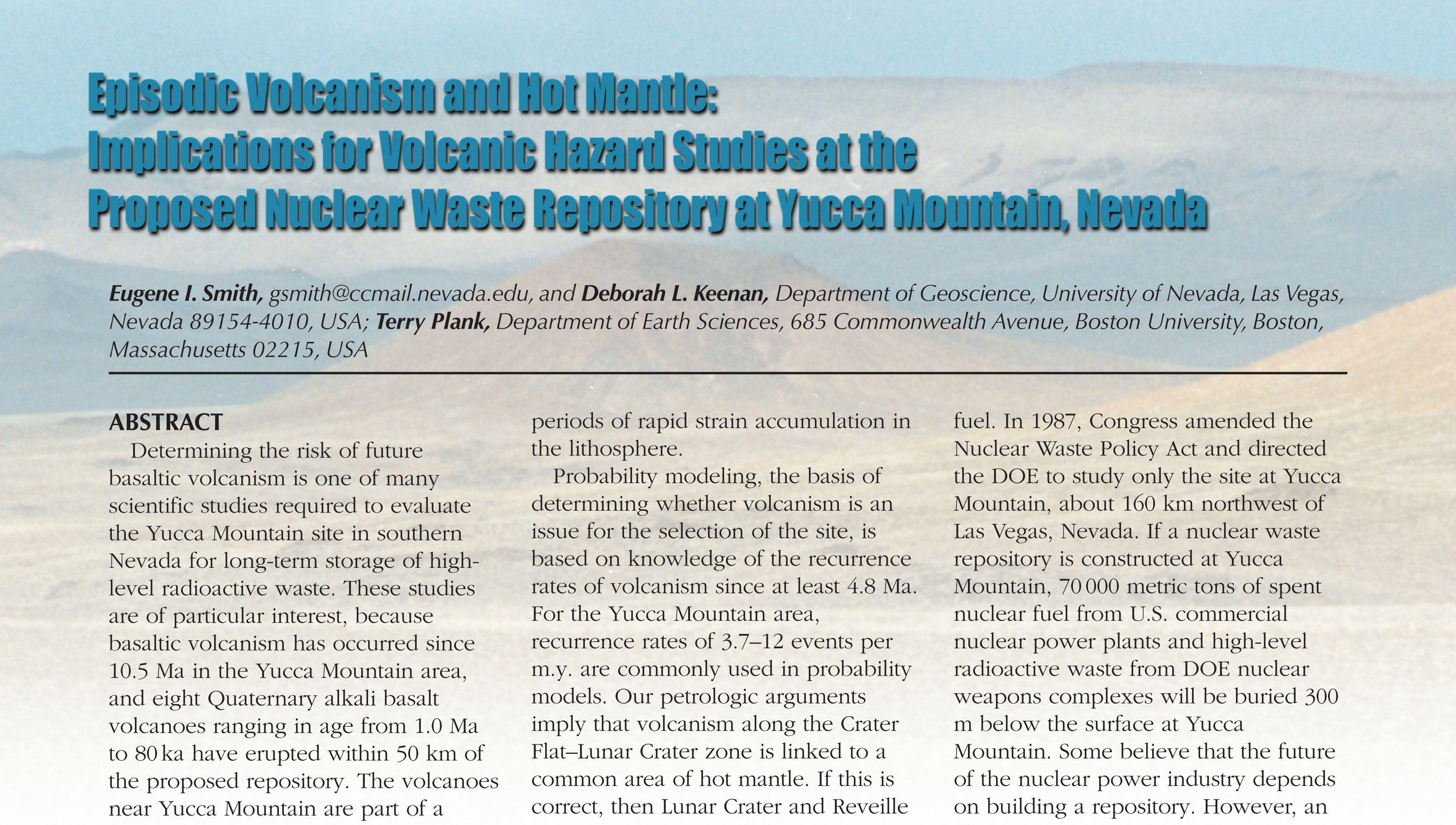

Episodic Volcanism and Hot Mantle: Implications for Volcanic Hazard Studies at the Proposed Nuclear Waste Repository at Yucca Mountain, Nevada

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ABSTRACT

Determining the risk of future basaltic volcanism is one of many scientific studies required to evaluate the Yucca Mountain site in southern Nevada for long-term storage of high-level radioactive waste. These studies are of particular interest, because basaltic volcanism has occurred since 10.5 Ma in the Yucca Mountain area, and eight Quaternary alkali basalt volcanoes ranging in age from 1.0 Ma to 80 ka have erupted within 50 km of the proposed repository. The volcanoes near Yucca Mountain are part of a larger zone of basaltic volcanism that stretches from Death Valley, California, to the Lunar Crater field in central Nevada (the Crater Flat–Lunar Crater zone). Within this zone, volcanism is coeval and episodic with three peaks of volcanism occurring since 9.5 Ma; one between 9.5 and 6.5 Ma, the second between 4.5 and 3.5 Ma, and the last between 1.5 and 0.5 Ma. Periods of low activity separate these peaks and last for 1–2 m.y. At the present time, volcanism in this zone is relatively quiet, with only three eruptions occurring in the past 80 000 years.

A common driving force for magmatism is suggested by coeval volcanism along the entire length of the Crater Flat–Lunar Crater zone. We propose that hot mantle exists beneath the zone and provides the impetus for volcanic activity. Recent geochemical modeling suggests that melting beneath the Crater Flat–Lunar Crater zone was especially deep. For Lunar Crater, the melting column extends from 162 km up to 110 km and for Crater Flat from 133 km up to 115 km. Deep melting requires hot and buoyant mantle with mantle potential temperatures about 200 °C greater than those in the western Great Basin. Episodic volcanism in the Crater Flat–Lunar Crater zone may be related to episodic periods of rapid strain accumulation in the lithosphere.

Probability modeling, the basis of determining whether volcanism is an issue for the selection of the site, is based on knowledge of the recurrence rates of volcanism since at least 4.8 Ma. For the Yucca Mountain area, recurrence rates of 3.7–12 events per m.y. are commonly used in probability models. Our petrologic arguments imply that volcanism along the Crater Flat–Lunar Crater zone is linked to a common area of hot mantle. If this is correct, then Lunar Crater and Reveille Range recurrence rates (11 to >15 events per m.y.) are possible in the Yucca Mountain area. Furthermore, if the Crater Flat–Lunar Crater zone is underlain by hot mantle as suggested here, another peak of volcanic activity is possible. Considering that recurrence rates may be underestimated, the episodic pattern of volcanism, and the likelihood of hot mantle sustaining volcanism, we suggest that there is a greater uncertainty in the current recurrence rates than that used in present probability models. Despite decades of work and debate, the underlying cause of volcanism and temporal models for calculating recurrence rates of volcanism are not firmly established. In our opinion, understanding the process of volcanism is a prerequisite to having confidence in volcanic hazard studies. If too many unanswered questions remain at the time of site approval, then perhaps an alternative repository site should be chosen in an area without the risk of volcanism.

INTRODUCTION

In 1983, the U.S. Department of Energy (DOE) selected nine locations in six states for consideration as potential sites for permanent storage of high-level nuclear waste and spent nuclear fuel. In 1987, Congress amended the Nuclear Waste Policy Act and directed the DOE to study only the site at Yucca Mountain, about 160 km northwest of Las Vegas, Nevada. If a nuclear waste repository is constructed at Yucca Mountain, 70 000 metric tons of spent nuclear fuel from U.S. commercial nuclear power plants and high-level radioactive waste from DOE nuclear weapons complexes will be buried 300 m below the surface at Yucca Mountain. Some believe that the future of the nuclear power industry depends on building a repository. However, an alternative to a single nuclear waste repository is dry cask storage at or near nuclear reactors. Although not approved for permanent storage, this method, already licensed by the Nuclear Regulatory Commission (NRC), is in use today and would not require the transport of waste long distances along public highways. DOE investigators were given the task of demonstrating that natural and engineered barriers at the Yucca Mountain site would prevent the waste itself or contaminated fluids from escaping to surrounding areas for 10 000 years. The waste needs to be contained for at least 10 000 years because of the extreme hazard to public health and the environment associated with these radioactive materials.

Although studies have been under way for several decades, 2002 is a critical time for scientific studies at Yucca Mountain. This year, the DOE recommended the site for licensing as a nuclear waste repository. President Bush approved the recommendation on February 15, 2002. If this decision survives a veto by Governor Kenny Guinn of Nevada and a lawsuit filed by the State of Nevada, work would enter a phase of site approval and license application and leave the site characterization stage. According to the DOE's schedule, if the repository is licensed, construction will begin in 2006 and waste accepted in 2010. Before the site characterization stage is completed, however, a variety of geological and hydrological studies must be finished to evaluate the Yucca Mountain site for long-term storage of high-level radioactive waste. Important issues related to site study range from transport of contaminants released from the repository in groundwater (e.g., Ferrill et al., 1999) to determining the risk of future basaltic volcanism and the consequences of eruption into or near the repository block. Studies of volcanic activity are of particular interest, because basaltic volcanism has occurred since 10.5 Ma in the Yucca Mountain area and eight Quaternary alkali basalt volcanoes ranging in age from ~1.0 Ma to 80 ka have erupted within 50 km of the proposed repository.

Volcanism studies by the DOE have been under way for over two decades (Crowe and Carr, 1980; Crowe et al., 1982, 1983a, 1983b, 1998; Geomatrix Consultants, 1996; Civilian Radioactive Waste Management System Management and Operating Contractor, 2000). In addition, oversight by the NRC and the State of Nevada has resulted in many important scientific contributions (e.g., Connor and Hill, 1995; Connor et al., 2000; Woods et al., 1999; Smith et al., 1990; Bradshaw and Smith, 1994; Ho and Smith, 1997, 1998). The DOE continued its probabilistic volcanic hazard studies by establishing a panel of 10 experts who evaluated past research and independently estimated the probability of future eruptions in the Yucca Mountain region (Geomatrix Consultants, 1996). The expert panel calculated the probability of magmatic disruption of the Yucca Mountain site at about 1.5×10^{-8} events per year. The DOE is currently using a probability of 1.6×10^{-8} (U.S. Department of Energy, 2001).

According to Environmental Protection Agency (EPA) guidelines, volcanism should not be considered an issue for site selection if there is less than 1 chance in 10 000 in 10 000 years of site disruption by volcanic eruption (Environmental Protection Agency, 1993). This requirement is reiterated in the new EPA rule for Yucca Mountain (Environmental Protection Agency, 2001). Although the number calculated by the expert panel is greater than this guideline value, the DOE and the NRC are continuing their studies of volcanism at the Yucca Mountain site (Macilwain, 2001). Substantial new information relating to volcanic probability and consequence has been published since the report of the expert panel in 1996. This paper focuses on studies completed since 1996 that may contribute to new probabilistic estimates of volcanic hazard assessment. It emphasizes that the final decision to place a repository at Yucca Mountain should be based on sound science. This important decision should not be rushed for political reasons or to satisfy program requirements.

DISTRIBUTION AND TIMING OF VOLCANISM

Volcanoes in the Yucca Mountain area are part of a larger zone of basaltic volcanism that stretches from Death Valley, California, to the Lunar Crater field in central Nevada (Vaniman and Crowe, 1981; Crowe et al., 1983b) (Fig. 1). This belt of Pliocene-Quaternary alkali basalt volcanoes lies along the axis of the Great Basin and is isolated from similar-aged basaltic volcanoes in the Basin and Range–Colorado Plateau transition zone to the east and volcanic fields along the eastern front of the Sierra Nevada Range to the west. In Figure 1, the distribution and age of Pliocene-Quaternary basaltic volcanoes in the area from Crater Flat near Yucca Mountain to Lunar Crater are shown. Volcanoes in the Death Valley area are not plotted because of poor age control; therefore, in the remainder of this paper, the zone will be referred to as the Crater Flat–Lunar Crater zone. Volcanism in the southern part of the zone at Crater Flat is coeval with volcanic activity to the north in the Reveille Range and at Lunar Crater.

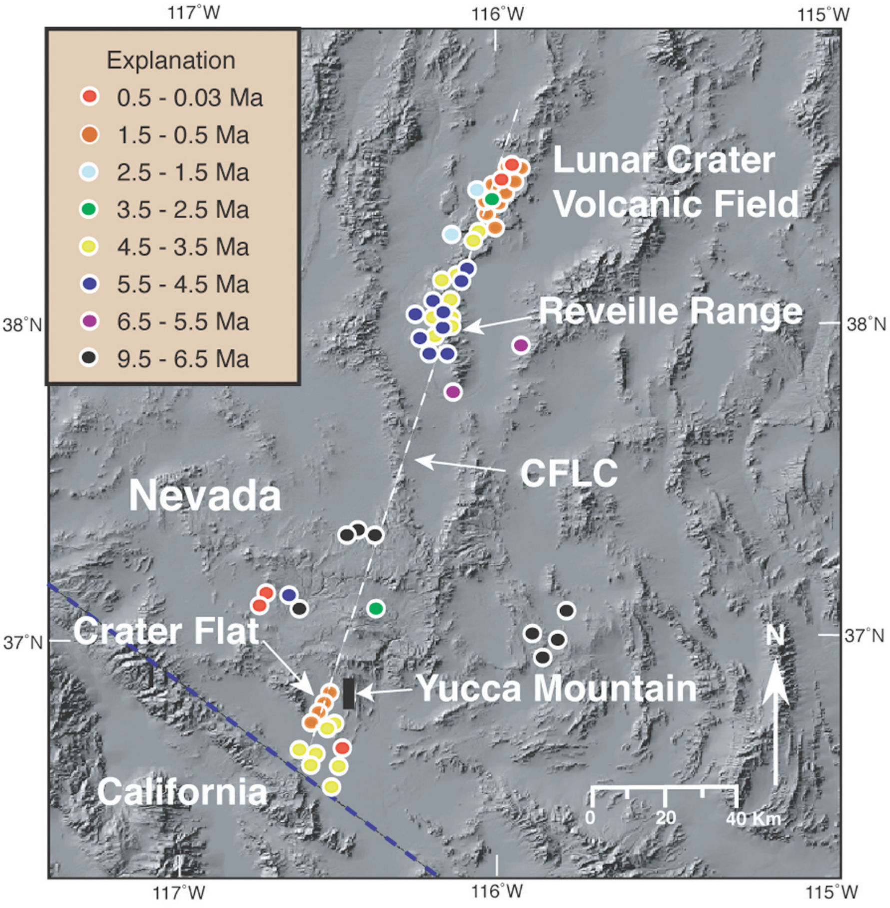

Figure 1. Age and distribution of Pliocene-Quaternary basaltic volcanoes in Crater Flat–Lunar Crater zone (CFLC).

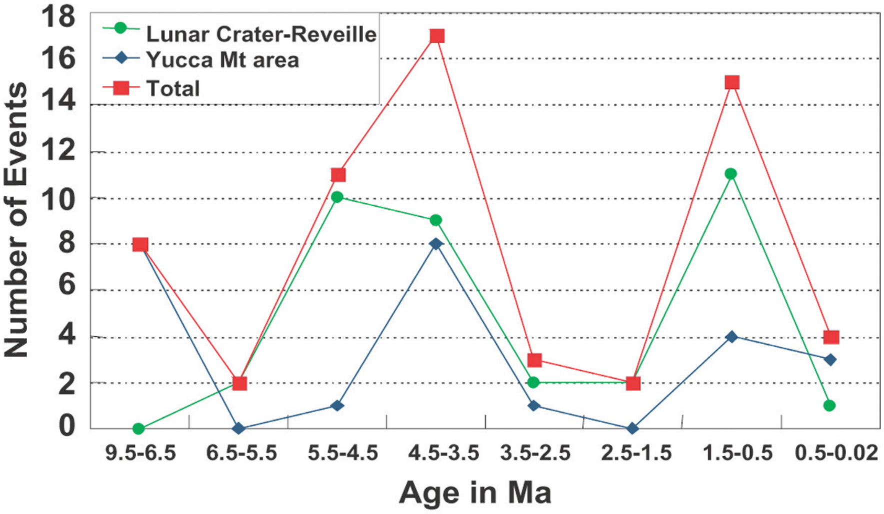

Figure 2. Time-event plot showing episodic nature of volcanism in Crater Flat–Lunar Crater zone.

Recurrence rates in the southern part of the Crater Flat–Lunar Crater zone near Yucca Mountain vary from 3.7 to 12 volcanic events per m.y. (Connor and Hill, 1995; Crowe et al., 1998; Connor et al., 2000). Recurrence rates in the northern part of the zone in the Reveille and Lunar Crater fields vary from 11 to >15 events per m.y. Furthermore, when volcanic events are plotted against time (Fig. 2), there is an episodic pattern. Since 9.5 Ma, there have been three peaks of volcanism: one between 9.5 and 6.5 Ma (only near Yucca Mountain), the second between 4.5 and 3.5 Ma, and the last between 1.5 and 0.5 Ma. Periods of relative quiet separate these peaks and last for 1–2 m.y. At the present time, volcanism in the Crater Flat–Lunar Crater zone is relatively quiet with only three eruptions in the past 100 000 years. The most recent eruptions occurred at the Lathrop Wells cinder cone (77.3 ± 6.0 ka; Heizler et al., 1999) at the southern tip of Yucca Mountain and from the Black Rock cones (two eruptions dated at 38.1 ± 9.7 ka, Shepard et al., 1995; E. Stickney, unpublished $^{40}Ar/^{39}Ar$ date) in the Lunar Crater volcanic field. The small number of eruptions, especially in the Yucca Mountain area, introduces uncertainty about the statistical significance of these trends. Nevertheless, these observations are based on all radiometrically dated volcanoes. Thus, we contend that observations related to coeval volcanism and episodic patterns within the Crater Flat–Lunar Crater zone are valid. Episodic patterns of volcanism were previously noticed by DOE volcanologists (Crowe et al., 1998). Additionally, based on Global Positioning System (GPS) surveys, Wernicke et al. (1998) suggested that the Yucca Mountain area is currently in a period of rapid strain accumulation and inferred that magmatic and tectonic events may be episodic with events lasting 100 000 years occurring every million years. These results were vigorously debated (Savage, 1998; Connor et al., 1998; Davis et al., 1998; Savage et al., 1999).

MANTLE CONTROL OF VOLCANISM?

Correlations of the timing of volcanism between the northern and southern parts of the Crater Flat–Lunar Crater zone infer a common driving force for magma generation. In the past, there was a reluctance to accept a common process to explain volcanism along the length of the zone because of geochemical data that demonstrate that basalt in the Reveille and Lunar Crater fields has high ε_{nd} and low $^{87}Sr/^{86}Sr$ while basalt near Yucca Mountain has lower ε_{nd} and higher $^{87}Sr/^{86}Sr$. The Reveille and Lunar Crater isotopic signatures are thought to represent melting of asthenospheric mantle (Foland and Bergman, 1992; Yogodzinski et al., 1996), whereas those in the Crater Flat area represent melts of the lithospheric mantle (Perry and Crowe, 1992). In support of different mantle sources for northern and southern parts of the Crater Flat–Lunar Crater zone, Yogodzinski and Smith (1995) defined the Amargosa Valley Isotopic Province for the southern part of the Crater Flat–Lunar Crater zone (including Death Valley) and suggested that because of its chemical properties, lithospheric mantle in the Amargosa Valley Isotope Province had a greater tendency to melt than surrounding mantle.

A recent study (Wang et al., 2002) bears directly upon the problems of magma generation in the Crater Flat–Lunar Crater zone and may provide a clue to the processes responsible for coeval episodic volcanism along the length of the zone. The study is based on approximately 400 samples of alkali basalt collected throughout the Great Basin. Techniques developed by Langmuir et al. (1992) quantify the depth and degree of mantle melting. All calculations assumed adiabatic ascent of dry mantle. Differentiation corrected values of FeO were used to constrain the base of the melting column and Na_2O the top. Based on these techniques, Wang et al. (2002) generated a melting profile across the Great Basin (Fig. 3) that showed shallow melting (50–75 km) in the west, deep melting in central Nevada in the Crater Flat–Lunar Crater zone (100–140 km) and somewhat shallower but still deep melting beneath the Colorado Plateau (>90 km). The tops of melting columns across the Great Basin roughly correspond to the asthenosphere-lithosphere contact determined by geophysical studies (Fig. 3). This model implies, therefore, that all melting occurred in the asthenosphere and that the lithospheric mantle did not melt. Melting beneath the Crater Flat–Lunar Crater zone was especially deep. For Lunar Crater, the melting column extends from 162 up to 110 km and for Crater Flat from 133 up to 115 km. According to Wang et al. (2002), deep melting requires hot and buoyant mantle with mantle potential temperatures about 200 °C greater than those in the western Great Basin. Further support for deep melting is the high Tb-Yb ratio in Crater Flat–Lunar Crater zone basalt. Tb/Yb is strongly sensitive to garnet in the source because heavy rare earth elements like Yb are strongly compatible in garnet and stay in the source during partial melting. Garnet is stable in mantle peridotite at depths >~100 km. Therefore, if melting is deep and garnet is in the source, Tb/Yb will be high. The concept of a deep mantle source for basalt near Yucca Mountain is not new. Previously, Vaniman and Crowe (1981), Perry and Crowe (1992), and Bradshaw and Smith (1994) noticed steep rare earth element patterns (high La/Yb), low Sc, low SiO_2, high FeO, and nepheline-normative compositions and suggested deep melting in the garnet field. In addition to the work of Wang et al. (2002), there are several recent geochemical and geophysical studies that support the presence of hot, buoyant mantle beneath the Crater Flat–Lunar Crater zone. Smith et al. (1999) indicated that pyroxene compositions in peridotite xenoliths from the Black Rock flow in the Lunar Crater volcanic field record equilibrium temperatures 200 °C higher than other similar composition xenoliths in the western United States. They interpreted these data as evidence for a plume. Parsons et al. (1994) and Saltus and Thompson (1995) argued that the Yellowstone plume has left a broad anomaly of buoyant mantle centered in northern Nevada (beneath the northern part of the Crater Flat–Lunar Crater zone).

Central Nevada has lower than average S-wave velocities at a depth of 300 km, which might be expected from hot, deep mantle (van der Lee and Nolet, 1997). Dueker et al. (2001) indicated lower compressional-wave velocities at a depth of 100 km for central and southern Nevada suggesting the presence of warm asthenosphere. Savage and Sheehan (2000) noted unusual patterns of shear-wave splitting in the Great Basin, with a null region surrounded by a semicircular alignment of fast polarization. They argued that this pattern, along with other supporting evidence (high dynamic elevation and high mantle buoyancy) is consistent with active mantle upwelling. Lowry et al. (2000) showed that high dynamic elevation anomalies in central Nevada are spatially correlative with Quaternary volcanism. Dynamic elevation is the elevation response to asthenospheric mantle buoyancy and is calculated by subtracting surface loads, crustal mass anomalies, and mantle thermal anomalies from the observed topography (Lowry et al., 2000). The authors argued that high dynamic elevation might be due to upwelling of anomalously hot mantle (plume) and phase and/or phase boundary deflections supported by high heat flow.

Collectively, these studies suggest that hot, buoyant mantle exists beneath the Crater Flat–Lunar Crater zone. We suggest that this hot mantle provides the common driving force for magmatism along the length of the Crater Flat–Lunar Crater zone.

QUESTIONS AND DISCUSSION

We realize that our observations and conclusions are controversial and anticipate that many questions will be asked about both temporal and mantle melting models. This section portrays some of the continuing scientific debates about the volcanism issue and presents the scientific uncertainties and controversies about both recurrence rates and causes of volcanism. Important questions yet to be answered about temporal models are:

1. Is the interval between times of peak volcanic activity (1–2 m.y.) too

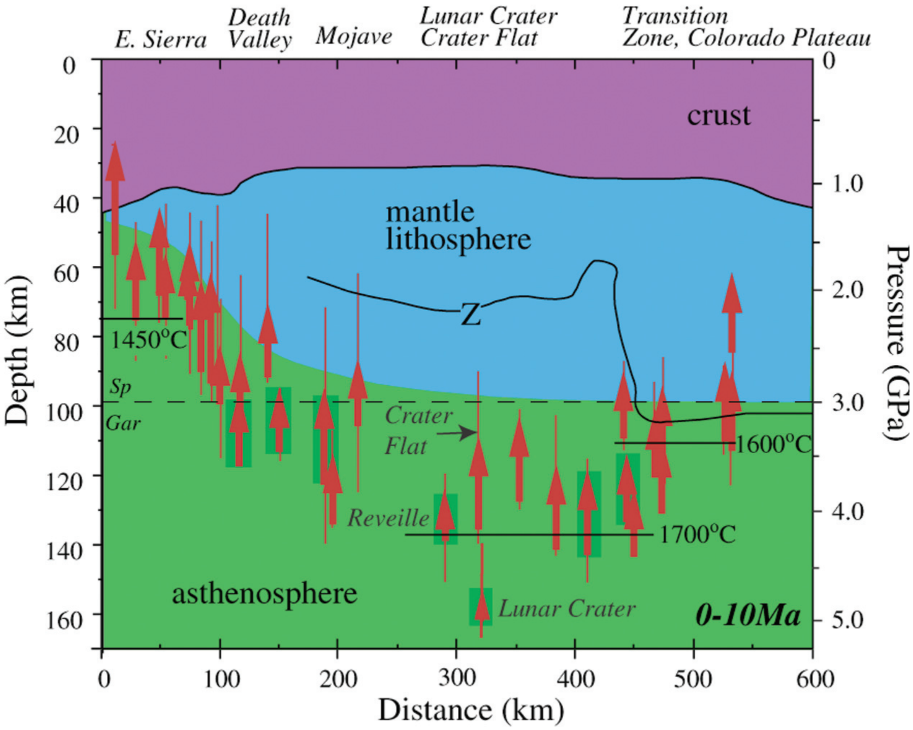

Figure 3. Melting profile across Basin and Range modified from Wang et al. (2002). Profile was constructed by projecting volcanic fields in Great Basin to a northeast-trending line extending from southern California through southern Nevada to southwestern Utah. Red arrow represents melting column calculated for each volcanic field, based on most primitive FeO and Na_2O compositions. Bottom of arrow marks onset of melting at solidus and is function of mantle temperature, while top of arrow marks end of decompression melting, presumably due to change in rheology near lithosphere-asthenosphere boundary. Thin line extension to arrows includes depth estimates and errors using Fe8.0 (see Wang et al., 2002, for details). Crustal thickness was compiled from Das and Nolet (1998). Blue-colored lithosphere is based on lithosphere thickness (Lm+Moho) estimates in Jones et al. (1996). Alternative boundary for base of lithosphere (marked with Z) based on P-wave residuals from Zandt et al. (1995). Spinel-garnet (Sp, Gar) transition in peridotite after Klemme and O'Neill (2000) and Robinson and Wood (1998). Dark green bars are for melting columns with average ε_{nd} of >+0.5. Temperatures given are solidus temperatures of adiabatically ascending mantle. Pressure axis calculated assuming 35 km crust with 2.85 g/cc density overlying mantle of 3.25 g/cc density.

long to be used with confidence for statistics that try to predict what might happen in the next 10 000 years? The answer to this question depends on whether the present day lies at the beginning, middle, or end of the current period of low activity. Although today's position within the eruption-low activity sequence is unknown, we observe that it has been nearly 1 m.y. since the last peak of activity and three eruptions have occurred (in the Crater Flat–Lunar Crater zone) in the past 80 000 years. Speculatively, these observations may indicate the end of the current period of low activity and an increase in the rate of eruption in the near future.

2. Does the magmatic system in the Crater Flat–Lunar Crater zone have the potential of producing another eruption peak? An answer to this question may lie in the mantle-melting model proposed by Wang et al. (2002). New eruption peaks, by this model, are possible and would be sustained by hot mantle.

3. Why is volcanic activity episodic? Periods of volcanism may be related to epochs of rapid strain accumulation in the lithosphere. According to Wernicke et al. (1998), elastic strain accumulation related to magmatic events may be episodic with events lasting 100 000 years occurring every million years. Cause-and-effect relationships between magmatism and accumulated strain in this model are unclear. Does magmatism cause rapid strain accumulation (as suggested by Wernicke et al., 1998) or does excess strain created by nearby faults provide an environment favorable for magma ascent? Nevertheless, patterns predicted by Wernicke et al. (1998) are similar to those depicted in Figure 2 except that both periods of observed eruption and low activity are of longer duration.

In regard to the mantle-melting model, we foresee three important questions:

1. Is a dry mantle-melting model valid? It could be argued that the data reflect variations in the water content of the mantle source rather than variations in depth of melting. Hornblende phenocrysts in basalt from Crater Flat suggest that the mantle source contained up to 0.5 wt% water (Hill et al., 1995). Although we agree that there is some water and/or CO_2 in the source of these basalts, melting of a hydrated source yields melts with lower FeO and higher SiO_2 than dry melting (Hirose and Kawamoto, 1995; Gaetani and Grove, 1998). Wet melting, therefore, may not explain the high FeO and low SiO_2 of Crater Flat–Lunar Crater zone basalts.

2. How does the model explain the isotopic differences between the northern and southern parts of the Crater Flat–Lunar Crater zone? Perry and Crowe (1992) and other authors indicate that the high $^{87}Sr/^{86}Sr$ and low ε_{nd} of alkali basalt near Yucca Mountain at the southern end of the zone reflect partial melting of lithospheric mantle at a relatively shallow depth. While we accept that lithospheric mantle melted prior to 10 Ma to produce voluminous calc-alkaline silicic volcanism in the Great Basin (the ignimbrite flare-up), we argue that melting of lithospheric mantle late during a volcanic and extensional episode is very difficult. Harry and Leeman (1995) showed difficulties in sustaining melting in the mantle lithosphere. Because the mantle lithosphere is generally too cold to melt, the only reasonable source of melts would be components with a lower solidus temperature than dry peridotite, such as mafic veins or hydrous components (e.g., amphibole or phlogopite peridotite). Harry et al. (1993) and Harry and Leeman (1995) argued that these components will produce melts during initial phases of extension, and may be responsible for the widespread silicic volcanism during the Oligocene. During further extension, however, these lithospheric components are exhausted, and melting continues largely in the asthenosphere, generating the predominantly basaltic volcanism during the past 10 Ma that we discuss here. Additionally, Gallagher and Hawkesworth (1992) and Hawkesworth et al. (1995) pointed out that lithospheric mantle will melt only if it contains volatiles (mainly water –0.5 wt%). They suggest that if hot mantle is brought in contact with cold lithosphere, lithospheric mantle will melt before the asthenospheric mantle. The authors postulated that calc-alkaline magmatism in Oligocene and Miocene is due to the melting of hydrous lithospheric mantle (in addition to subsequent magma mixing and/or commingling and fractional crystallization). They concluded that after a certain amount of lithospheric extension, asthenosphere will melt by decompression thus forming most of the Pliocene and Quaternary basaltic fields. Their models predicted that during the Quaternary, very little melt can be generated in the lithospheric mantle (even for high rates of sustained extension), and that it is more probable that melts are generated in the asthenospheric mantle. Both of these studies, therefore, point to difficulties in melting lithospheric mantle late during a magmatic-extension event. Thus the question remains as to why basalts in the southern part of the Crater Flat–Lunar Crater zone have high $^{87}Sr/^{86}Sr$ and low ε_{nd}. Lee et al. (2000) suggested that basalt with this isotopic signature may be related to either contamination of deep mantle magma as it passes through the lithospheric mantle or to the overprinting of asthenospheric mantle melts with fluids and/or melt derived from subducted crustal material. We speculate that the isotopic signature of magmas in the southern Crater Flat–Lunar Crater zone may be related to similar processes.

3. Does hot mantle exist beneath the Crater Flat–Lunar Crater zone? We present evidence here to support this assertion, but there is much disagreement. For example, Perry and Crowe (1992) pointed out that high $^{87}Sr/^{86}Sr$ and low ε_{nd} have been a common feature of magmatism in the Yucca Mountain area since at least 10 Ma. Miocene and Pliocene mafic magmas were generated by melting lithospheric mantle; it is unreasonable to assume a different process for younger (late-Pliocene and Quaternary) magmatism. Hawkesworth et al. (1995) and Bradshaw et al. (1993) also argued against a mantle plume for the following reasons: (a) although the average elevation in the central Great Basin is anomalous, "the present-day topography is unlike the symmetrical domes which are inferred to characterize lithosphere underlain by a mantle plume" (Hawkesworth et al., 1995, p. 10 280); (b) the position of the Yellowstone plume lies well to the

north of the central Great Basin; and (c) small to moderate volumes of magmatism, especially that with ocean-island basalt chemistry, dispute the presence of a mantle plume. Wang et al. (2002) countered the last point by arguing that the volume of magmatism is dependent on the total length of the magma column and not magma temperatures alone. Thick lithosphere, like that present in central Nevada, will cap the melting column and lead to small volumes of magma.

IMPLICATIONS

The probability of magmatic disruption of the repository (Prdr) is defined as a conditional probability: Prdr = Pr(E2 given E1)Pr(E1) (Crowe et al., 1982). E1 is the volcanic recurrence rate and E2 the probability of the intersection of the repository by a dike or volcanic conduit. A knowledge of recurrence rates is crucial to the calculation of probability of magmatic disruption. We contend that there is more uncertainty in recurrence rate estimates than assumed by the DOE, the expert panel, and the NRC. Our petrologic data suggest that volcanic fields in the Crater Flat–Lunar Crater zone are linked to a common area of hot mantle. Also, we show that volcanism is episodic with a good possibility of a new peak of activity occurring in the future. These observations imply that volcanism is not dead in the Yucca Mountain area and that a future pulse of activity could have recurrence rates equivalent to those recorded in the Lunar Crater–Reveille area of the Crater Flat–Lunar Crater zone. Specifically, the DOE and the NRC have used recurrence rates of from 3.7 to 12 events per m.y. to calculate probability of volcanic disruption (Connor and Hill, 1995; Crowe et al., 1998; Connor et al., 2000). Based on our arguments, recurrence rates of 11 to >15 events per m.y. are possible. Because higher recurrence rates raise the likelihood of magmatic disruption of the repository, we recommend that future probability studies factor these higher rates into probability models.

CONCLUSIONS

Our principal point is that Pliocene-Quaternary volcanism in the Crater Flat–Lunar Crater zone is episodic and sustained by an area of hot mantle. Our petrologic arguments suggest that recurrence rates of volcanism used by the DOE and the NRC may be underestimated and that higher rates typical of the Lunar Crater–Reveille part of the Crater Flat–Lunar Crater zone may be applicable to the Yucca Mountain area. Moreover, if models of hot mantle are correct, volcanism is not dead and another eruption peak is possible. These statements are supported by several recent geochemical and geophysical studies. We suggest that future calculations of volcanic risk take into account higher recurrence rates and patterns of volcanism directly determined by examining the geological record. Despite decades of work on volcanism, there are still many unanswered questions related to the suitability of Yucca Mountain to store nuclear waste. Sound science should take precedence over politics and program requirements when making the decision to place a repository at Yucca Mountain. If too many questions remain unanswered, then perhaps another repository site should be selected in an area without the risk of volcanism.

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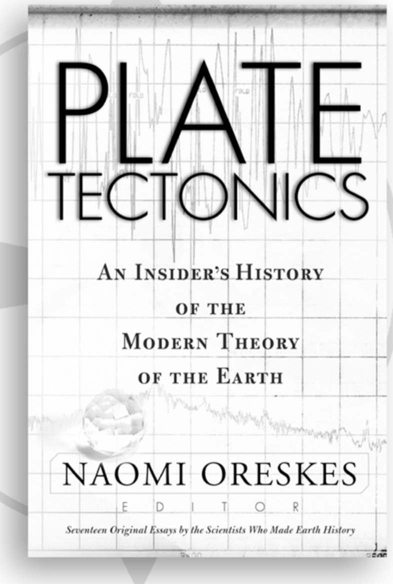

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