TESTING MODELS FOR BASALTIC VOLCANISM: IMPLICATIONS FOR YUCCA MOUNTAIN, NEVADA

Eugene Smith [1,2], Clinton P. Conrad[3], Terry Plank[4], Ashley Tibbetts [1,2], Deborah Keenan[2]

1 Department of Geoscience, University of Nevada, Las Vegas, Las Vegas, NV 89014, gene.smith@unlv.edu
2 Geoscience Consultants, Henderson, NV, 89014
3 School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, HI 96822.
4. Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964

The determination of volcanic risk to the proposed high-level nuclear waste repository at Yucca Mountain requires an understanding of the process of volcanism. This includes knowledge of the depth of melting, volatile content of the source region, patterns of flow in the asthenospheric mantle, lithospheric thickness, and the geometry of low viscosity pockets embedded in the asthenosphere. If melting is shallow in the lithospheric mantle, then volcanism in the future may not be a significant threat to Yucca Mountain. On the other hand, if melting is deep in the asthenosphere, another pulse of volcanism is probable, thus posing a greater risk to the waste repository. Our geochemical and geophysical work suggests that deep melting of asthenospheric mantle caused by upwelling associated with low-viscosity "pockets" and a step in lithospheric thickness explain the reoccurrence of volcanic activity near Yucca Mountain, and the episodic nature of volcanism. An implication of this model is that a future peak of magmatism may occur near Yucca Mountain thus inferring a higher risk to the proposed waste repository.

I. INTRODUCTION

Basaltic volcanism has occurred episodically near Yucca Mountain, Nevada, for the past 11 m.y., and understanding its origin and distribution is critical to assessing the hazard and probability of disruption of the proposed high-level nuclear waste repository. Basaltic magmatism beneath the western US derives from the mantle, but considerable uncertainty exists as to the cause and location of mantle melting beneath volcanoes. There are valid arguments for magma sources in the mantle lithosphere (the old, cold roots to continents). Equally valid arguments have been made that magma derives from the mantle asthenosphere (the deeper, hot, flowing upper mantle). This distinction is important because lithospheric melting models lead to waning volcanism[1], while asthenospheric melting models lead to continued volcanism and a higher probability of future volcanic activity [2]. Our work in the Yucca Mountain area is designed to test and revise current models for basaltic volcanism by determining (1) the depth and origin of the magma source, (2) the role of mantle flow patterns and lithospheric basal topography in producing magma, and (3) the size and shape of the volcanic field.

II. DEPTH OF MELTING AND WATER CONTENT OF THE MANTLE

One reason for the controversy regarding the source region for basaltic magma is the lack of constraints on critical variables, such as the depths and temperatures of melting. Melting temperatures in excess of 1300°C are one clear requirement of asthenospheric melting, as dry mantle will flow at these temperatures over long time scales and so will not persist as lithosphere. Melting depths in excess of 70 km also point to melting in the asthenosphere, as this depth exceeds the lithosphere-asthenosphere boundary that has been seismically determined in the actively-deforming western United States [3, 4]. Other scenarios, however, are also possible. Shallow asthenospheric melting (at < 70 km) may occur in regions where the lithosphere has been recently extended, eroded, or foundered, as geophysical data point to beneath Owens Valley, California[5, 6]. Melting may also occur at temperatures less than 1300°C in the asthenosphere if substantial amounts of water are present, as water dramatically lowers the mantle solidus. Thus, a full understanding of the mantle melting process requires constraints on not just the pressure and temperature of melting, but also on the water content of magmas, as well as geophysical constraints on the depth of the local lithosphere-asthenosphere boundary.

The most comprehensive study to date on the conditions of the melting region beneath the Basin and Range [7] used chemical composition of mafic magmas to invert for the depth and degree of melting in the mantle. Specifically, the Fe content of a primary magma in equilibrium with mantle olivine varies with mantle temperature, which governs the depth at which melting may initiate at the mantle solidus. The Na content of magmas depends on the degree of melting (for a source with known Na content). Within a model of decompression melting, then, Fe constrains the start of melting, and Na constrains the end, and so together, they provide information on the melting path in the mantle[8]. Wang et al.[7] used this theory to develop a profile of melting across the western United States, from the Sierra Nevada to the Colorado Plateau (Fig 1). They found shallow melting in the west, and deeper melting in the central region, but interpreted all of it to occur at temperatures and pressures appropriate to mantle asthenosphere. Such an interpretation is consistent with the removal of mantle lithosphere beneath the western part of the region, which allows shallow asthenospheric melting, and with the isotopic compositions of magmas beneath the central part of the region, which are consistent with an asthenospheric source.

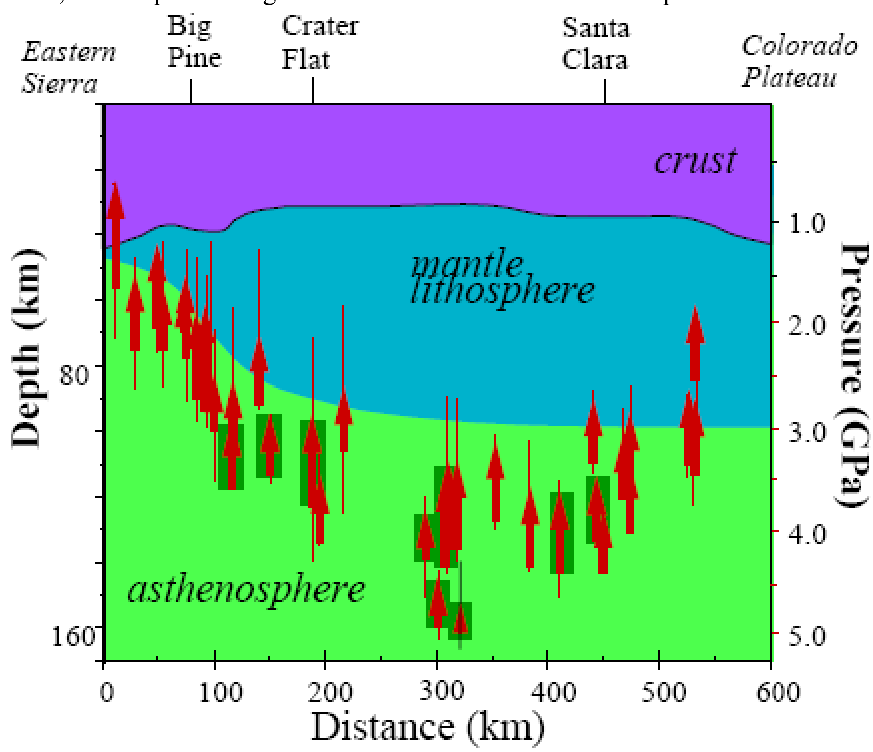

Fig. 1. Mantle melting profile across Basin and Range[7]. Arrows are decompression melting paths calculated from the Fe and Na content of erupted basalts. Lithosphere-asthenosphere boundary after Jones et al. [9]. Location of study regions indicated along the SW-NE profile.

Despite some of the independent evidence for these views, there are several weaknesses of the Wang et al.[7] model. One is a critical assumption in the inversion, that the mantle source region contains no H_2O. The addition of water to the mantle has the effect of strongly lowering melting temperature, and would permit melting in mantle that is otherwise too cold to melt. Such a mechanism is inherent in many models for melting of cold, lithospheric mantle. If melting is limited by water, then it may have a finite future, limited by the quantity of water in the lithosphere [10]. Thus, an accurate view of the source of magmas and mechanisms of melting require measurements of magmatic water contents.

Currently, no published data exist on the water content of western US magmas, despite the fact that geophysical models predict a wet mantle over a broad region [11]. This is largely because volcanic rocks degas almost completely upon ascent and eruption. Only recently has it been possible to accurately estimate how much water is dissolved in magmas before they erupt. This estimate requires very rare samples of melt trapped in tiny crystals, now preserved as glass inclusions. If trapped at depth, and early in the magma's crystallization history (i.e., in the mineral olivine, which crystallizes at the highest temperatures in these magmas), such melt inclusions may still contain the dissolved inventory of volatiles species, especially H_2O[12]. Ion and electron microprobe techniques enable in situ analysis of the 30-100 micron melt inclusions. Two previous studies of melt inclusions in olivine from basalt near Yucca Mountain indicated water contents of 1.2 to 3.5 wt. % (Ref. 35) and 1.9 to 4.6 wt. % (Ref. 36). Phase equilibria studies[35] indicated eruption temperatures of about 975° C for basalt from Little Cone in Crater Flat and about 1000°C for the Lathrop Wells volcano. Our preliminary efforts have focused on samples of mafic scoria from cinder cones in the Santa Clara volcanic field in Utah, within the transition zone between the Colorado Plateau and Basin and Range, and in the Big Pine volcanic field in California, on the eastern side of the Sierra Nevada, in Owens Valley.

Figure 2 shows our results to date for Big Pine (BP) and Santa Clara (CL) basaltic melt inclusions. Excluded from this figure are melt inclusions derived from large lapilli clasts (> 2 cm) as these show signs of diffusion of H out of the melt inclusion during slower cooling in these larger clasts. In melt inclusions from the small clasts, H_2O and CO_2 can be combined to deduce the pressure of entrapment and degassing systematics of the melt inclusions. Entrapment pressures are taken from the Newman and Lowenstern [13] mixed-vapor solubility model, and demonstrate that BP magmas derive from pressures as high as 2 kb, or approximately 8 km depth, while the Snow Canyon and Diamond Valley volcanic fields originate from ~ 6 km depth. These depths may relate to regions of magma storage in the upper crust, with the rest of the melt inclusions recording crystallization in the conduit during magma ascent prior to eruption. Because CO_2 is much less soluble than H_2O in magmas at crustal pressures, degassing paths generally show rapid loss of CO_2 from melts to vapor before appreciable degassing of H_2O, as illustrated in Figure 2. Such degassing behavior is consistent with different initial H_2O contents in the magmas, up to 2.2 wt% H_2O at BP and up to 1.2 wt% H_2O at SC. Additional data may reveal yet higher H_2O contents, but these quantities are already non-trivial. Magmatic H_2O concentrations on the order of 1-2 wt% exceed those found in all mid-ocean ridge basalts[14], but overlap with those found in some ocean island basalts [15, 16], and back-arc basin basalts [17].

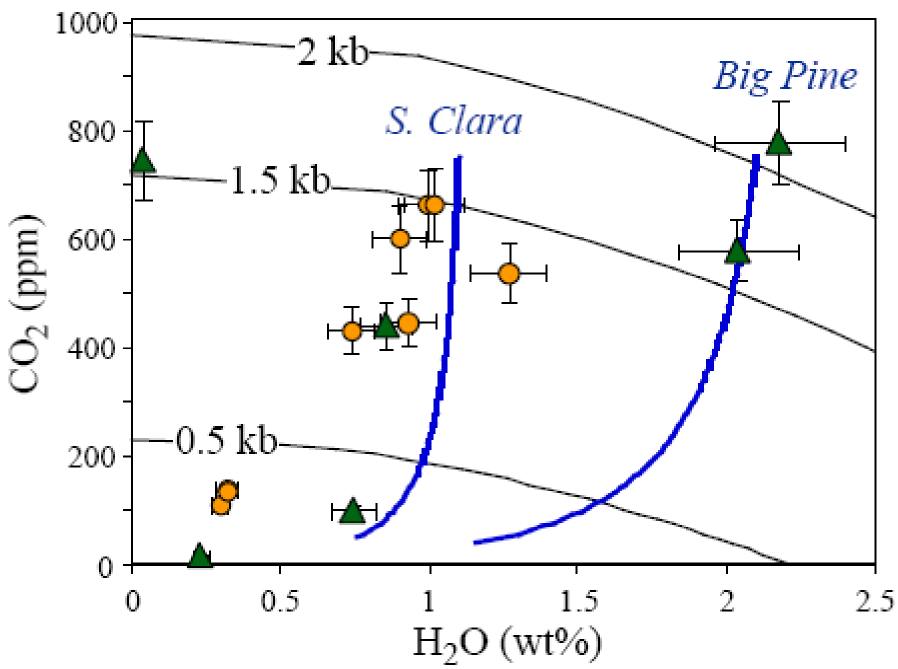

Fig. 2. Volatile concentrations measured in olivine-hosted melt inclusions from scoria cinder from the Big Pine volcanic field in eastern California (Fish Creek Cone, green triangles) and the Santa Clara volcanic field in Utah (Snow Canyon and Diamond Valley cones, orange circles). Vapor-saturation isobars and closed system degassing paths (1100°C and with 2 wt% initial vapor) from VolatileCalc[13]. Error bars derive from 10% uncertainty on SIMS ion microprobe measurements.

With these H_2O concentrations, we can now revise melting temperature estimates, using a recently published parameterization of the effect of H_2O on the olivine liquidus[18]. For SC magmas, 1.2 wt% H_2O leads to a 44°C reduction in olivine liquid temperatures, which is a minor temperature adjustment, and will not on its own lead to a revision of earlier conclusions. Figure 3 summarizes the original P-T estimates [7] based on Fe-Na relationships, a revised estimate based on Mg-Na, the effect of H_2O on these estimates, and an independent calculation based simply on olivine-liquid temperatures (see caption for details). These different approaches predict deep (> 90 km) and hot (> 1400°C) melting beneath SC, most consistent with asthenospheric flow.

For the BP magmas, 2.2 wt% H_2O leads to a 75°C lowering of olivine-liquid temperatures, and estimates here converge on melting mantle-melt equilibration at 50 km and 1300°C (Fig. 3), in agreement with independent calculations based on clinopyroxene-liquid thermobarometry from Mordick and Glazner[19].

Such shallow melting may be occurring in the uppermost mantle lithosphere, but temperatures are high enough that such lithosphere would have to have been recently eroded and heated by hot asthenosphere. Such melting conditions are also fully consistent with asthenospheric upwelling of a mantle adiabat (Tp ~ 1330°), well within the range of upper mantle potential temperatures [20], with melting occurring at a "damp" solidus (~1000 ppm H_2O).

.

Given the prominent low seismic velocity zone that occurs here at 50-70 km, we favor such an asthenospheric decompression melting mechanism.

Thus, our preliminary results require melting either in hot, flowing asthenosphere, or in lithosphere that has been recently eroded and heated by upwelling asthenosphere. Either way, flowing asthenosphere is implicated in driving the melting process.

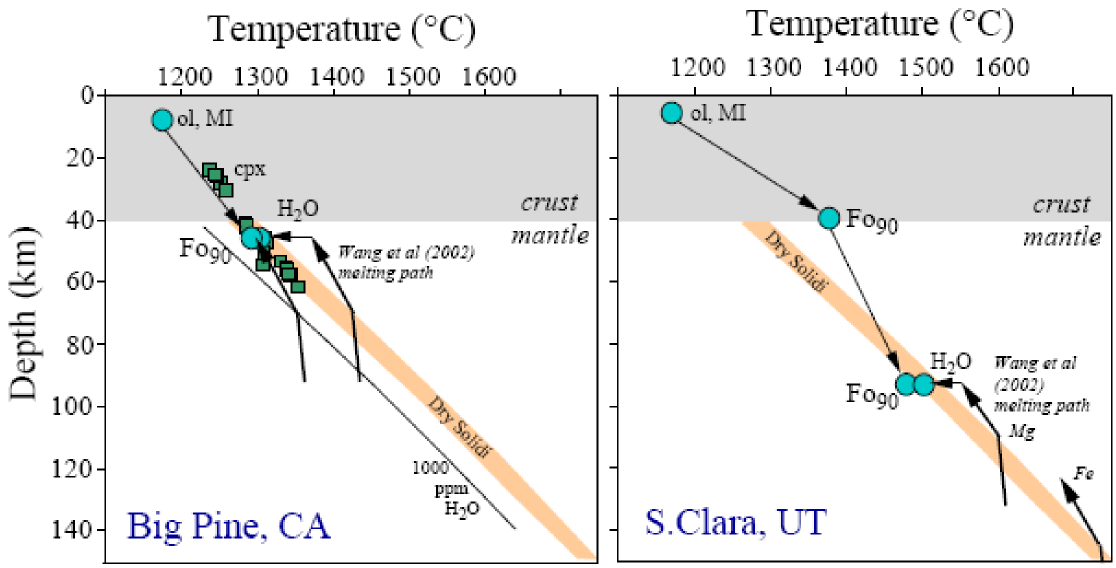

Fig. 3. Estimates of the depth and temperature of melting in the mantle beneath the Big Pine and Santa Clara volcanic fields. For the Santa Clara estimates, bold upwelling arrows are adiabatic decompression paths[7], based on the Fe and Na contents of primary melts. The original Fe-based estimates give very high temperatures; an independent estimate can also be calculated from the Mg content of primary melts, predicting lower temperatures and pressures of melting. Another independent estimate of melting temperature is obtained from olivine-liquid temperatures [21]; with the effects of adding 1.2 wt% H_2O from Medard and Grove[18], calculated first for magmas at the shallow crustal pressures indicated from melt inclusion entrapment (ol MI). Olivine is then added to the most primitive whole rock sample (SCC02; Ref. 22) until it is in equilibrium with Fo_{90}, mantle olivine, and a new temperature is calculated at the crust-mantle boundary (Fo_{90}). This represents the minimum mantle temperature for SC magma (~ 13 80°C). If this primary melt is placed at the top of the Mg-melting path, then its temperature agrees closely with that temperature, taking into account again the H_2O content. Thus, both the bottom-up and top-down approaches converge on a mantle-melt equilibration temperature of 1480-1500 at 95 km. Such conditions are very close to the dry solidus, and require high melting temperatures consistent with hot asthenosphere. For Big Pine, a similar calculation was carried out for a primitive Big Pine basalt (Z-5 from Dodge and Moore[23]), assuming 2.2 wt% H_2O. Note convergence here at ~ 50 km and ~ 1300°C, and with clinopyroxene thermobarometry (green squares) from Mordick and Glazner[19]. Again, such conditions are consistent with those of the dry solidus, although given the water contents of the magma, might instead result from decompression melting at a "damp" solidus (1000 ppm H_2O in the source; calculated from the method in Langmuir et al., 2006), shown with melting path off-set to ~ 75°C lower temperatures due to the H_2O content of the melt. Such shallow melting at ~ 1300°C is consistent with thinned or non-existent lithosphere in this region, as implicated by numerous geophysical studies[5, 3, 24]. Melting may thus be sustained by asthenospheric upwelling into the region, following lithospheric foundering.

III. MANTLE FLOW PATTERNS

Beneath Nevada and the rest of the Basin and Range Province, the asthenosphere is unusually shallow because of the extensional deformation that has thinned the overlying lithosphere [3, 7]. However, thin lithosphere by itself will not produce melting of asthenospheric rocks to produce basaltic magma; the patterns of viscous flow in the asthenosphere must include an upwelling component of flow for adiabatic melting to occur. Therefore, it is necessary to examine the asthenospheric flow patterns beneath the southwestern United States more carefully to determine if upwelling flow in this region is feasible.

Mantle flow beneath North America is thought to be dominated by descent of a region of dense mantle rocks that lie about 1500 km below the Midwest and Eastern portion of the continent. This region, known as the "Farallon Slab" can be imaged seismically and was produced by subduction of dense oceanic lithosphere in the mantle interior off the western coast of North America prior to about 30 million years ago [25]. Several studies have shown that descent of this slab produces a broad region of mantle downwelling beneath the eastern portion of North America that depresses the Earth's surface[26] and influences the westward motion of the North American plate [27]. Numerical models of global-scale mantle flow[28] confirm this flow pattern (Fig. 4). Within the asthenosphere beneath the southwestern United States, these models show eastward-directed flow toward the region of downwelling (Fig. 4A, arrows). The rate of eastward flow at the base of the asthenosphere is up to 3 cm/yr (Fig. 4B). Because the overlying North American plate is moving westward at rates of about 2 cm/yr (Fig. 4B), the asthenosphere beneath the southwestern United States is shearing at rates of up to about 5 cm/yr (Fig. 4B).

The vigorous shear flow occurring beneath the southwestern United States occurs within a region of asthenosphere that exhibits large lateral variations in material properties; these variations can be observed seismically. In particular, variations in seismic velocity observed by *van der Lee and Frederiksen* [29] at about 110 km (Fig 4A) show several trends that will influence the flow field of the asthenosphere beneath the southwestern United States. First, there is a general increase in seismic velocity moving from the southwest toward the continental interior. In general, faster seismic velocities are thought to represent denser and colder material, with lithospheric rocks featuring both. Thus, the eastward increase in seismic velocity is consistent with an increase in continental thickness moving from the Basin and Range province (with lithosphere shallower than 110 km) to the stable craton of the Midwest (with lithosphere thicker than 110 km). This increase in thickness has been observed by some authors to occur as a sharp increase in lithospheric thickness beneath the Nevada region [3, 7]. Second, several "pockets" of low-velocity anomalies are evident within the asthenosphere of the southwestern United States at a depth of 110 km (Fig. 4A). These "pockets" may represent portions of the asthenosphere that are unusually low-density, and therefore presumably hotter than the surrounding asthenosphere. These low-velocity "pockets" of asthenosphere have also been observed in other tomographic studies of the western United States [30]. Thus, the flow field within asthenosphere of the southwestern United States likely encounters both a sharp increase in the thickness of the cold lithosphere, as well as several "pockets" of unusually hot asthenosphere. Because the viscosity of mantle rocks is thought to vary strongly with temperature[31], the cold lithosphere and hot "pockets" can be thought of as high-viscosity and low-viscosity features, respectively. As we show below, both types of lateral viscosity variations may interact with the background mantle flow field to produce asthenospheric upwelling flow.

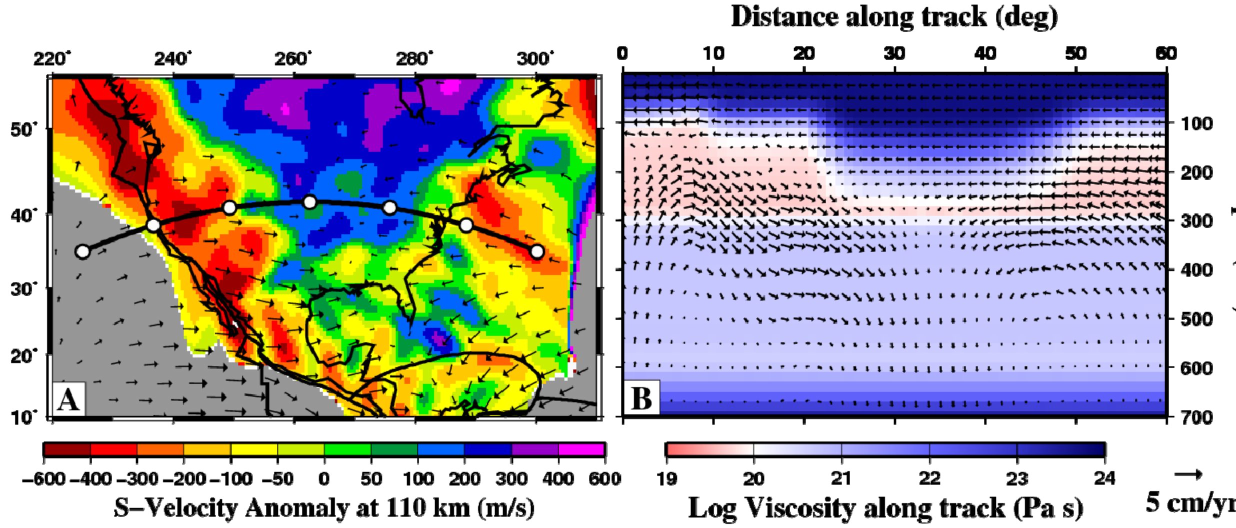

Fig. 4. Patterns of mantle flow and lithospheric thickness across North America. (A) S-wave velocity anomalies from the surface wave tomography model of *van der Lee & Frederiksen* [29] for North America at 110 km depth (colors). The fast velocity anomalies in the Midwest and central Canada (blue) are associated with the thick lithosphere of the Canadian Craton. The slow velocity anomalies in western North America indicate asthenosphere at shallow depths beneath a thin lithosphere. In addition, variable wave speeds in the Basin and Range region may indicate the presence of lateral heterogeneity within the asthenosphere, as has been observed by others[30]. (B) A section across North America (track outlined in (A)) of the global mantle flow model of *Conrad et al.* [28]. Shown in colors is the viscosity field of that model, which employs a thick craton in the central North America, and thinner lithosphere in the west. The flow field beneath North America is dominated by downwelling flow associated with the descent of the Farallon slab[25, 27]. This downwelling beneath the cratonic region causes convergent flow in the upper mantle and asthenosphere (shown in cross section in (B); arrows in (A) show the flow field at 300 km depth). For western North America (i.e. the Basin and Range), asthenospheric shear flow dominates as the North American plate moves westward above an eastward-directed flow of the lower asthenosphere. The vigorous shear flow shown in (B) may interact with lateral viscosity variations inferred from the tomographic model depicted in (A) in ways that complicated the basic shear flow patterns in (B).

We used the numerical flow model CONMAN[32] to examine how asthenospheric shear flow interacts with the lateral viscosity variations described above. To do this, we examine flow within a two-dimensional layered structure that features a high-viscosity lithosphere and a low-viscosity asthenosphere (Fig. 5). By pinning the surface lithosphere and imposing a velocity boundary condition on the base of the asthenosphere, we generate a shear flow within asthenospheric layer that models the one occurring beneath the western United States (Fig. 4).

To test the effect of varying lithospheric thickness on the flow field, we have imposed lateral variations in the thickness of the lithospheric layer. To do this, we inserted a "cavity" of asthenospheric fluid into the lithospheric layer. Within the "cavity" region, the lithosphere is thin; outside of it the lithosphere is thicker. Shear flow in the asthenosphere generates circulation within the lithospheric "cavity" of the sort that has been previously described for various engineering applications [33, 34]. For a relatively narrow cavity, circulation develops within the cavity with an upwelling arm on the upstream side of the shear flow. For a wider cavity (or a step function increase in lithospheric thickness as expected for the southwestern United States), a small "vortex" develops in the corner of the cavity, with upwelling flow along the vertical face of the lithospheric step. For the geometries of lithospheric variations that are expected for the southwestern United States, we found that the amplitude of upwelling may be up to about 5% of the shear flow magnitude, or about 0.25 cm/yr for the 5 cm/yr of shear flow expected for the southwestern United States (Fig. 4). Lower viscosities of the upwelling fluid, which we would expect to accompany adiabatic melting, tend to amplify this effect.

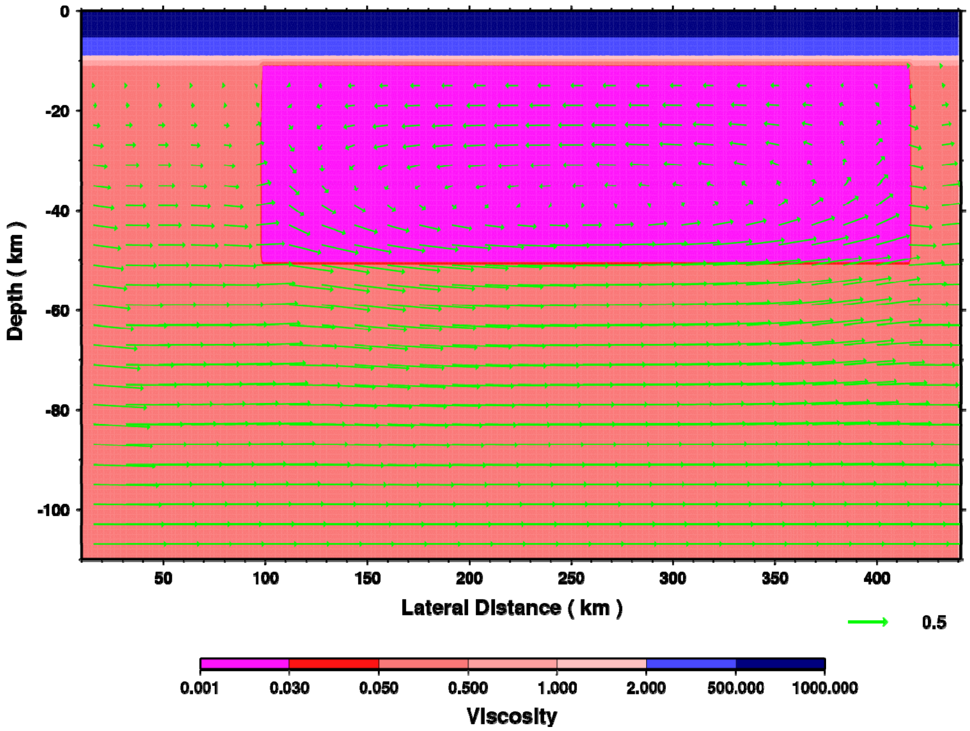

Fig. 5. Flow field of a shearing asthenospheric layer with an embedded "pocket" of fluid (pink) that is 100 times less viscous than the surrounding asthenosphere (tan colored). Shear flow is induced by pinning the surface of the lithosphere (blue) while imposing a velocity boundary condition (of dimensionless amplitude V=1.0) on the base of the asthenospheric layer. The upstream side of the low-viscosity "pocket" experiences upwelling flow with amplitudes up to about 20% of the magnitude of the imposed velocity at the asthenospheric base. For the 5.0 cm/yr shear flow expected for the southwestern United States, this 20% magnitude corresponds to 1.0 cm/yr of upwelling.

In a second test, we embedded a "pocket" of low-viscosity fluid within the asthenospheric layer (Fig. 5). If this pocket is positioned immediately below the lithospheric layer, the faster velocities that the shear flow exerts on the base of the pocket generate a circulation within the low-viscosity pocket itself (Fig. 5). We find that this circulation develops if the viscosity of the pocket is more than about 10 times less than the viscosity of the surrounding asthenosphere. If the pocket viscosity is 100 times smaller than the viscosity of the asthenosphere (which would be expected if the temperature of the pocket were about 200° C hotter than the asthenosphere), then we find that upwelling portion of the circulatory flow may feature upward velocities that are up to ~20% of the magnitude of asthenospheric shear. Thus, for the 5 cm/yr of shear flow, up to 1 cm/yr of upwelling is predicted within a low-viscosity "pocket" of asthenosphere (Fig. 5). The low-densities of the hot fluid should augment this upwelling.

We have found that the vigorous shear flow that occurs beneath the western US can interact with lateral viscosity variations in both the lithospheric and asthenospheric layers to produce upwelling flow. At least two viable mechanisms, associated with heterogeneity in lithospheric thickness and asthenospheric viscosity, produce upwelling flow at maximum rates estimated to be ~1 cm/yr. Since both types of heterogeneity are present beneath the southwestern United States, either mechanism may produce the upwelling responsible for adiabatic melting in the asthenosphere. It is also possible that both mechanisms may be interacting to produce even more vigorous upwelling flow.

IV. IMPLICATIONS FOR YUCCA MOUNTAIN

Understanding the process of volcanism is key to calculating the probability of future events and the probability of disruption of the repository by magmatic processes. If basaltic magmas are generated in the shallow lithospheric mantle, then a model of waning volcanism and low future risk to the repository area is probable. Alternatively, if melting is deep in the asthenospheric mantle, then another peak of activity is possible with the implication of higher risk of future igneous activity. Our petrologic studies suggest the involvement of the asthenospheric mantle in the melting process to produce basaltic magma. In addition, mantle flow models using geophysical data for mantle flow, lithospheric thickness, and the presence of mantle viscosity (temperature) pockets imply that mantle may be upwelling at a lithospheric step beneath central Nevada and near Yucca Mountain. In this upwelling zone, asthenospheric mantle may melt due to decompression to produce basaltic magma. Near Yucca Mountain volcanism has occurred episodically for the last 11 m.y. also volcanoes near Yucca Mountain lie near the southern end of a belt of Pliocene-Quaternary basalt that stretches from Death Valley, California to the Reveille-Lunar Crater area of central Nevada[2]. Studies are currently underway in the Death Valley area to determine whether this field, located just south of Yucca Mountain, is related to volcanism in the rest of the belt. This belt of volcanoes rarely exceeds a width of 20 km and is completely isolated from similar aged basaltic volcanic fields in the Basin Range-Colorado Plateau transition zone to the east and the eastern front of the Sierra Nevada Range to the west. These observations are difficult to explain by shallow melting in the lithospheric mantle or by utilizing crustal structures to control volcano location. A better solution to understanding the geographic distribution and timing of volcanism in this region requires a more complete knowledge of mantle volatile content, flow patterns, lithospheric thickness, and distribution of low-viscosity pockets. We suggest that melting of the asthenospheric mantle controlled by upwelling associated with low-viscosity pockets, and a step in lithospheric thickness explain both the reoccurrence of volcanic activity in the Yucca Mountain area for the past 11 m.y., and the episodic nature of volcanism. An implication of this model is that a new episode of volcanism may occur near Yucca Mountain, thus inferring a higher risk to the proposed waste repository.

ACKNOWLEDGMENTS

We thank the Clark County Nevada, Nuclear Waste Office, the State of Nevada, Agency for Nuclear Projects, and the Inyo County, California Yucca Mountain Repository Assessment Office for their funding and support. We also thank Racheal Johnsen for help in formatting and editing the manuscript.

REFERENCES

1. A. G. VALENTINE and V. F. PERRY, “Time-predictable Basaltic Volcanism from a Lithospheric Mantle Source (central Basin and Range Province, USA),” *Earth and Planetary. Science. Letters*, doi, 10.1016 (2007)
2. E. I. SMITH, D. L. KEENAN, and T. PLANK, “Episodic Volcanism and Hot Mantle: Implications for Volcanic Hazard Studies at the Proposed Nuclear Waste Repository at Yucca Mountain, Nevada,” *GSA Today*, **12**, *4*, 4-11 (2002).
3. G. ZANDT, S. C. MYERS, and T. C. WALLACE, “Crust and mantle structure across the Basin and Range-Colorado Plateau boundary at 37 N latitude and implications for Cenozoic extensional mechanism,” *Journal of Geophysical Research,* **100**, 10,529– 10,548 (1995).
4. X. LI, X. YUAN, and R. KIND, “The Lithosphere–asthenosphere Boundary beneath the Western United States,” *Geophys. J. Int.*, DOI: 10.1111/j.1365-246X.2007.03428 (2007).
5. O. S. BOYD, C. H. JONES, and A. F. SHEEHAN, “Foundering Lithosphere Imaged Beneath the Southern Sierra Nevada, California, USA,” *Science*, **305**, 660-662 (2004).
6. G. ZANDT, H. GILBERT, T. J. OWENS, M. DUCEA, J. SALEEBY, and C. H. JONES, “Active Foundering of a Continental Arc Root Beneath the Southern Sierra Nevada in California,” *Nature*, **431**, 41-46 (2004).
7. K. WANG, T. PLANK, J. D. WALKER, and E. I. SMITH, “A Mantle Melting Profile Across the Basin and Range, Southwestern USA,” *Journal of Geophysical Research,* **107**, *B1,* DOI10.1029/2001JB000209 (2002).
8. C. H. LANGMUIR, E. M. KLEIN, and T. PLANK, *Mantle Flow and Melt Generation at Mid-Ocean Ridges*, pp. 183–280, J. MORGAN PHIPPS, D. K. BLACKMAN, AND J. SINTON, Eds., Geophysical Monograph Series, AGU, Washington, D. C. (1992).
9. C. H. JONES, B. P. WERNICKE, G. L. FARMER, J. D. WALKER, D. S. COLEMAN, L. W. MCKENNA, and F. V. PERRY, “Variations Across and Along a Major Continental Rift: An Interdisciplinary Study of the Basin and Range Province, Western, USA,” *Tectonophysics*, **213**, 57– 96 (1992).
10. D. L. HARRY and W. P. LEEMAN, “Partial Melting of Melt Metasomatized Subcontinental Mantle and the Magma Source Potential of the Lower Lithosphere,” *Journal of Geophysical Research*, **100**, 10,255–10,269 (1995).
11. J. E. DIXON, T. H. DIXON, D. R. BELL, and, R. MALSERVISI, “Lateral Variation in Upper Mantle Viscosity: Role of Water,” *Earth and Planetary Science Letters*, **222**, 451-467 (2004).
12. J. A. WADE, T. PLANK, W. G. MELSON, G. J. SOTO, and E. HAURI, “The Volatile Content of Magmas from Arenal Volcano,” *Journal of Volcanology and Geothermal Research*, **157**, 94-120 (2006).

13. S. NEWMAN and J. B. LOWENSTERN, "VOLATILECALC: A Silicate Melt–H2O–CO2 Solution Model Written in Visual Basic for Excel," *Computers and Geosciences*, **28**, 597–604 (2002).
14. J. E. DIXON, J. E. LEIST, LANGMUIR, and SCHILLING, "Recycled Dehydrated Lithosphere Observed in Plume-influenced Mid-ocean Ridge Basalts, *Nature*, **420**, 385-389 (2002).
15. J. E. DIXON, D. A. CLAGUE, P. WALLACE, and R. POREDA, "Volatiles in Alkalic Basalts from the North Arch Volcanic Field, Hawaii: Extensive Degassing of Deep Submarine-erupted Alkalic Series Lavas," *Journal of Petrology*, **38**, 911-939 (1997).
16. R. K. WORKMAN, E. HAURI, S. R. HART, J. WANG, and J. BLUSZTAJN, "Volatile and Trace Elements in Basaltic Glasses from Samoa: Implications for Water Distribution in the Mantle," *Earth and Planetary Science Letters*, **241**, 932-951 (2006).
17. K. A. KELLEY, T. PLANK, S. NEWMAN, E. STOLPER, T. L. GROVE, and HAURI, "Mantle Melting as a Function of Water Content at Subduction Zones, I: Back-arc Basins. J. Geophysical Research, **111**, B09208 (2006).
18. E. MEDARD and T. L. GROVE, "The Effect of H2O on the Olivine Liquidus of Basaltic Melts: Experiments and Thermodynamic Models," *Contributions to Mineralogy and Petrology*, in press, DOI 10.1007/s00410-007-0250-4 (2007).
19. B. E. MORDICK and A. F. GLAZNER, "Clinopyroxene Thermobarometery of Basalts from the Coso and Big Pine Volcanic Fields, California," *Contributions to Mineralogy and Petrology*, DOI 10.1007/s00410-006-0097-0 (2006).
20. K. PUTIRKA, M. PERFIT, R. RYERSON, and M. JACKSON, "Ambient and Excess Mantle Temperatures, Olivine Thermometry, and Active vs. Passive Upwelling, *Chemical Geology*, **241**, 177-206 (2007).
21. T. SUGAWARA, "Empirical Relationships between Temperature, Pressure, and MgO Content in Olivine and Pyroxene Saturated Liquid," *Journal of Geophysical Research*, **105**, *B4*, 8457-8472 (2000).
22. M. FAUST, *Petrogenesis and geochemistry of Pleistocene and Pliocene basalt flows of the Pine Valley Volcanic Field, Utah and their Relationship to the Tectonics of the Utah Transition Zone*, 116 pp, MS THESIS, UNLV, Las Vegas, Nevada (2005).
23. F. C. DODGE and J. G. MOORE, "Late Cenozoic Volcanic Rocks of the Southern Sierra Nevada, California: II. Geochemistry," *Geological Society of American Bulletin*, **92**, 1670–1761 (1981).
24. Y. YANG and D. W. FORSYTH, "Rayleigh Wave Phase Velocities, Small-scale Convection and Azimuthal Anisotropy beneath Southern California," *Journal of Geophysical Research*, **111**, B07306, doi:10.1029/2005JB004180 (2006).
25. H. P. BUNGE and S. P. GRAND, "Mesozoic Plate-motion History below the Northeast Pacific Ocean from Seismic Images of the Subducted Farallon Slab, *Nature,* **405**, 337-340 (2000).
26. C. P. CONRAD, C. LITHGOW-BERTELLONI, and K. E. LOUDEN, "Iceland, the Farallon Slab, and Dynamic Topography of the North Atlantic," *Geology,* **32***,* 177-180 (2004).
27. G. H. R. BOKELMANN, "Which Forces Drive North America?," *Geology,* **30**, 1027–1030 (2002).
28. C. P. CONRAD, M. D. BEHN, and P. G. SILVER, "Global Mantle Flow and the Development of Seismic Anisotropy: Differences between the Oceanic and Continental Upper Mantle," *Journal of Geophysical Research,* **112***,* B07317, doi:10.1029/2006JB004608 (2007).
29. S. VAN DER LEE and A. FREDERIKSEN, *Seismic Earth: Array Analysis of Broadband Seismograms*, pp. 67-80, G. NOLET and A LEVANDER, Eds., *Geophysical Monograph Series,* **157** (2005).
30. K. DUEKER, H. YUAN, and B. ZUREK, "Thick-structured Proterozoic Lithosphere of the Rocky Mountain Region," *GSA Today,* **11(12)**, 4-9 (2001).
31. D. L. KOHLSTEDT, B. EVANS, and S. J. MACKWELL, "Strength of the Lithosphere: Constraints Imposed by Laboratory Experiments," *Journal of Geophysical Research,* **100**, 17587-17602 (1995).
32. S. D. KING, A. RAEFSKY, and B. H. HAGER, "ConMan: Vectorizing a Finite Element Code for Incompressible Two-dimensional Convection in the Earth's Mantle," *Physics of the Earth and Planetary Interiors,* **59**, 195-207 (1990).
33. C. SHEN and J. M. FLORYAN, "Low Reynolds Number Flow Over Cavities," *Physics of Fluids,* **28**, 3191-3202 (1985).
34. P. PEYMAN, S. H. SPIEGELBERG, and G. H. MCKINLEY, "Cavity Flows in Elastic Liquids: Two-dimensional Flows," *Physics of Fluids*, **9**, 3123-3140 (1997).
35. M.G. NICHOLIS and M.J. RUTHERFORD, "Experimental Constraints on Magma Ascent Rate for the Crater Flat Volcanic Zone Hawaiite," *Geology,* **32,** 6, 489–492 (2004).
36. J.F. LUHR and T.B HOUSH, "Melt volatile contents in basalts from Lathrop Wells and Red Cone, Yucca Mountain Region (SW Nevada): Insights from glass inclusions": *Eos (Transactions, American Geophysical Union),* 83, Abs. V22A–1221 (2002).