5th International Symposium on Three-Dimensional Electromagnetics
Sapporo, Japan, May 7-9, 2013

Three dimensional modeling of a large scale magnetotelluric data: Final results from 3-D inversion of the US-Transportable Array

Naser Meqbel[1], Gary D. Egbert[2] and Phil E. Wannamaker[3]
[1]GFZ German Research Centre for Geosciences, Potsdam, Germany
[2]CEOAS- Oregon State University, Corvallis, OR, USA
[3]Energy & Geoscience Institute, University of Utah, Salt Lake City, UT, USA

SUMMARY

The northwestern United States accommodates long history of tectonic activities which vary from subduction system associated with modern arc volcanism in the west to the cratonic stabile lithosphere in the east via an extensional regime in-between. With help of 325 long-period MT sites deployed in 2006-2011 in the framework of the Earthscope project we attempt to shed additional light on the recent and ancient tectonic activities of the northwestern United States. With a nominal spacing of ~ 70 km between sites, our study area spans a rectangular region covering most of the NW USA. For the 3-D inversion of Earthscope MT data we used the full impedance tensor and the vertical magnetic field components of the 325 sites and a fine grid with a horizontal resolution of 12.5 km. Here we present our efforts and discuss final results from 3-D inversion of Earthscope long-period MT data. Our preferred 3-D conductivity model reveals regional to "semi-continental" structures located at various depths from middle to lower crust through the upper mantle. The spatial extents of the main resistive and conductive structures vary from a few hundred to several 100's of km. The 3-D conductivity model is dominated by structures which characterize the spatial variations of the subsurface electrical conductivity and reflect the transition from the tectonically active NW Pacific in the west to the more stable North American tectonic plate in the east. Although rapid development of computation resources and the availability of numerical codes make a 3-D modeling of magnetotelluric (MT) a practical tool even on a personal computers, cautions must be taken into account while handling a large scale real data set. In addition to discussing major conductive and resistive features revealed in our 3-D model we also report on model and data resolution studies conducted to better understanding structures obtained in the preferred model.

Keywords: 3-D forward modeling, inversion, US-Transportable Array.

INTRODUCTION

The northwestern United States exhibits several fundamental tectonic elements of global import. Principally these are subduction-driven assembly of micro-continents to a cratonized core, imprint of modern arc volcanism, back-arc extensional collapse, and possible deep-sourced plume input. Associated with these processes are regional-scale temperature variations as well as the generation and migration of fluids and melts. Both processes can be controlled by and redefine prior continental rheology, and are key in element transport, ore deposition and geothermal activity. Early terrain boundaries can become cryptic to the surface due to later events. Because bulk electrical resistivity in the Earth can be strongly affected by small degrees of fluids and other mineral boundary constituents such as graphite, a magnetotelluric (MT) component to the U.S. Earthscope transportable array program was undertaken and has operated since 2006. To date, 325 tensor MT sites in a roughly grid-like format with 70 km average spacing have been acquired in the U.S. Pacific Northwest region and are freely available for interpretation. Here we present a fully 3-D inversion model of resistivity from the lower crust to the mantle transition zone and correlate properties to the region's tectonic inheritance and modern activity.

THREE DIMENSIONAL INVERSION PROCEDURE

For 3-D modeling and inversion we used the ModEM code of Egbert and Kelbert (2012). This inversion code is based on a finite difference (FD) forward solver, with conductivity parameterized in terms of the numerical grid cells, regularized by penalizing deviations from a prior model. Minimization of the penalty functional is based on a non-linear conjugate gradient search algorithm (NLCG), parallelized using the scheme of Meqbel (2009).

For the 3-D inversion effort reported here we directly invert all components of the impedance tensor (**Z**), as well as vertical magnetic transfer functions (**T**) for the 325 stations. We assigned error floors of 5% of $\left|Z_{xy}Z_{yx}\right|^{1/2}$ for all **Z** components and a constant value of 0.03 for **T** components. Although data quality is generally good, we omitted ~3 % of the data which were determined to be noisy or possibly biased.

To reduce the size of the model domain we adopted a nested modeling approach, based on extracting (by interpolation) the tangential electric component from a larger and coarser grid. This strategy results in a considerable run time reduction and improves boundary values. For the preferred model presented below the inner grid had a uniform horizontal resolution of 12.5 km (so N_x= 124 and N_y= 156), while the outer grid was of dimension 78 x 98 with a resolution of 25 km in the central part, grading to larger cells at the edges. In the vertical direction, 43 layers were spaced logarithmically increasing by a factor of 1.2 from 50 m, extending to a total depth of 1500 km.

To explore the model and data spaces and set proper inversion parameters we conducted numerous inversion runs. Some particular conclusions from these sensitivity tests include: i) A homogeneous prior model of a 100 Ω.m in which the Pacific Ocean (0.3 Ω.m) is embedded seems to be a proper choice. ii) The depth resolution of the data is ~ 350 km. iii) The finer grid with 12.5 km horizontal resolution results in a much better data fit in comparison to the 25 km horizontal resolution grid. This suggests that small scale features are required by the data.

RESULTS AND DISSCUSION

The 3D model presented in this study provides comprehensive insight into the electrical conductivity distribution in the northwestern US. Figure 1a, showing an E-W cross-section extracted from the 3D model near latitude 42˚N, illustrates many of the principal features of the inverse solution. The subducting oceanic Gorda plate lithosphere appears as a resistive structure underlying the Coast Range province. The lower crust and, in places, the upper mantle just below the moho is highly conductive in extensional areas beneath Oregon, southern Idaho, northeast California and Nevada and western Utah (Label C1). The eastern margin of the model is dominated mostly by resistive structures reflecting the thick Proterozoic stable craton of the North American tectonic plate (e.g., Wyoming craton, WYC). In the mantle between the Gorda and the WYC, resistivities are moderately low (20-30 Ω.m; feature C2) below ~200 km, but are higher (~100 Ω.m) from ~60 through 150 km. These principal model resistivities are consistent with a thin thermal continental lithosphere only ~50-60 km thick in the active provinces of the west, increasing to around 200-250 km under the cratonic stable areas (Goes and van der Lee, 2002). To illustrate the lateral extent of conductive and resistive features revealed in the preferred model plan views at four depths (31-37, 136-164, 197-236 and 284-341 km) are presented in Fig. 1b. Low resistivities are found at deep crustal/uppermost mantle depths (31-37 km) over most tectonically active areas in the region, including the Northern Basin and Range (NBR), Snake River Plain (SRP), and High Lava Plains (HLP). As discussed in Wannamaker et al. (2008), high lower crustal conductivities in extensional areas such as the NBR are most plausibly explained by underplated, hybridized magmas and highly saline fluids exsolved therefrom, residing below the brittle-ductile transition down to moho depth levels. Higher conductivities are observed in SRP and extend to the uppermost mantle (~50 km). The higher conductivities in the mantle are most likely related to the presence of melt (e.g., Wannamaker et al., 2008; Kelbert et al., 2012).

Along the Cascade Volcanic Arc (CVA) high conductivities are revealed at mid- to lower crustal depths. The high conductivities beneath the CVA are most likely due to aqueous fluids, in this case associated with slab dehydration and arc magmatism (Wannamaker et al., 1989; Peacock, 1993), although some melt could also be present beneath the arc (e.g., Hill et al., 2009). In the east-northeastern portion of the model area, low resistivities are also found in the 30-65 km depth range in a northeast trending Great Falls Tectonic Zone (GFTZ; Whitmeyer and Karlstrom, 2007), in the Cheyenne Belt (CB) and in the Vulcan Suture (VS). Crustal conductive anomalies in the Proterozoic GFTZ and CB are not likely to be associated with fluids, given the great age of these geologic features. High conductivities such as these have been frequently observed along terrain boundaries and sutures, and are most often interpreted as resulting from graphite or sulfides metamorphosed and emplaced deep within the crust during subduction and/or orogenesis (e.g., Boerner et al., 1996; Jones et al., 2005).

The aforementioned conductive trends separate major deep resistive blocks in the northeast (depth slice 136-164 km in Fig. 1b). The two clearest are readily identified with well-known terranes of stable Archean continental lithosphere: WYC and the Medicine Hat Block (MHB), which together were accreted to the North American core at ~1.8 Ga across the GFTZ (Whitmeyer and Karlstrom, 2007). Another deep resistive feature is observed underneath the Columbia River Plateau (CRP) reaching a depth of ~ 60 km. Humphreys (2009) interprets the roughly triangular continental block (dashed white line in depth slice 31-37 km in Fig. 1b; referred to as Siletzia), as a piece of Farallon lithosphere that accreted within the Columbia Embayment at ~48 Ma (Madsen et al., 2006).

In deeper plan views through the upper mantle a large coherent resistive volume underlies northwestern Washington and northern Idaho states (depth slices 136-164 and 197-236 km in Fig. 1b). This feature coincides spatially with the sub-vertical, high velocity feature (dashed black and white outline in Fig. 1b) interpreted by Schmandt and Humphreys (2010) to be a piece of

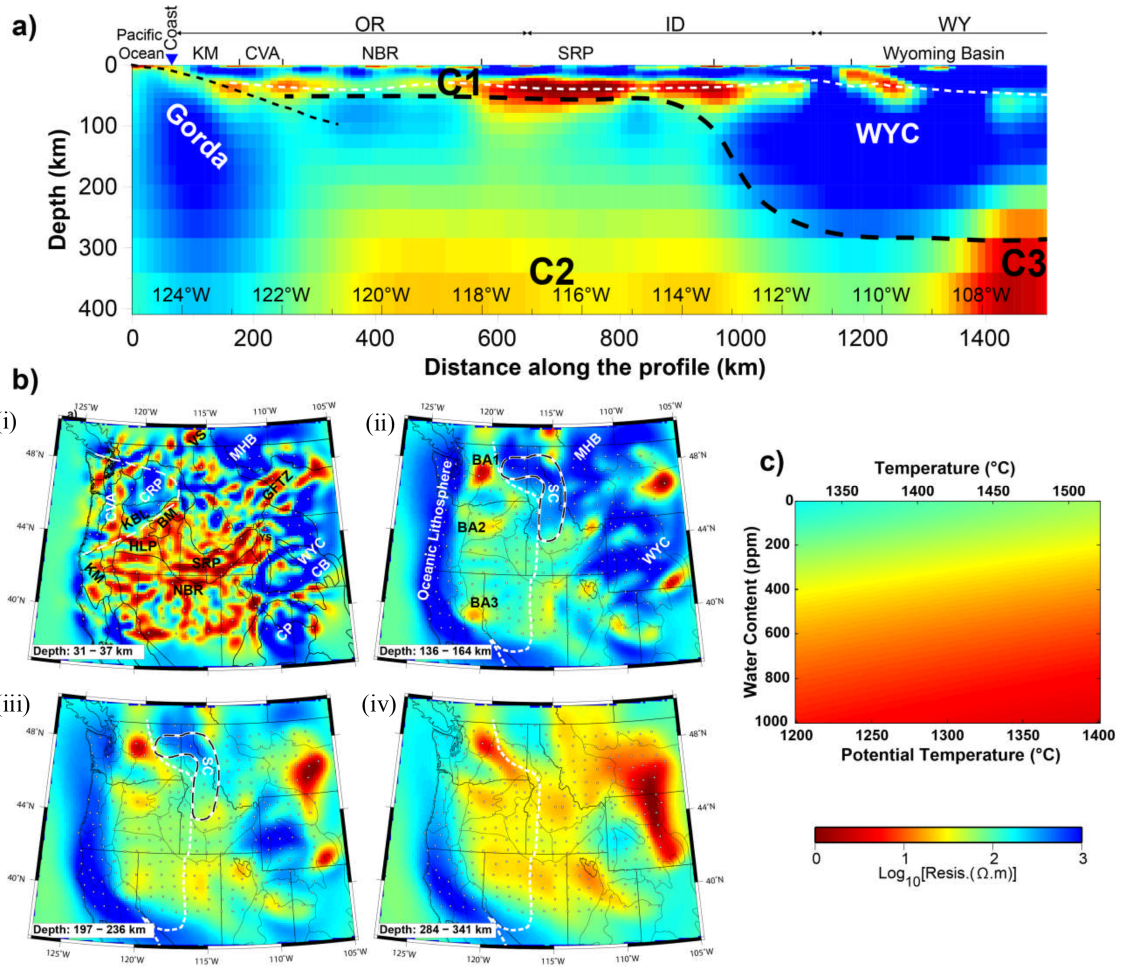

Figure 1: **a)** Representative east-west cross section (at a latitude of 45.5N), illustrating some of the main features revealed in the preferred model. Black short-dashed line illustrates the top of the subducting Juan de Fuca plate (McCrory et al., 2012), dashed white line gives an estimate of moho from receiver functions (A. Levander, personal communication), and black long-dashed line represents a schematic LAB. WYC: Wyoming craton; C1: conductive layer near the moho C2: hydrated aesthenospheric mantle. **b)** Model resistivity for four depths, with features discussed in text labeled. KBL: Klamath-Blue Mts. Lineament; BM: Blue Mountains; CRP: Columbia River Plateau; CP: Colorado Plateau. Dashed white line in (i) represents the outline of Siletzia as interpreted by Humphreys (2009). White and black dashed line in (ii) and (iii) shows the outline of the "slab curtain" (SC) of Schmandt and Humphreys (2010). White dashed line in (ii), (iii) and (iv) represents the Sr0.706 line (inferred to define the boundary between Precambrian North American and accreted terrains to the west; DeCelles, 2004). Site locations are denoted by small dots in all sections. **c)** The inset shows conductivity as a function of temperature and water content, inferred from Poe et al. (2010).

relict subducted Farallon plate, which they refer to as the "slab curtain" (SC).Although directly adjacent to the MHB to the east, closer examination of the 3D resistivity model suggests that the SC is a separate structure, and generally provides strong support for the model of Schmandt and Humphreys (2010).

Resistive oceanic lithosphere appears as a continuous feature all along the western edge of the continent (Fig. 1b). The imaged top of this resistive feature generally agrees well with seismic constraints on slab geometry to 90 km depth (McCrory et al., 2012, Fig. 1a). Resolution tests suggest that the bottom of this resistive feature is in fact poorly constrained; a conductive oceanic aesthenosphere (which would be expected; e.g., Wannamaker et al., 1989) is permitted by the MT TA data.

Three deep conductive zones (10-100 Ω.m) rise to shallow depths in the back arc above the subducting plate (BA1, BA2 and BA3, depth slice 136-164 km in Fig. 1b). In several places the low resistivities appear to connect into the sub-arc conductive zone, but there is significant along-strike variation. The most prominent

(BA1 in Washington State), is the very conductive structure dipping to the southeast, as clearly seen in the depth slice 197-236 km in Fig. 1b. This may represent upwelling aesthenospheric corner flow driven by subduction, forced through a relatively narrow conduit by the highly viscous slab curtain to the east.

Below the active regions in Fig. 1a, the upper asthenosphere from just below the crust to depths of ~150 km lies near 100 Ω.m, consistent with laboratory results for dry olivine at ~1300°C (Poe et al., 2010). From 200 km downward, resistivities mainly are in the 15-30 Ω.m range, requiring moderate levels of hydration. Under cratonic areas, we interpret a simple but large drop in resistivity to typical values of a few 10's of Ω.m. We have concerns that the deep even lower resistivities at the eastern edge of the array (C3 in Fig. 1a) may reflect contamination by the NACP (North American Central Plains) anomaly, 200 km further east.

For a plan view perspective, the 283-340 km model layer in Fig. 1b should be well within the aesthenosphere throughout the model domain (except in the subduction zone). To compare the model slice to laboratory results we also plot resistivity at 300 km depth for a range of temperatures and water contents (Fig. 1c), computed from the geometric average of the single crystal laboratory resistivity measurements for olivine given in Poe et al. (2010). Over most of the domain, model resistivities at this depth are consistent with the laboratory results at reasonable mantle potential temperatures (~1300˚C), assuming moderate levels of hydration (several hundred ppm).

REFERENCES

Boerner, D. E., Kurtz, R. D. and Craven, J. A., 1996, Electrical conductivity and Paleo-Proterozoic foredeeps, J. Geophys. Res., 101(B6), 13775–13791, doi:10.1029/ 96JB00171.

Egbert, G. D., and Kelbert, A., 2012. Computational Recipes for Electromagnetic Inverse Problems, Geophys. J. Int. 189: 251–267. doi: 10.1111/j.1365-246X.2011.05347.x.

Gao, H., Humphreys, E. D., Yao, H. and van der Hilst, R. D., 2011, Crust and lithosphere structure of the northwestern U.S. with ambient noise tomography: Terrane accretion and Cascade arc development. Earth and Planetary Science Letters, 304 (1-2), 202-211,. doi:10.1016/j.epsl.2011.01.033.

Goes, S., and van der Lee S., 2002, Thermal structure of the North American uppermost mantle inferred from seismic tomography, J. Geophys. Res. 107(B3), 2000JB000049.

Hill, G. J., Caldwell, G. T., Heise, W., Chertkoff, D. G., Bibby, H. M., Burgess, M. K., Cull, J. P., and R. A. F. Cas, 2009, Distribution of melt beneath Mount St Helens and Mount Adams inferred from magnetotelluric data, Nature Geosci., 2, 785-789.

Jones, A. G., Ledo, J., and Ferguson, I. J., 2005. Electromagnetic images of the Trans-Hudson orogen: the North American Central Plains anomaly revealed, Can. J. Earth Sci. 42: 457–478

Kelbert, A., Egbert, G. D., and deGroot-Hedlin, C., 2012. Crust and upper mantle electrical conductivity beneath the Yellowstone Hotspot Track, Geology, 40, 447-450, doi: 10.1130/G32655.1.

Madsen, J. K., Thorkelson, D. J., Friedman, R. M. and Marshall D.D., 2006, Cenozoic to Recent plate confi gurations in the Pacifi c Basin: Ridge subduction and slab window magmatism in western North America, Geosphere, v. 2; no. 1; p. 11–34; doi: 10.1130/GES00020.

McCrory, Patricia A., 2012, Juan de Fuca slab geometry and its relation to Wadati-Benioff zone seismicity, ournal of Geophysical Research, 117, 2156-2202.

Meqbel, N. M., 2009, The electrical conductivity structure of the Dead Sea Basin derived from 2D and 3D inversion of magnetotelluric data, PhD-Thesis, Free University of Berlin, Germany.

Peacock, S. M., 2003, Thermal structure and metamorphic evolution of subducting slabs. in Inside the Subduction Factory, (ed Eiler, J.), Amer. Geophys. Monogr., 138, 7-22.

Poe, B.T., Romano, C., Nestola, F., Smyth, J.R., 2010. Electrical conductivity of dry and hydrous olivine at 8 GPa. Phys. Earth Planet. Int. 181, 103–111.

Schmandt, B., and Humphreys, E., 2010, Complex subduction and small-scale convection revealed by body-wave tomography of the western United States upper mantle. Earth and Planetary Science Letters, 297(3-4), 435-445, doi:10.1016/ j.epsl.2010.06.047.

Wannamaker, P. E., Hasterok, D. P., Johnston, J. M., Stodt, J. A., Hall, D. B., Sodergren, T. L., Pellerin, L., Maris, V., Doerner, W. M., Groenewold, K. A., and Unsworth, M. J., 2008, Lithospheric dismemberment and magmatic processes of the Great Basin-Colorado Plateau transition, Utah, implied from magnetotellurics, Geochem. Geophys. Geosyst., 9, No.5, Q05019, doi:10.1029/2007GC001886.

Wannamaker, P. E., Booker, J. R., Jones, A. G., Chave, A. D., Filloux, J. H., Waff, H. S., and Law, L. K., 1989, Resistivity cross section through the Juan de Fuca subduction system and its tectonic implications, J. Geophys. Res., 94, B10, 14,127-14,144.

Whitmeyer, Steven J. and Karlstrom, Karl E., 2007, Tectonic model for the Proterozoic growth of North America, Geosphere, 3, 220-259.