamorphic) rocks; SNB—Sierra Nevada
batholith. The real (red) and imaginary (blue) induction arrows at a period of 1000 s are shown at each station and scaled using the key
shown below the map. Rose diagrams of principal axes of MT impedance tensors are shown across top. From left to right, the diagrams
show directions of aggregates of sites 213–216, 209–212, 205–208, and 201–204. Colors in rose diagrams represent different stations, all for
periods longer than 30 s. See text for discussion of MT parameters.
Rodin and Mackie’s (2001) inversion was used to obtain a model that produced synthetic responses matching our observed ones. The inversion minimizes a weighted combination of data misfit and model roughness with the weighting factor, \( \tau \), being applied to the model roughness. A larger value of \( \tau \) places more emphasis on a smooth model and a smaller value places more emphasis on minimizing data misfit. Inversions were initially tried with several different weighting factors in order to determine which provided the best tradeoff. We found that a weighting factor of 0.2 produced the lowest weighted combination of data misfit and model roughness. The inversion was run for 400 iterations, resulting in a model with an overall root mean square of 1.70, or a fit within 1.70 times the data error (Fig. 3). The TE mode apparent resistivities were not fit as well as the TM mode values due to the large apparent resistivity error floor for the TE mode (Fig. 3).

The final model (Fig. 4) reveals the absence of resistive material underlying the eastern Sierra Nevada below 45 km depth. A comparison of the resistivity section with a receiver function section (Frassetto et al., 2011) shows that the Moho coincides with a band of resistivity (A in Fig. 4) that is 1–2 orders of magnitude lower than the batholith or an underlying resistor (B in Fig. 4). The Moho thus separates the resistive batholith from this underlying resistor. West of the range, features in the resistivity section are not as well correlated with the Moho, which deepens in this region to ~60 km, passing through a conductive region spanning depths of 40–120 km (C in Fig. 4). However, this is also the region where Frassetto et al. (2011) interpreted the Moho as a fossil structure within high-wave-speed material imaged by Reeg (2008) with P wave tomography. It is common for electrical and seismic images to be sensitive to different aspects of the physical and chemical state of rocks, and we discuss the comparison between sections after we assess the reliability of our model (Fig. 4).

Sensitivity tests were conducted to evaluate the robustness of each model feature in Figure 4. Because interactions between different resistivities in a model control the overall MT response, we could not simply change one model feature and then argue that changes in responses prove...
sensitivity to that feature. It is possible that there is an alternative model without that feature that fits the data equally well. To assess sensitivity, we fixed the resistivity of that feature to something different from the preferred model (Fig. 4). We then ran the inversion again and allowed it to continue until convergence. If an alternate model with a fixed resistivity fit the data as well as did the final model in Figure 4, then we concluded that the alternate model was permissible and that the feature was not constrained well by the data. Multiple inversions with different fixed values of resistivity for each feature were run in order to establish the bounds on features shown in Figure 4. Alternatives were eliminated if misfits at sites exceeded the errors in the observed data (following the procedures in Park et al., 1996).

More than 120 inversions were run in order to establish bounds on features A–E in the model (Fig. 4). Based on these tests, both the westernmost (D in Fig. 4) and easternmost (E in Fig. 4) resistive bodies at the edges of the MT section are not required to be resistive. Models with these set to resistivities <100 ohm-m fit the data equally well. The maximum depth of sensitivity for this section is 120 km; below this depth, changes to structure have little to no effect on the model fit to the data. Therefore, structure deeper than 120 km cannot be resolved. A 10:1 contrast is required between resistor B and conductors A or C (Fig. 4), thus supporting the earlier statement that resistor B is not attached to the Sierra Nevada. Additional tests focusing on just the western part of A above resistor B showed that this 10:1 contrast was also preferred; misfits at sites 207, 208, and 209 were elevated if this region were as resistive as B.

**DISCUSSION**

Electrical resistivity (and its inverse, conductivity) and seismic wave speeds can be used in a complementary fashion to determine the physical and chemical state of rocks. Bulk wave speeds are good indicators of mineralogy (e.g., Christensen and Mooney, 1995), while electrical resistivity is almost insensitive to the minerals composing the solid portion of a rock (Jones, 1992). Resistivity is extremely sensitive to fluid content, chemistry, and connectivity, with orders of magnitude change resulting from fractions of a percent of fluid (e.g., Waff, 1974). While seismic properties such as attenuation and Vp/Vs (P and S wave velocity) ratios can indicate fluid content, the variation of these properties with fluid fraction is a few percent and not orders of magnitude as with resistivity. Both seismic and electrical properties are sensitive to temperature; wave speeds and resistivity of the solid matrix decrease as temperature increases.

Upper mantle resistivities of 20–30 ohm-m require elevated temperatures and some melting. One of us (Park, 2004) found that melt fractions of <1% and temperatures of 1200–1250 °C could explain such low resistivities at mantle depths of 30–60 km. Assuming a model in which a small percentage of basaltic melt forms an interconnected grain boundary film, solution of the Hashin-Shtrikman (1962) equation for the effective conductivity of a two phase material estimates a melt fraction of 0.72% for conductor C (Fig. 4). This is consistent with elevated temperatures and partial melting found in the western Basin and Range (e.g., Wang et al., 2002) and beneath the southern Sierra Nevada (Park, 2004). Coupled with the fact that the resistivity of E need not be >100 ohm-m, we propose that conductor C is the westernmost extension of hot, buoyant asthenosphere beneath the Sierra Nevada. This asthenosphere could provide support for high elevations in the absence of a deep crustal root.

The P wave speed seismic tomography (Reeg, 2008) shows that conductors A, C, and E mostly are within a broad region of normal to slightly slow (<2%) mantle beneath a fast crust (Fig. 5). The correlation between wave speed tomography and electrical resistivity is not good, however, with part of conductor C extending into a fast region west of station 208 and resistor D not extending into the fastest region above 50 km.

The narrow conductor A that is along or just above the Moho and beneath the Sierra Nevada batholith is also likely due to partial melt from hot asthenosphere. If E is conductive, then A could be its western extension and simply result from decompression melting of shallow asthenosphere. If E is instead resistive, then conductor A could be melt generated beneath the batholith that is ascending eastward from C along the base of the batholith. In either case, this melt could be the source of eruptions in the Inyo Domes between sites 203 and 204 (Fig. 2). The melt fraction has to be small because the P wave speeds in conductor A range from normal to 4% fast (Fig. 5).

Resistor B is the most enigmatic portion of the model. It is clearly beneath the Moho (Fig. 4), and yet is the most resistive section of mantle.
that is well constrained by data. The P wave seismic tomography shows that the resistor has wave speeds characteristic of mantle just below the Moho and is not anomalous (Fig. 5). It is clearly separated from the Sierran batholith by conductor A along the Moho. There are several possible interpretations of resistor B: it could be an extension of the mafic root of the batholith, a region of cooler mantle lithosphere that has not yet melted, a region of asthenosphere from which the melt has been extracted, or an eclogitic fragment of the root that has detached from the batholith and has not yet sunk. If resistor B were simply a mafic root separated from the rest of the Sierran batholith by a fault along conductor A, then we would not expect it to have mantle wave speeds.

Another alternative is that resistor B is mantle lithosphere but simply cooler and melt free. A consequence of this interpretation is that B is lithosphere from the Mesozoic formation of the batholith. Ducea and Saleeby (1996) used xenolith thermobarometry to show that the Miocene eclogite root extended to a depth of at least 70 km and possibly to 100 km. Xenoliths from these crustal root extended to a depth of at least 70 km from the batholith. Ducea and Saleeby (1996) used xenolithospheric fragments of the root that has detached from the Moho and is not anomalous (Fig. 5). It is possible that the resistor is delaminated and possibly to 100 km. Xenoliths from these crustal root extended to a depth of at least 70 km from the batholith. Ducea and Saleeby (1996) used xenolithospheric fragments of the root that has detached from the Moho and is not anomalous (Fig. 5). It is possible that the resistor is delaminated and foundering rates of continental arcs: A California arc perspective: Journal of Geophysical Research, v. 107, 2304, doi: 10.1029/2001JB000643.


CONCLUSIONS

A 14 site magnetotelluric profile imaged widespread mantle asthenosphere extending beneath the western Sierra Nevada. The absence of a deep crustal root beneath highest elevations and the presence of a conductive body immediately beneath the resistive batholith imply that the Sierra’s high elevations are supported by hot buoyant asthenosphere. The thick eclogitic crust that was present during the Miocene Epoch (Ducea, 2002) was not imaged in this section. A small resistive body at the top of the asthenosphere is inferred to be a remnant of this eclogitic crust that is no longer attached to the batholith.

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