**Upper Mantle Physical State and Lower Crustal Igneous Input:
A Test of Current Models with Data from the U.S. Great Basin**

Extended Abstract for
Plume IV: Beyond the Plume Hypothesis
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Introduction

Hotspot activity and continental rifting have motivated numerous models for physical state of the upper mantle prior to extension and the importance of igneous material input to crustal growth. Upper mantle conditions and dynamics are believed to determine the amount and characteristics of igneous crustal input; alternately, igneous underplate properties provide clues as to the mantle physical state and fluxes which generated the underplate (e.g., Holbrook et al., 2001; Korenaga et al., 2002; Trumbull et al., 2002). The tectonically active southwestern United States interior (Humphreys and Dueker, 1994; Parsons, 1995) exemplifies one of three types of mantle hotspot in the classification of Courtillot et al. (2003). Within there, the eastern Great Basin spanning central Nevada to central Utah resembles the early-middle stages of margin formation, and thus allows formulation of tests for globally applied models of upper mantle physical state and its controls on subcrustal magmatism at volcanic continental margins, such as the Greenland-Iceland province or the central Atlantic continental margins (Lizzaralde and Holbrook, 1997; Holbrook et al., 2001; Ernst and Buchan, 2002).

Igneous Underplate and Mantle Physical State

Research on margins over the past decade has yielded a new appreciation of the large volumes of magmatic material produced at most rifted continental edges (e.g., White and McKenzie, 1989; Menzies et al., 2002). The amount and composition (and thus seismic properties) of magmatic underplating that occur during rifting depend on three factors: mantle potential temperature (T_p), active upwelling ratio (χ), and thickness of the lithospheric lid (defined by degree of lithospheric thinning (β)) (Kelemen and Holbrook, 1995; Holbrook et al., 2001; Korenaga et al., 2002) (Figure 1). Magma volume increases with T_p and β and decreases with increasing lid thickness. V_p increases with T_p, decreases slightly with increasing lid thickness, and is relatively insensitive to β.

The simplest magmatic state under the eastern Great Basin (EGB) would be of negligible underplate (Figure 1a). Surface divergence rate equals mantle upwelling rate (χ = 1) which is passive stretching as defined by White and McKenzie (1989). Mantle thermal state shows limited change from that just following the general exhumation of the Great Basin by Middle Miocene time, presumed to be the average current mantle adiabat (ACMA; Thompson, 1992), as discussed later, with $T_p \approx 1280^oC$. The melting window is narrow and shallow, and average velocity is medium (6.9-7.0 km/s; Korenaga et al., 2002). This state is compatible with modeling of White and McKenzie where little underplate (<1 km) is produced for $\chi = 1$ until the late rift stages near final oceanic breakthrough, which the EGB has not reached. There are no significant high-T plumelike upwellings.

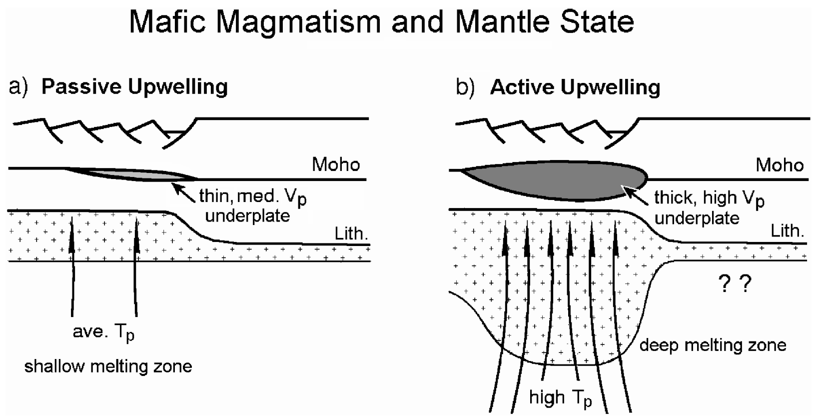

Figure 1. Modes of rift magmatism, applied to the eastern Great Basin: a), thin, moderate V_p (6.9-7 km/s) rift pillow forms in response to normal T_p and passive upwelling; b), rift pillow of substantial thickness and high V_p (>7.3 km/s) forms in response to high T_p and active upwelling in upper mantle.

At the other extreme, suppose material of higher T_p than ACMA was introduced below the EGB in the Late Cenozoic, and a high active upwelling ratio χ has existed pumping a greater amount of source material through the solidus (Figure 1b). Underplate in this case could be thick (10 km or more) and of high V_p (7.3 km/s or more for T_p > ACMA + 200^oC) because the solidus is intersected at greater depth, allowing a broader, deeper melting interval for a given degree of mantle upwelling and melt compositions with increased MgO and reduced SiO_2 (White and McKenzie, 1989; Kelemen and Holbrook, 1995; Korenaga et al., 2002). Concentrated upwellings of high-temperature (plume?) mantle material currently are advanced as the means of producing significant quantities of pre-rift or syn-rift magma occurring before oceanic breakthrough at continental margins (Menzies et al., 2002).

Intermediate scenarios are possible, of course. Passive upwelling of high T_p material could generate a limited amount of high-V_p underplate. High active upwelling ratio may form a moderate degree of underplate but of only medium V_p. Thick, high V_p underplate under the easternmost GB is suggested by four lines of evidence, each of which is quite tentative, as discussed next.

Mantle Physical State, Evidence on Crustal Underplating, and Mode of Extension in the Eastern Great Basin

The Late Cenozoic-present extension in the Great Basin shows a concentration at its eastern margin (Smith et al., 1989; Wannamaker et al., 2001). Correspondingly, Quaternary basaltic magmatism shows a clear N-S trend in extended western Utah evolving from alkalic compositions characteristic of ancient metasomatized mantle lithosphere to tholeiitic magmas more akin to fertile, asthenospheric input (Hawkesworth et al., 1995; Nelson and Tingey, 1997; Wannamaker et al., 2001). The crust in the eastern GB appears to have thinned by ~2 since the mid-Miocene (Wernicke, 1992; Wannamaker et al., 2001), meaning rather limited mantle material would have been pumped through the melting interval in a passive mode. Lithospheric-scale simple shear rifting and other modes of NUE can produce high-degree mantle thinning (χ) locally promoting melt production and underplating (Buck and Su, 1989; Harry and Bowling, 1998; Boutelier and Keen, 1999). Degree of mantle thinning also may be cryptic to crustal indicators.

Great Basin extension initiated in north-central Nevada but quickly spread throughout the province, with broadscale exhumation and differentiation from the Colorado Plateau in the Early-Middle Miocene (Zoback et al., 1994; Stockli, 1999; Dumitru et al., 2000). The broadscale upper mantle thermal regime in the region likely is close to the current global average adiabat ACMA (Thompson, 1992) (Figure 2). From V_p and V_s estimates, Goes and van der Lee (2002) advance a geotherm for the central GB which is close to ACMA. Likewise, a deep electrical resistivity profile for the central GB compared to conductivity of dry lherzolite indicates that the geotherm there should be no greater than ACMA (Wannamaker et al., 1997, 2002).

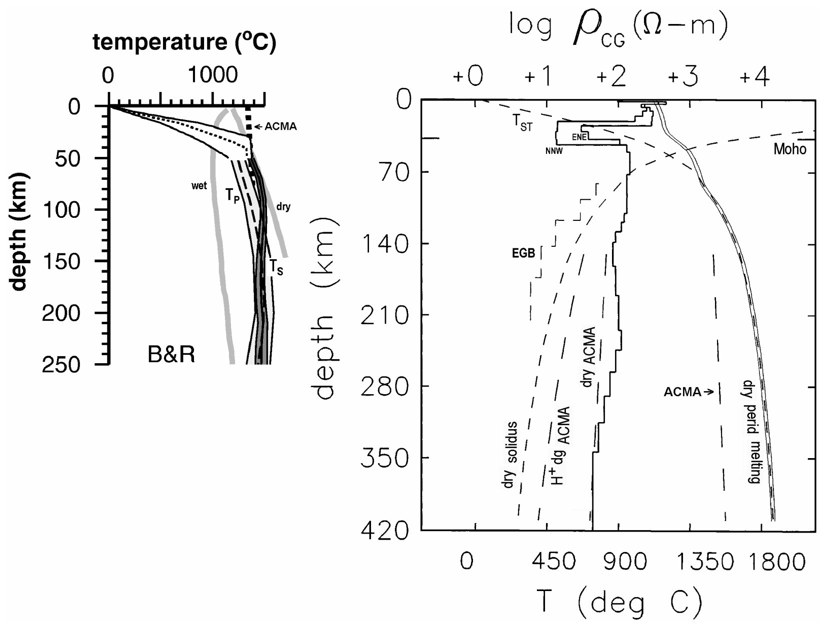

Figure 2. Left: Mantle thermal profile for central Great Basin from seismic tomography by Goes and van der Lee (2002), interpreted to be close to ACMA. Right: Mantle resistivity and thermal profiles in same region from deep MT data (Wannamaker et al., 2002). Curves toward right are temperature, curves toward left are resistivity. "Dry ACMA" is resistivity predicted for dry lherzolite and ACMA geotherm. "H^+dg ACMA" is with hydrogen defects in random olivene at reduced water activity (0.15). "Dry solidus" is unmelted lherzolite resistivity at dry solidus temperatures. ENE and WNW denote the principal directions and magnitudes of anisotropic resistivity in the lower crust. EGB is resistivity profile for eastern GB near latitude 39°S (Wannamaker et al., 2001).

Furthermore, given that central GB mantle resistivity is consistent with ACMA temperatures and dry lherzolite, the upper mantle there appears largely absent of elements which would alter geophysical properties from their dry peridotite state (cf. Karato, 1990). Original volume of low-melting components there apparently was insufficient to create its own resolvable underplate in the central GB (Holbrook, 1990; Satarugsa et al., 2000); the same is presumed throughout the GB prior to the modern concentration of rifting in the EGB.

Since the Late Miocene (~10 Ma), extension and volcanism have concentrated near the GB margins, in particular the relatively straight tectonic margin of western Utah (Christiansen and Yeats, 1992; Wernicke, 1992; Wannamaker et al., 2001). Though debated, evidence is perhaps stronger that highly non-uniform extension (NUE) occurs under the easternmost GB and its transition zone (TZ) with the Colorado Plateau based on heat flow, Curie depth, some crustal thickness models, earthquake travel times, and intracrustal conversions (Bodell and Chapman, 1982; Wernicke, 1985; Smith et al., 1989; Sheehan et al., 1997; Wannamaker et al., 2001; Gilbert et al., 2003; but see Pakiser, 1989) (Figure 3). High-Vp "rift pillow" material of 7.4-7.5 km/s in the 20-35 km depth interval there is suggested from earthquake travel times and tomography, and receiver functions. Garnet should be present to increase velocity only for depths >30 km.

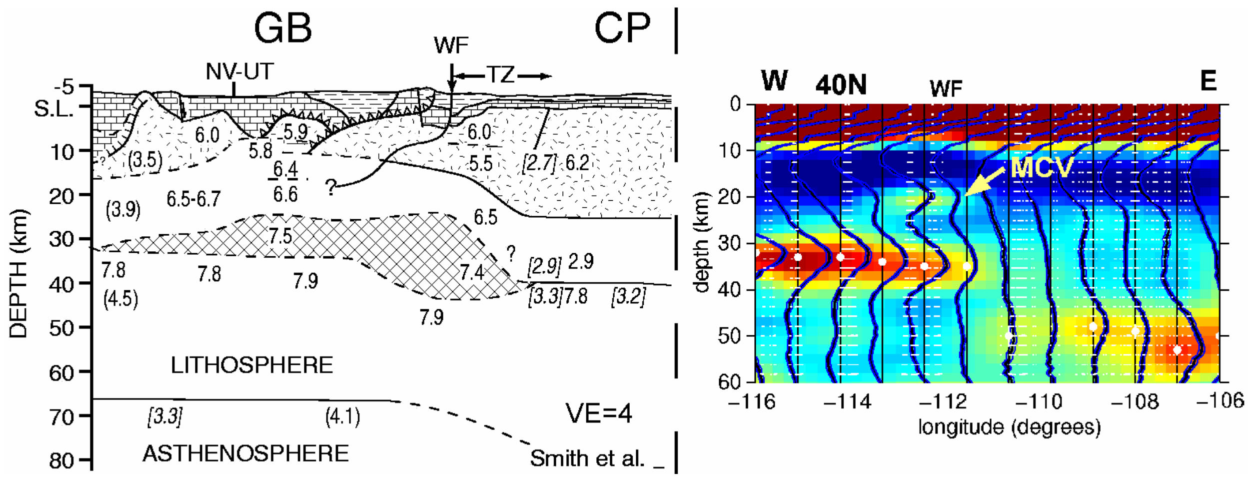

Figure 3. Left: crustal cross section through west-central Utah redrawn from Smith et al. (1989). P-wave velocities (km/s) are in bold, S-wave in parentheses, and densities (gm/cc) are in italics. Right: West-east cross-sections of common conversion point (CCP) stacked receiver functions in the western U.S. at approximately the latitudes of our proposed transects (Gilbert et al., 2003). Radial P waves are scaled to unity. Red color indicates positive polarity conversion, blue color represents negative. Stacked receiver functions shown in black, thinner blue lines are 1 s.d. derived from bootstrap resampling. Seismic rays shown as dashed white dotted lines converging to projections of instrument locations. Depths calculated assuming Vp = 6.4 km/s and Vp/Vs = 1.73. Mid-crustal converter beneath Wasatch Front (WF) is MCV.

Although various mantle tomographic images show the lowest upper mantle velocities and P and S delays under the easternmost GB and TZ (Humphreys and Dueker, 1994; Savage and Sheehan, 2000; Dueker et al., 2001; Lastowka et al., 2001), upper mantle temperate estimates have not been advanced to test the relation between mantle state and lower crustal underplating. However, a high conductivity concentration under the TZ implies mantle involvement in large-scale NUE to depths of 300 km or more (Figure 4). If dry peridotite compositions apply, as some evidence suggests, conductivity implies that temperatures reach the solidus with generation of some melt. Since this solidus is significantly hotter than ACMA, the EGB temperature profile represents a high temperature upwelling.

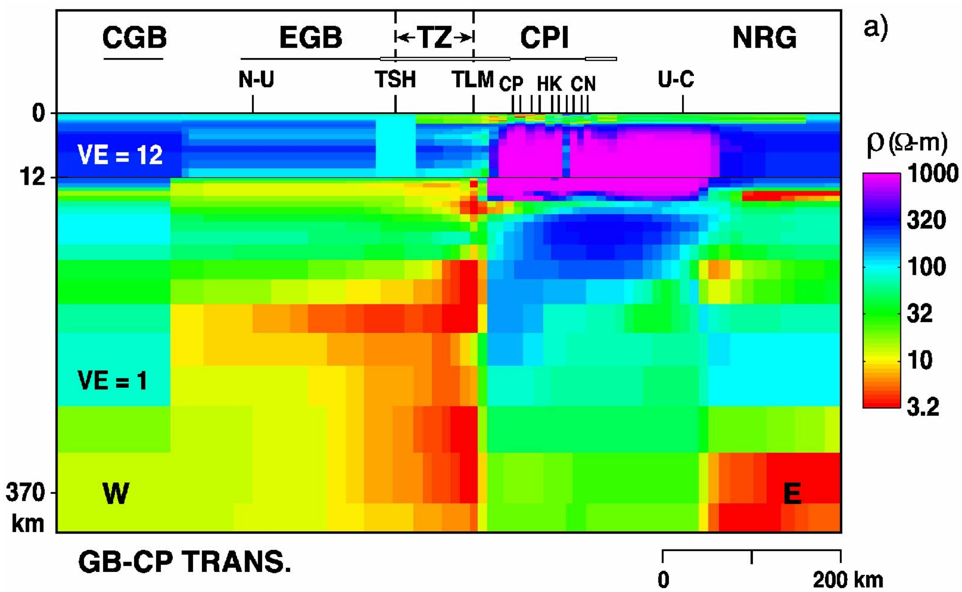

Figure 4. Inversion model of MT data to 10,000 s period in the EGB and the CP (Wannamaker et al., 2001). Projection of data profiles drawn overhead. Geographic features include Tushar Rangefront (TSH, S. extension of Wasatch Front), Thousand Lake Mountain (E. limit of TZ normal faulting), Capital Reef (CP), Hanksville (HK), and Canyonlands (CN). NRG is northern Rio Grande Rift. Open thin bars over TZ and eastern CPI are subject to upcoming MT fill-in. The starting average for EGB is shown in Figure 2.

Conclusions

Evidence is sparse, but taken at face value the properties of the eastern Great Basin confirm globally applied models relating mantle physical state to properties of mafic igneous underplate. A high-T upwelling is interpreted under the easternmost GB and TZ which may have generated a high-V_p rift pillow. We note that these melting models are based on laboratory experiments and have not been tested rigorously, largely because they have been applied to ancient rifted margins where any mantle anomalies responsible for producing margin magmatism are long gone. Further efforts should be made to obtain images of low velocity, attenuation, phase transition topography, and high conductivity in the upper mantle which will constrain mantle temperature and domains of melting. Studying a region like the GB-CP transition is advantageous, in that it is active allowing lower crustal structure and mantle state to be directly compared.

Experience in this setting begs the question of whether definition of a globally averaged temperature profile such as ACMA has fundamental tectonic significance. Does unequivocal identification of temperatures significantly higher than ACMA through geophysical or geochemical means require the conclusion that material has risen from mid-mantle or greater depths? However, identification of mantle temperatures will rarely be straightforward. Deriving mantle temperatures from either seismic velocity or electrical conductivity requires assumptions about mantle composition, in particular that dry peridotite or some other simple composition can be approximated. Presence of volatiles or alkali components in significant quantities promote melting and complicate velocity- or conductivity-temperature relations. The eastern Great Basin may be one of the few intracontinental regions where adequate constraints are at hand.

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