Hydration State of the Upper Mantle in the Arc-Extended Backarc Regions of Southern Cascadia and the Great Basin, Western U.S., from Magnetotellurics

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Abstract: The distribution of water in the upper mantle is believed to have strong influence upon global dynamics by influencing mantle rheology, modal mineralogy, melting systematics and chemical differentiation. The principal input of water is the process of subduction which is estimated to have introduced one to several ocean volumes to the mantle over Earth history. In principle, a large proportion of this water may be dissolved in the nominally anhydrous silicate minerals (NAMs), but quantifying this has been challenging. Electrical conductivity is strongly sensitive to mineral hydration and could provide estimates of mineral water content with suitable constraints. A 1300 km E-W transect of ~400 magnetotelluric (MT) soundings from the northern California coast over the Gorda plate, across the Great Basin of Nevada and western Utah, and spanning the Colorado Plateau of eastern Utah, reveals an upper mantle whose resistivity below the broad Great Basin falls progressively with depth from values of ~100 ohm-m near 50 km to <10 ohm-m by 400 km depth. We test the hypothesis that the vertical resistivity profile is consistent with the maximal degree of hydration allowed by ambient T-P short of triggering H2O-undersaturated melting (cf. Ardia, 2012, EPSL). Assuming standard and enhanced adiabats, deep resistivity profiles predicted using lab data suggest only resistivities in the near 'hanging wall' of the Gorda subduction zone under northwestern Nevada are low enough to represent full NAMs hydration. Under the central (eastern Nevada) and eastern (western Utah) Great Basin, large-scale resistivities are at least 2-3x too high, nominally.

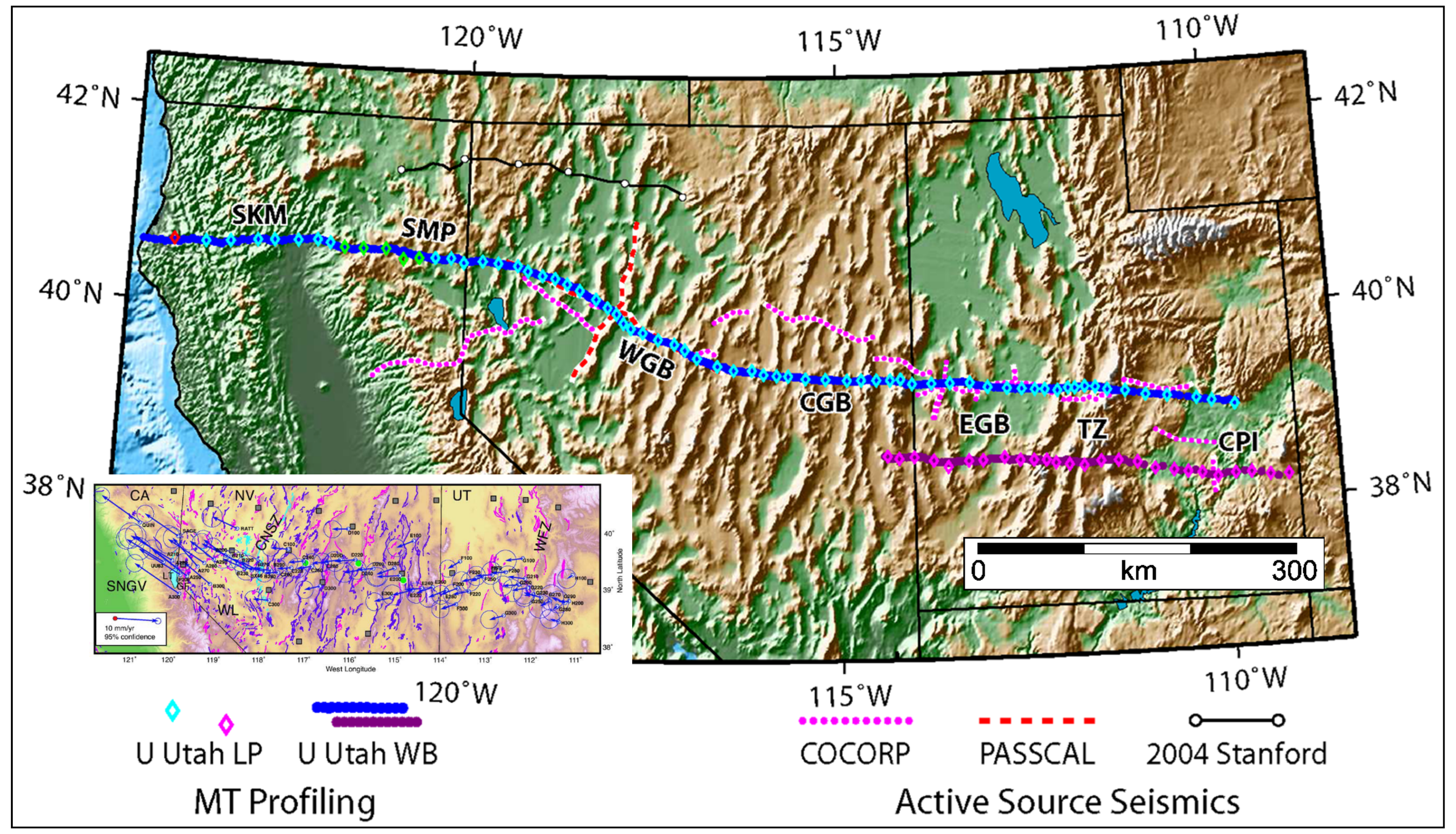


Figure 1. Transect map of ~400 wideband (0.005 - 800 s) and 68 long period (10-17480 s) MT sites across subducted Gorda plate (Klamath Mtns), transtensional Modoc Plateau, extensional Great Basin, and unextended Colorado Plateau. Lower left inset shows GPS vectors of Hammond and Thatcher (2004, JGR). MT data quality generally excellent and built up over >a decade. Period range covers depths of sensitivity from ~300 m to >400 km. We will use the electrical conductivity model from these data to assess solid-state hydration of peridotite mineralogy given that seismic velocity appears insensitive to that property (Cline et al., 2018, Nature).

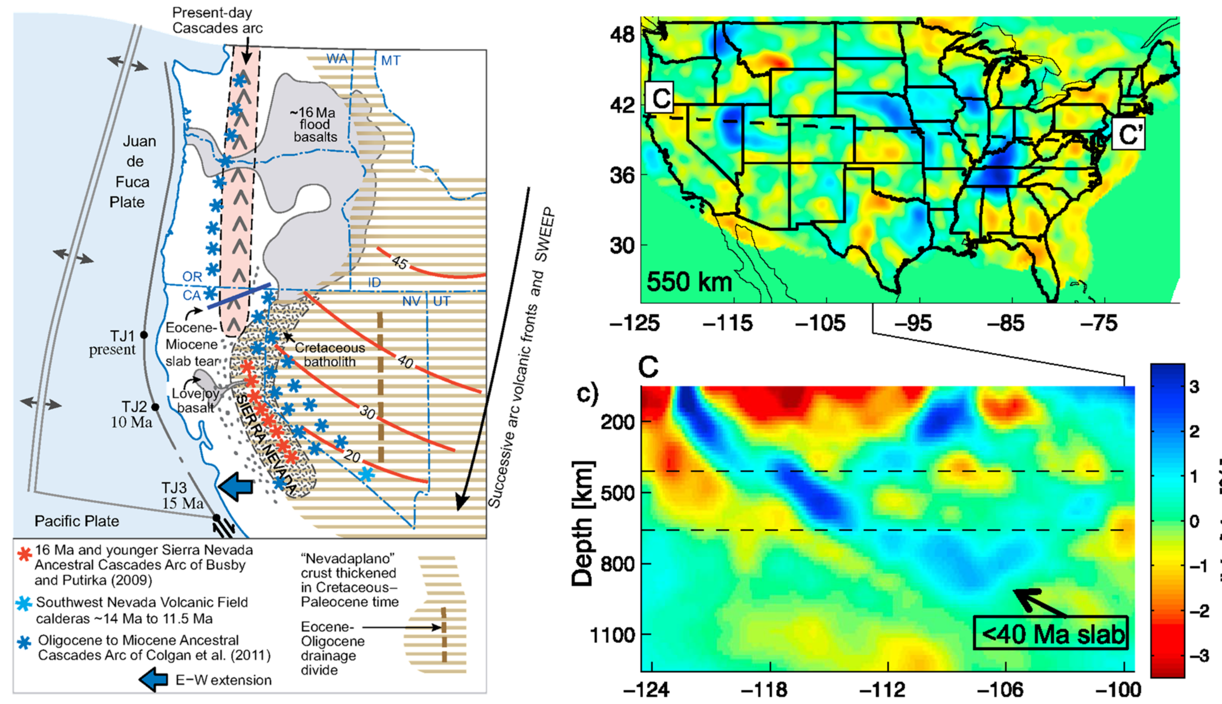


Figure 2. Some regional tectonic context. Left: Southern edge of current Gorda plate extended considerably further south than inferred today, prior to development of the MTJ and Walker Lane (Busby, 2013, Geosphere). Thus, we can consider upper mantle hydration to have been a steady process since the Eocene and we are not merely over its southern edge. Right: P-wave tomography (Schmandt and Lin, 2014, GRL) images the current disposition of Gorda plate at depth, which appears to be somewhat flattened in the Transition Zone under much of the project area.

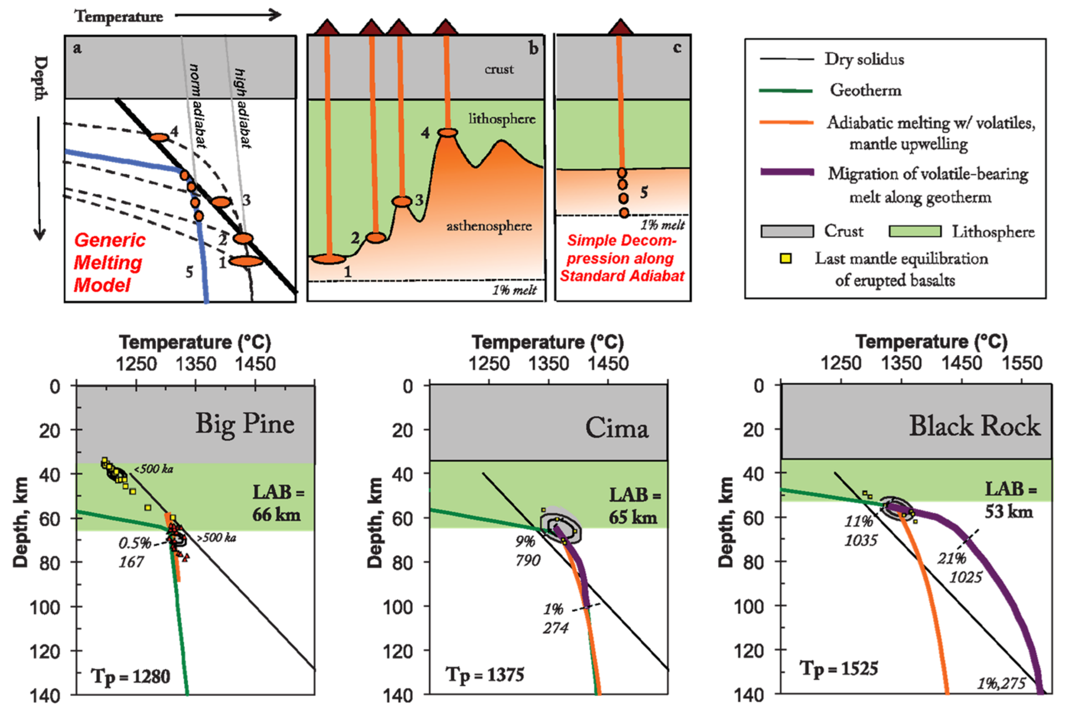


Figure 3. Thermo-petrological model of Plank and Forsyth (2016, GGG) across the Great Basin based on combined basalt melting-shear wave velocity modeling. This suggests wetter, cooler melts controlled by adiabat with lower Tp in the west and dryer, hotter melts controlled by adiabat with higher Tp in the east. Upwelling asthenosphere along variable adiabats leads to melt burrowing into base of lithosphere with significant melt fractions. Wetter melts in west compatible with Gorda plate influence. However, inference of superadiabatic under western Utah is predominantly due to large low seismic velocity anomaly there.

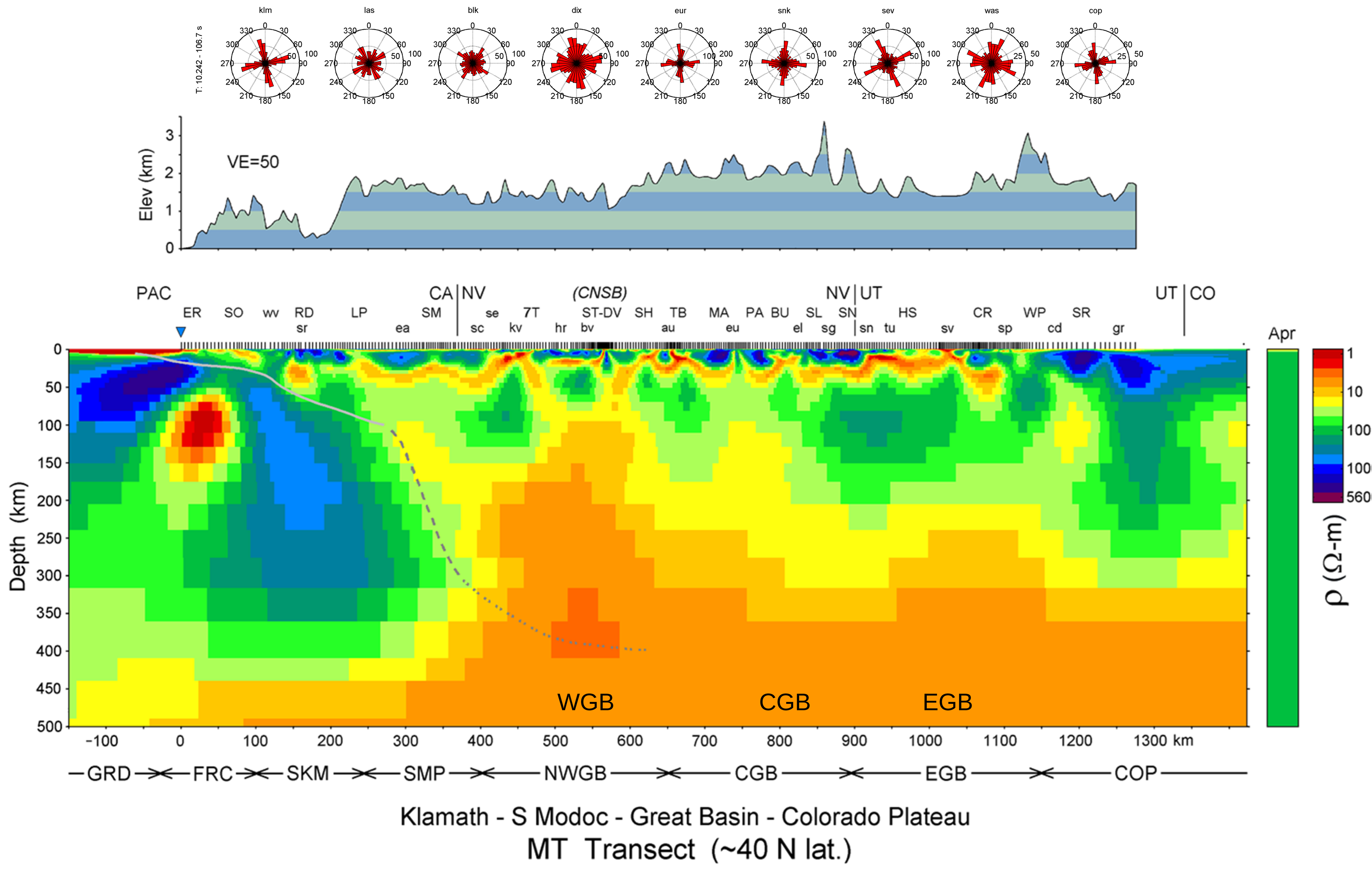


Figure 4. 2D MT resistivity model from TM mode inversion of integrated WB and LP sites along transect, plus LP Re(Kzz) near distal transect ends. Starting model was 100 o-m. East-deepening resistive Gorda Plate obvious in the west (McCrory et al, 2012, JGR; Tauzin et al, 2016, EPSL). Low resistivity within the Gorda plate resembles low Vp anomaly of Hawley (2016, Science) as a melt accumulation. Flux melting is seen above its surface from Lassen Peak (LP) eastward to California border. Extensive undulatory Moho-level magmatic underplating is seen beneath entire Great Basin, with occasional high-angle conductors extending upward into geothermal systems. Blobby green zones in the 50-150 km depth range, esp below western Utah, appear to be low of hydration and melt content. Resistivity of 100-200 o-m is compatible with dry peridotite and typical mantle adiabat. From 150-410 km, low resistivities are pervasive below Great Basin. Relatively higher water concentration looks possible under western Nevada just east of Gorda plate interface from subduction fluxing.

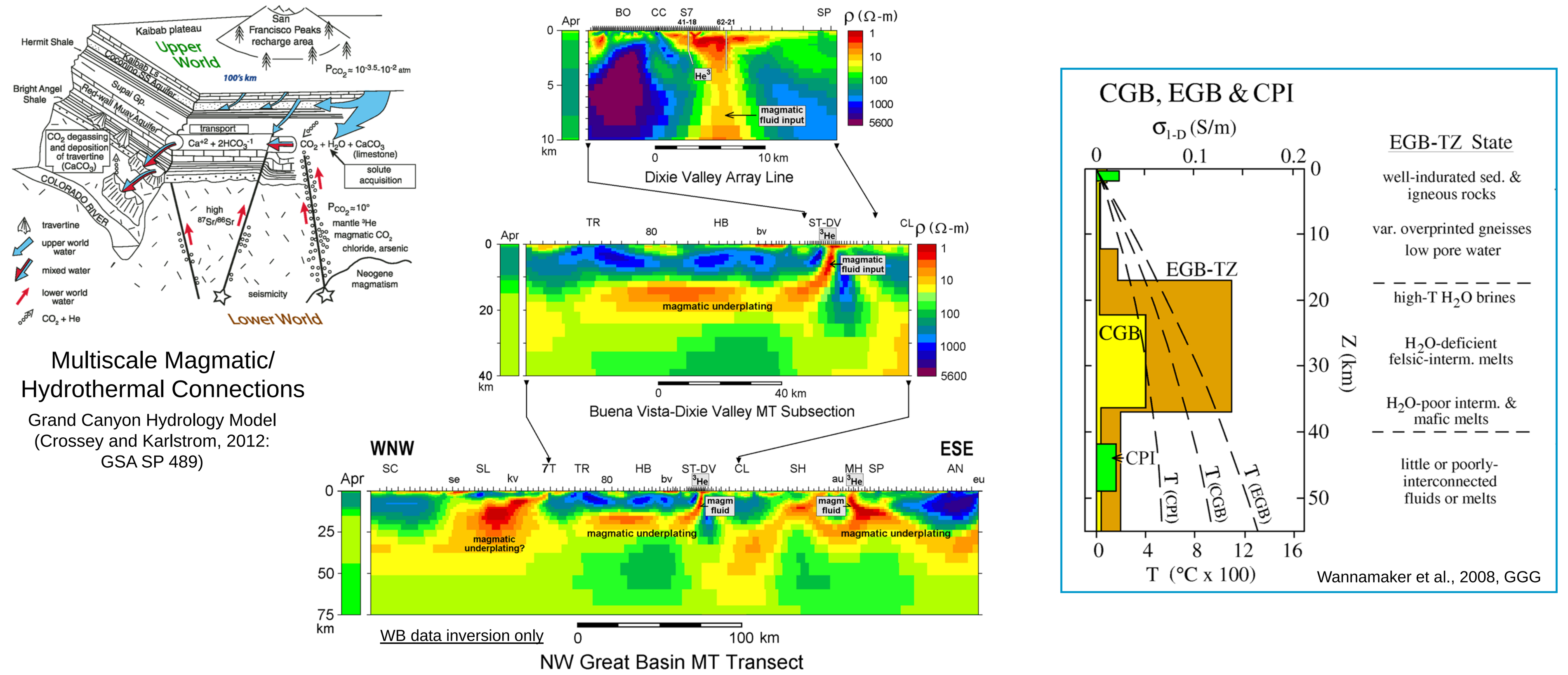
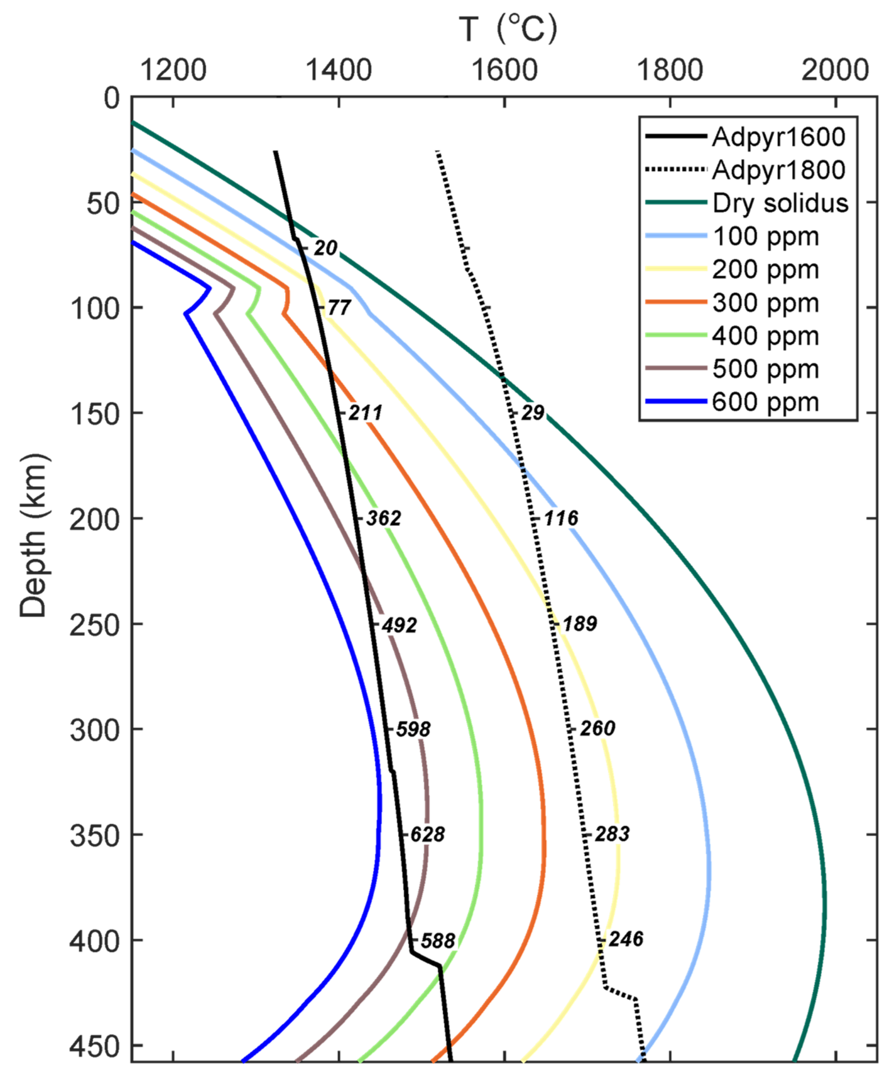


Figure 5. Closeup view of MT transect resistivity centered upon the Dixie Valley geothermal system in northwestern Nevada. This inversion was performed prior to integration of the long period data and so differs slightly but not majorly from previous slide. Quasi-horizontal low resistivity in deep crust is interpreted to be magmatic underplating and fluid release based on likely temperatures, and the seismic observations of P-wave attenuation, high reflectivity and high velocity under Buena Vista valley area. High angle conductive 'fault' zones connect upward to known geothermal systems, which exhibit elevated 3He emissions (Wannamaker et al., 2007, GRC Trans.; Kennedy and van Soest, 2007, Science). A supportive regional hydrological/tectonic interpretation based on spring and alteration geochemistry by Crossey and Karlstrom (2012, GSA SP 489) appears in upper left and correlates well with our interpretation of crustal scale MT resistivity. Rightside panel offers broadscale fluid/melt state for central and eastern Great Basin (CGB, EGB) and Colorado Plateau interior (CPI) from regional MT impedance averages (Wannamaker et al, 2008, GGG).



Is upper mantle conductivity explained by adiabatic temperatures and maximal NAMs hydration (short of melting), cf. Ardia et al (2012, EPSL)?

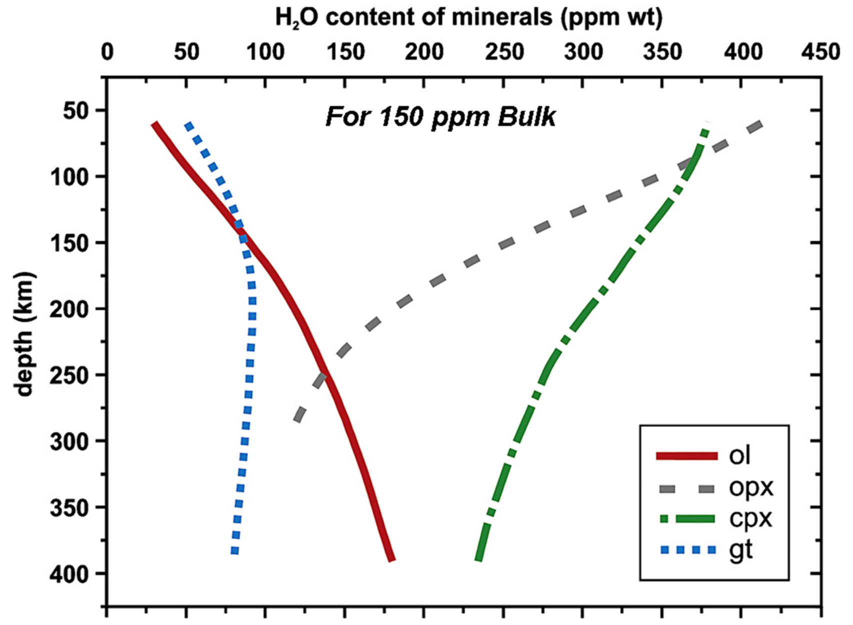


Figure 6. Peridotite solidi versus bulk water concentration in wt ppm computed from model of Hirschmann (2009, PEPI), supplied by Marc Hirschmann. Overlain are two model mantle adiabats from Stixrude and Bertelloni (2011, GJI), provided by Lars Stixrude for Tp = 1600K and 1800K. For normal adiabat, H2O ppm of 500-600 in peridotite can exist in lower half of upper mantle before melting occurs. For enhanced adiabat, only ~200 ppm can exist. Water ppm in olivine is <bulk peridotite due to partitioning, estimated using partition coefficients of Novella et al (2014) and written at regular depth intervals along the adiabats.

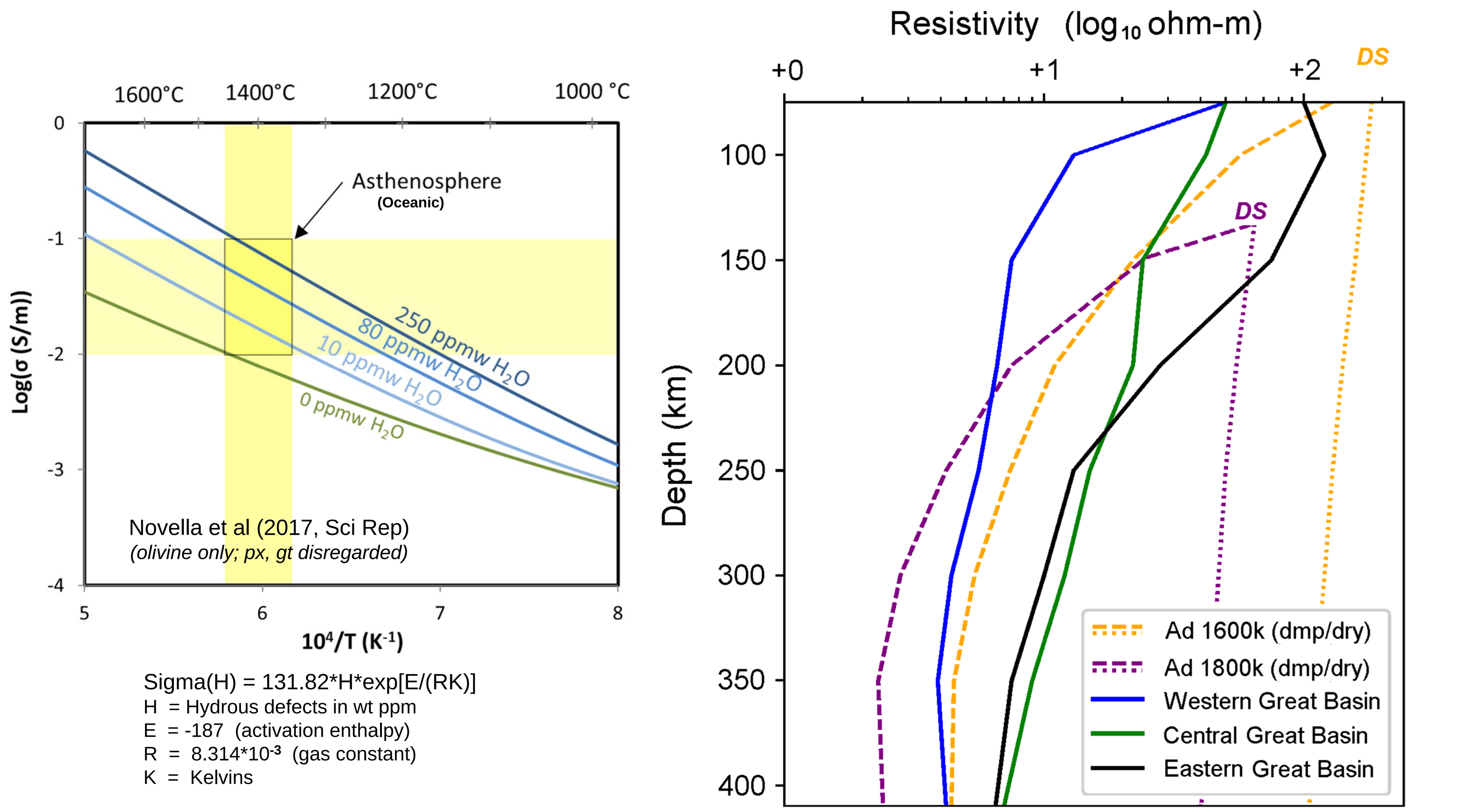


Figure 7. Current laboratory results on conductivity of hydrated olivine based on H self-diffusion, following Novella (2017, Sci. Rep., left panel). Operant relation is their eq'n 6 repeated here. On the right, values are computed for olivine hydration levels of Figure 6 for both adiabats, then added to dry olivine baseline values from duFrane (2005, GRL) (dashed curves). Field resistivity profiles drilled down through the model of Figure 4 are as solid lines. For western Great Basin above Gorda plate, agreement is reasonable, but away from Gorda plate they appear 2-3x more resistive. Resistivity along the higher adiabat is somewhat lower than along the normal due to higher T despite lower permissible hydration. Model resistivity exceeding 100 o-m at ~100 km depth below western Utah appears too high to allow superadiabatic conditions in terms of dry olivine. Resolution will be tested further. Many thanks to Prof. Jim Tyburczy, ASU, for helping us on these calculations, plus Marc Hirschmann and Lars Stixrude for auxiliary data. U.S. DOE DE-0006732 and NSF EAR-0838043, OPP-1443532, and numerous prior, supported the research.