Earthquake and volcano clustering via stress transfer at Yucca Mountain, Nevada

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ABSTRACT

The proposed national high-level nuclear waste repository at Yucca Mountain is close to Quaternary cinder cones and faults with Quaternary slip. Volcano eruption and earthquake frequencies are low, with indications of spatial and temporal clustering, making probabilistic assessments difficult. In an effort to identify the most likely intrusion sites, we based a three-dimensional finite-element model on the expectation that faulting and basalt intrusions are sensitive to the magnitude and orientation of the least principal stress in extensional terranes. We found that in the absence of fault slip, variation in overburden pressure caused a stress state that preferentially favored intrusions at Crater Flat. However, when we allowed central Yucca Mountain faults to slip in the model, we found that magmatic clustering was not favored at Crater Flat or in the central Yucca Mountain block. Instead, we calculated that the stress field was most encouraging to intrusions near fault terminations, consistent with the location of the most recent volcanism at Yucca Mountain, the Lathrop Wells cone. We found this linked fault and magmatic system to be mutually reinforcing in the model in that Lathrop Wells feeder dike inflation favored renewed fault slip.

Keywords: earthquake, volcano, magmatism, hazard, nuclear waste repository, clustering, stress transfer, Yucca Mountain, extension, Basin and Range Province.

INTRODUCTION

The Yucca Mountain region is characterized by normal faulting, plate-boundary shear, and basaltic volcanism (e.g., Morris et al., 2004, and references therein). The likelihood of tectonic events disrupting the proposed high-level nuclear waste repository site is of keen interest. Of particular concern is the possibility that the repository could be breached by renewed basaltic intrusion. Quantification of probable location and timing of future intrusions has been guided by geologic information and expert knowledge (Crowe et al., 1982; Ho and Smith, 1997; Connor et al., 2000; Coleman et al., 2004). We attempt here to supplement that knowledge by noting that, given a supply of basaltic magma from the mantle, the orientations and locations of intrusions may be controlled by the crustal stress field (e.g., Nakamura, 1977; Rubin and Pollard, 1988). We therefore use three-dimensional (3-D) finite-element methods to calculate regional crustal stresses. We address processes that influence magmatic emplacement in the shallow crust; thus, our model includes stresses imparted by regional extension, variable overburden pressure, and influences from oblique normal faulting. Additionally, we examine stresses imposed by magmatism back onto local faults.

Neotectonic Setting of Central Yucca Mountain

Yucca Mountain is a series of Miocene-aged volcanic tuffs sliced by N-S–trending oblique normal faults; we focus here on the most important (e.g., Morris et al., 2004; Potter et al., 2004) of these faults that have recorded late Quaternary activity, which are the Solitario Canyon (earthquakes occurred ca. 30 and 75 ka; Ramelli et al., 2004), Windy Wash (earthquakes occurred ca. 3, 40, and 75 ka; Whitney et al., 2004), and Fatigue Wash faults (earthquakes occurred ca. 9, 38, and 75 ka; Coe et al., 2004). The Yucca Mountain region has also been magmatically active since Miocene time. After cessation of the caldera-related tuff eruptions, small-volume basalt eruptions continued, including several ~1-m.y.-old cinder cones near Yucca Mountain (Sawyer et al., 1994; Crowe et al., 1995). The 0.08-m.y.-old Lathrop Wells cone resulted from the most recent volcanic event, ~15 km southwest of the proposed repository site. Several buried intrusions have been identified with aeromagnetic techniques, mostly south of Yucca Mountain, and are of indeterminate age except one that was drilled and dated at ca. 3.7 Ma (e.g., O'Leary et al., 2002).

There is paleoseismic evidence for temporal clustering of earthquakes and magmatism at Yucca Mountain. Abundant ash from the ~78-k.y.-old Lathrop Wells cone was found in earthquake fissures in trenches across the Solitario Canyon, Fatigue Wash, and Windy Wash faults (Keefer and Menges, 2004). It is likely that earthquakes occurred either during or very shortly after (weeks to months) the Lathrop Wells eruption, because fissures typically begin to infill after the first significant rainfall (Ramelli et al., 2004).

MODELING

We simulated central Yucca Mountain crustal deformation using a 3-D finite-element model. The model had cuts in it that corresponded with the dipping (~70°W; Menges and Whitney, 2004) Solitario Canyon, Fatigue Wash, and Windy Wash faults. We did not include every known fault in the model. Instead, we focused on a set known to have ruptured at the same time as the Lathrop Wells volcanic eruption, which represents a remarkable clustered volcano-earthquake episode. Major corrugation features of the oblique-normal faults observed at the surface were assumed to extend to depth (Ferrill et al., 1999). The modeled crust was composed of 10-node elastic tetrahedral elements, while faults were lined with zero-thickness contact elements that obeyed Coulomb friction behavior (e.g., Parsons, 2002). The model simulated a 15-km-thick upper crust, the top of which was located 3 km below sea level. Model boundaries extended at least 50 km from the central Yucca Mountain region (an additional 20 km more on all sides than shown in Fig. 1) to avoid boundary conditions contaminating the solutions. All model elements were given uniform density of 2720 kg/m^3.

Model Loads

Orientation and location of tabular basaltic intrusions of the type that feed cinder cones are sensitive to the magnitude and direction of the least principal stress (e.g., Nakamura, 1977; Rubin and Pollard, 1988). Thus, all processes that influence crustal stress are also expected to influence magmatism. Our model included loading by four mechanisms: (1) variable pressure from the overburden, (2) remote regional extension, (3) slip on faults, and (4) opening and filling of dikes. Throughout this paper we use the term "extensional" to describe a stress or strain state in which the least principal axis is near horizontal, the greatest principal axis is near vertical, and where normal fault and dike trends are expected to be approximately orthogonal to the least principal axis.

A point at depth in the crust experiences

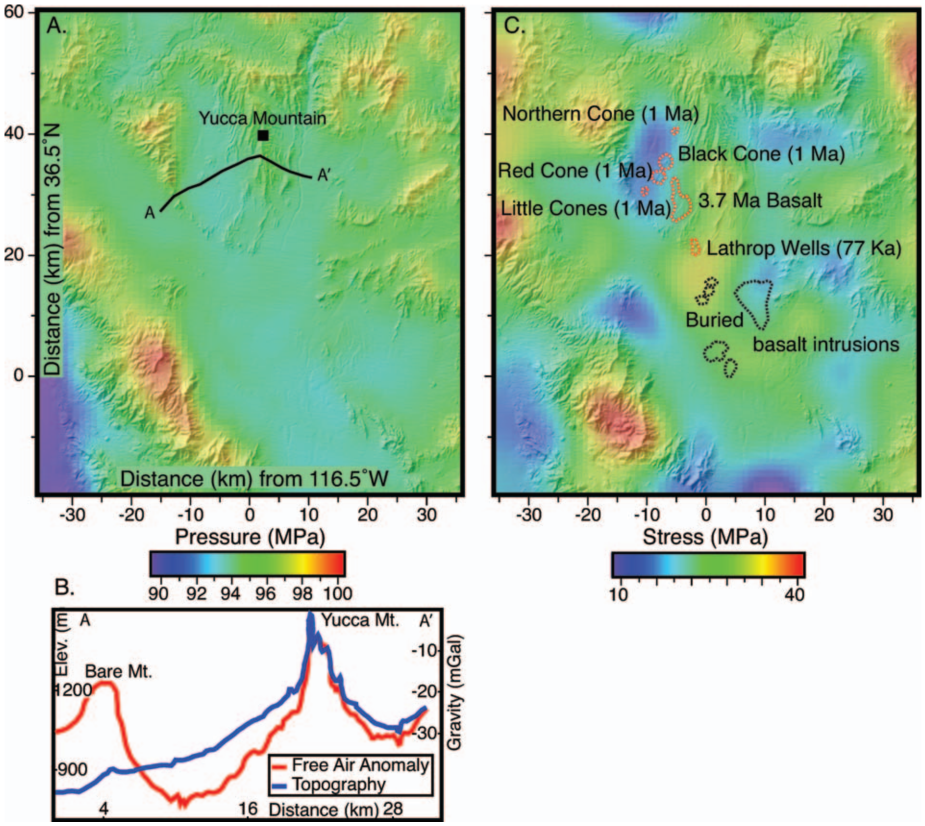

Figure 1. A: Vertical pressure at 3 km depth exerted by overburden as calculated from free air gravity anomaly (see text for derivation). Pressures tend to be higher where topography and/or shallow crustal density is highest. B: Cross-section A–A′ shows example relationship between topography and free air gravity anomaly; this section corresponds with seismic model of Brocher et al. (1998). C: Calculated least principal stress magnitudes in unbroken elastic slab averaged over 3–6 km depth resulting from applied pressures shown in A. Lower values (blue colors) are places where basalt intrusions might be more favored in absence of other stress influences.

pressure resulting from the weight of the overburden. The amount of pressure is a result of the integrated density of the rock above it, which varies with topography and lithology. A convenient way to calculate the overburden pressure is to use variations in the free air gravity anomaly ($\Delta\gamma_{fa}$), which is sensitive to topography and crustal density. If we assume that $\Delta\gamma_{fa}$ can be approximated by a slab of thickness $h + t$, where h is a reference depth and t is elevation above sea level, then we find that $\Delta\gamma_{fa} = 2\pi G\bar{\rho}(h + t)$, where $\bar{\rho}$ is mean density, and G is Newton's gravitational constant. Pressure (P), being the integrated density, is given by

$$P = g \int_0^{h+t} \rho(z)\, dz, \qquad (1)$$

where g is gravitational acceleration, and z is depth. Average density is then

$$\bar{\rho} = \frac{1}{h + t} \int_0^{h+t} \rho(z)\, dz. \qquad (2)$$

Solving for pressure yields $P = g\Delta\gamma_{fa}/2\pi G$, which, when the constants are expressed numerically, allows us to arrive at the simple result that $P = 0.234\Delta\gamma_{fa}$ in units of MPa. Using equations that account explicitly for topographic variations, rather than using the slab approximation, can be done, but that approach only makes very slight differences in the calculated pressure values.

The finite-element model was loaded by pressure applied to its top (a depth of 3 km, which lies beneath the deepest parts of Crater Flat basin; Brocher et al., 1998) according to variations in the free air gravity anomaly (Fig. 1). In addition to the variable pressure applied to the model top, it was allowed to compress elastically under gravity, with the model base held fixed in the vertical dimension. Regional extension at Yucca Mountain has an observed least principal stress direction of ~N60°W (Stock et al., 1985; Harmsen, 1994; Morris et al., 1996). We therefore applied uniaxial strain across the model at a rate of 20 nstrain yr^{-1} on a N60°W orientation, consistent with geodetic (Savage et al., 2001; Wernicke et al., 2004) and geologic (Fridrich et al., 1999) rates. The north and south model boundaries were left unconstrained, and the model base was free to move horizontally.

We ran a progression of tests to examine different influences on the 3-D stress field at Yucca Mountain. Initially, we applied only overburden pressure and gravity loading to isolate their effects in the absence of remote extension. Next, since the major central Yucca Mountain faults predate the Lathrop Wells cone, we extended the model for a calculated 80 k.y. period, which is the time since the last eruption and simulates ~2 seismic cycles. We allowed the faults to slip freely (resisted by friction), and examined stress changes. Last, we calculated stress changes caused by inflation of our estimated most-likely Lathrop Wells feeder dike.

Model Results

Given that basaltic intrusions are encouraged under extension where the least principal stress is at the lowest magnitude, we tested a hypothesis that suggests in the absence of other influences, intrusions might cluster preferentially where the overburden pressure (hence the horizontal least principal stress as related by Poisson's ratio) is smallest. The results of this test indicated that influence from variation in overburden stress is not dominant in controlling where basalt intrudes the shallow crust (Fig. 1); the chain of ~1-m.y.-old cinder cones at Crater Flat is located at a calculated low least-principal-stress zone, whereas Lathrop Wells and a series of buried basalt intrusions correspond with higher calculated least principal stress. While not dominant, we did include overburden pressure as a contributing effect in subsequent calculations.

Normal faulting and basaltic intrusions are observed to accommodate tectonic extension interchangeably since both processes cause strain and increase the least principal stress (Parsons and Thompson, 1991). We sought to calculate crustal stresses resulting from the combination of remotely applied extension and slip on faults. Major central Yucca Mountain faults significantly predate the Lathrop Wells cone (Potter et al., 2004), so we allowed the model faults to slip freely under applied extension for a simulated 80 k.y. period. The duration of the calculation was chosen to be long enough to represent multiple earthquakes on each fault (Keefer and Menges, 2004), and to coincide with the time elapsed since the last volcanic eruption. In the model, the faults accumulated up to 2 m of slip (Fig. 2A), and the highest slip rates were on the Windy Wash fault, which is commensurate with observations (Fridrich et al., 1999). Mapping the calculated change in least principal stress resulting from fault slip showed the region around the faults to be less favorable to magmatic in-

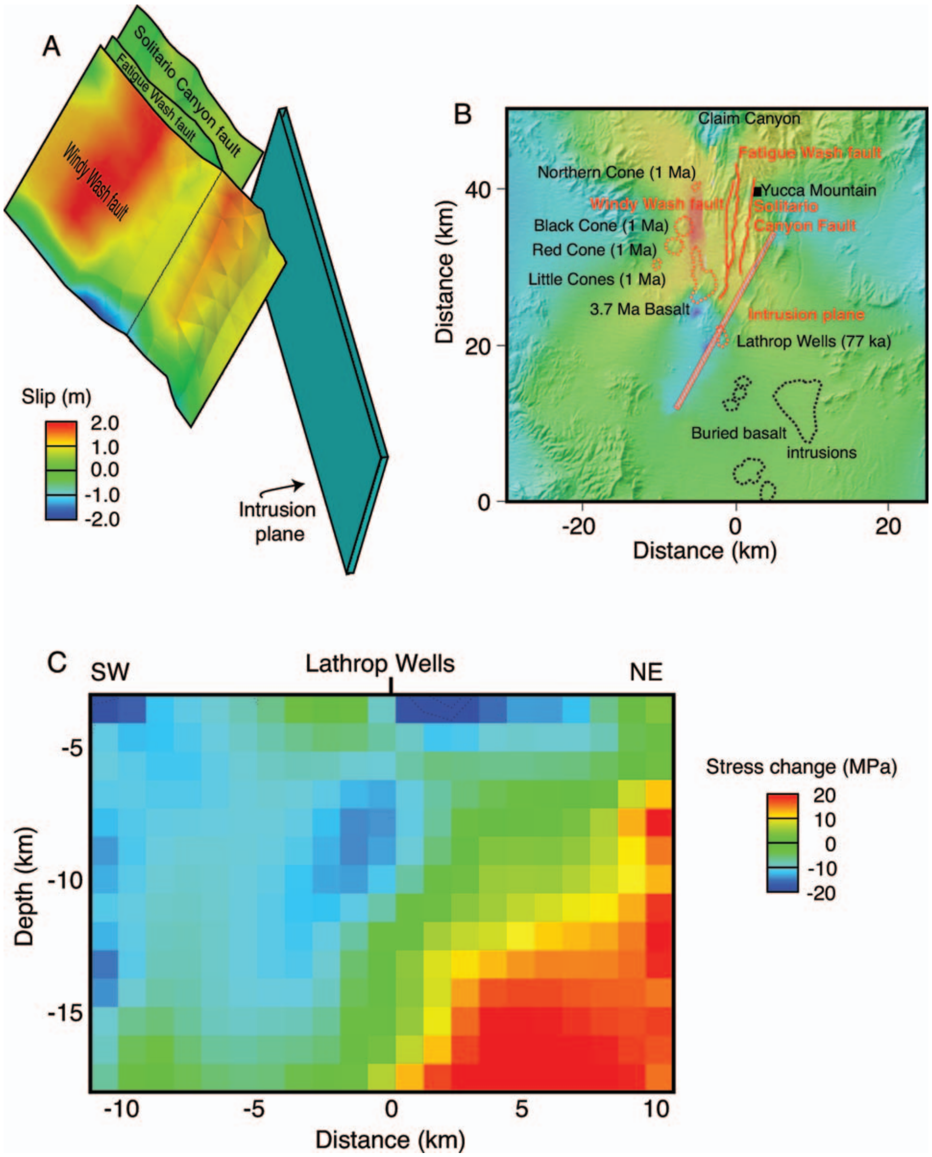

Figure 2. A: Modeled central Yucca Mountain faults contoured with 80 k.y. of oblique slip caused by remote extension. Negative slip implies rate change caused by basal model boundary conditions. B: Mapped change in least principal stress magnitude resulting from fault slip shown in A. Warm colors (least stress increased) indicate areas less favored for basalt intrusions, while cool colors indicate places where fault slip encourages intrusion. Contour scale is same as in C. C: Magnitude of the least principal stress projected onto a N30°E-striking plane, which is orthogonal to extension direction and, thus, is a likely orientation for basalt feeder dikes at Lathrop Wells.

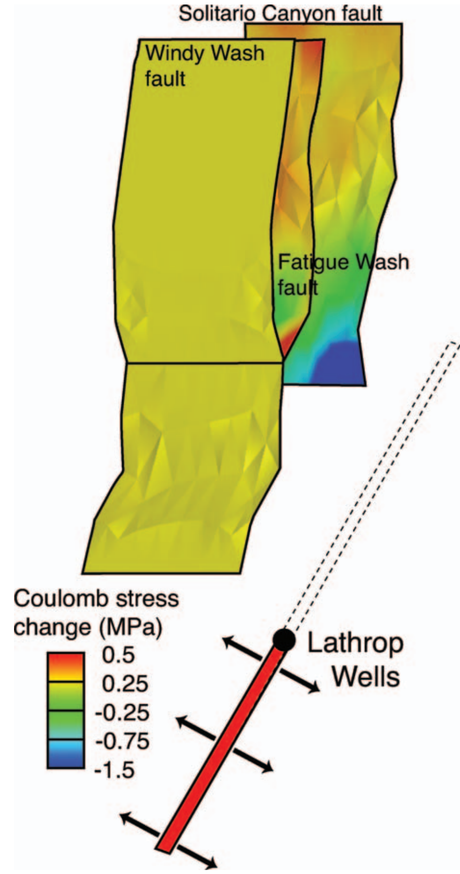

Figure 3. Map view of Coulomb stress change on dipping Solitario Canyon, Fatigue Wash, and Windy Wash faults from a vertical dike opening (shaded red) beneath Lathrop Wells. We modeled a 2 m opening on a N30°E-striking plane at locations where least stress was reduced by fault slip as shown in Figure 2C. In this scenario, fault slip and dike opening are mutually reinforcing processes.

trusion, whereas regions north and south of the faults were more favorable, including the Lathrop Wells site (Fig. 2B). While the ~1-m.y.-old chain of cinder cones in Crater Flat was favorable in the model when just overburden pressures were considered (Fig. 1), it would not be favorable after slip on central Yucca Mountain faults (Fig. 2B).

To study the effects of dike intrusion on faults, we assumed that a vertical Lathrop Wells feeder dike(s) was oriented orthogonally (N30°E) to the least principal stress direction. We calculated that magma ascent would be most favored on the N30°E-striking plane at, and southwest of, the Lathrop Wells cone (Fig. 2C). To calculate stress-change effects on central Yucca Mountain faults from the Lathrop Wells intrusion, we assumed a 2 m dike opening on the N30°E plane, where the least principal stress was reduced by modeled fault slip (blue areas on Fig. 2C). We found that this ~10-km-long dike intrusion would have increased Coulomb failure stress (increasing likelihood of slip) on all three major faults in the model, with the strongest effect on the Solitario Canyon and Fatigue Wash faults (Fig. 3).

We calculated that the Lathrop Wells intrusion decreased the least principal stress north of the modeled dike in the Yucca Mountain block. In Figure 3, we show this as increased likelihood of normal-fault slip. That same stress change would encourage more dike intrusion to the north as well. Evidence from the paleoseismic record indicates that instead of more intrusions into the Yucca Mountain block, each of the major faults had at least 1–2 earthquakes subsequent to the Lathrop Wells eruption (Keefer and Menges, 2004).

CONCLUSIONS

Observation of volcanic ash in the bottoms of fissures along major Yucca Mountain faults demonstrates temporal clustering of earthquakes and a volcanic eruption. Using a 3-D finite-element model, we found that slip on faults and dike opening can work in concert to accommodate extension at Yucca Mountain. The inferred geometry of the system appears to mutually enhance both processes. We found in the absence of fault slip, that overburden pressure creates a stress state favoring clustering of magmatic intrusions at Crater

Flat (Fig. 1). However, we also found that after fault slip, volcanic clustering is less likely in the Crater Flat region, and is instead favored near terminations of the major faults (Fig. 2B). Given that the central Yucca Mountain faults have all slipped at least twice since the last volcanic episode, we conclude that the stress field favors basalt intrusions near and southwest of the Lathrop Wells site, and north of the major faults in the Claim Canyon Caldera region (Fig. 2B). Interactions between, and triggering of, earthquake and magmatic events have been noted worldwide (e.g., Parsons and Thompson, 1991; Nostro, et al., 1998; Toda et al., 2002; Hill et al., 2002; Díez et al., 2005). Thus, volcano forecasts at Yucca Mountain should incorporate the physics of its linked fault and magmatic system.

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