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Decreasing magmatic footprints of individual volcanoes in a waning basaltic field

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Abstract

The distribution and characteristics of individual basaltic volcanoes in the waning Southwestern Nevada Volcanic Field provide insight into the changing physical nature of magmatism and the controls on volcano location. During Pliocene-Pleistocene times the volumes of individual volcanoes have decreased by more than one order of magnitude, as have fissure lengths and inferred lava effusion rates. Eruptions evolved from Hawaiian-style eruptions with extensive lavas to eruptions characterized by small pulses of lava and Strombolian to violent Strombolian mechanisms. These trends indicate progressively decreasing partial melting and length scales, or magmatic footprints, of mantle source zones for individual volcanoes. The location of each volcano is determined by the location of its magmatic footprint at depth, and only by shallow structural and topographic features that are within that footprint. The locations of future volcanoes in a waning system are less likely to be determined by large-scale topography or structures than were older, larger volume volcanoes.

1. Introduction

Basaltic volcanic fields in continental settings consist of scattered volcanoes such as scoria cones, maars, tuff rings, small shields, and attendant lava flows [*Connor and Conway*, 2000]. Such volcanic fields are common in regions of tectonic extension such as the Basin and Range Province of North America and the African-Arabian rift system [e.g., *Crowe*, 1986; *Aranda-Gómez*, 2003; *Camp et al.*, 1991], subduction zones [*Connor*, 1990] as well as more stable intraplate settings such as around Auckland, New Zealand and the Colorado Plateau (USA) [e.g., *Briggs et al.,* 1994; *Condit et al.,* 1989]. The nature of such volcanic fields during initial birth and the final waning stages is not well understood, and is important from the perspectives of determining volcanic hazards and understanding continental basaltic magmatism. Here we show that as the volume flux for a volcanic field in southwestern Nevada (USA) has waned, so have the effusion rate, eruptive volume, and the length scale of eruptive fissures at individual volcanoes. Simultaneously, the rate of formation of new volcanoes and their explosivity has increased. The length scale of eruptive fissures reflects the length scale of dikes that transport magma upward through the Earth's crust. We infer that the decreasing length scale of fissures is related to a decrease in the areal extent of the underlying magma source zone for each volcano, which we term the "magmatic footprint". The location of a given volcano is mainly affected by the location of its magma source zone – a conclusion also reached by *Condit and Connor* [1996] for the Springerville volcanic field in Arizona - and geologic structures within its magmatic footprint. Long-term volcanic risk assessments in waning basaltic volcanic fields, which require estimates of the probability of forming new vents at a given location and the resulting consequences, must account for changes in the magmatic footprints of volcanoes. In addition, the compositions of individual volcanoes in such systems represent samples of progressively smaller length scales of the mantle source region and, in principle, should provide insight into the nature of upper mantle variability.

2. Southwestern Nevada Volcanic Field

The Southwestern Nevada Volcanic Field has experienced volcanism since mid-Miocene times. Major caldera-forming, silicic eruptions occurred between 15.25-9.4 Ma [*Sawyer et al.*, 1994] and gave way to scattered basaltic volcanoes. The mass or volume flux of the volcanic field as a whole has decreased with time, indicating that it is a waning system [*Crowe*, 1986]. Eruptive volume per basaltic volcano has simultaneously decreased with time from ~10 km^3 for volcanoes in the 9-11 Ma range, to the <0.1 km^3 Lathrop Wells volcano [*Crowe*, 1986] that formed ~76,000 years ago [*Heizler et al.*, 1999]. We focus on volcanoes that formed during the Pliocene and Pleistocene epochs (Figure 1) because they are sufficiently well preserved to allow reconstruction of eruptive processes and volumes based upon lavas and pyroclastic deposits [*Crowe et al.*, 1983; *Valentine et al.*, 2005, in review], and because their ages are sufficiently constrained [*Fleck et al.*, 1996; *Perry et al.*, 1998; *Heizler et al.*, 1999] for the conclusions we present. Some Pliocene volcanoes have been buried by alluvial sediments and are only known by indirect geophysical evidence (aeromagnetic anomalies) or drilling [*Connor et al.*, 2000; *Perry et al.*, 2005]; these are not included in the below discussion because they cannot be easily characterized, but based upon their inferred areal dimensions these buried volcanoes would reinforce our conclusions.

3. Characteristics of the Pliocene-Pleistocene volcanoes

Key characteristics of the Pliocene-Pleistocene volcanoes are summarized in Table 1; volume of erupted products, fissure length, and maximum lava effusion rate are plotted in Figure 2. Eruptive volume is an indicator of the total mass and therefore the heat energy that fed each volcano (realizing that the erupted materials only represent a fraction of the total magma produced for a volcanic event, the remainder being trapped in the subsurface). Volume was determined by integrating the digital elevation data above the reconstructed paleosurface that underlies each volcano. Some volume has been lost from each volcano due to erosion (For the Pliocene volcanoes, most of this loss has been erosion around the edges of their lava fields. For the Pleistocene volcanoes most of the loss is from erosion of fallout deposits that extended beyond their lava fields, as well as some loss due to cone degradation.), but the trends in volume reflect real changes in volcano size. Volumes of Pleistocene volcanoes are approximately one order of magnitude smaller than the volumes of Pliocene volcanoes (Figure 2).

Basaltic magmas move upward through the Earth's crust in self-propagating, magma-filled fractures (dikes); fissure length represents the length of a dike where it intersects the surface. Fissure length for the volcanoes of interest was determined from geophysical data (Thirsty Mountain [*Grauch et al.*, 1997]) and surface mapping (Pliocene Crater Flat and Buckboard Mesa) for the three Pliocene volcanoes. Except for Makani volcano, the Pleistocene volcanoes each have only one central vent area that is represented by a variably eroded scoria cone [*Valentine et al.*, 2005, in review]. It is likely, based upon historical scoria-cone forming eruptions such as Parícutin (Mexico [*Luhr and Simkin*, 1993]), that the eruptions of each of these small volcanoes began along a fissure and became focused into a single main vent that grew to form a scoria cone with lavas emanating from its base. The inferred initial fissure is now buried beneath lavas and pyroclastic deposits. The fissure lengths shown in Figure 2 for these volcanoes are therefore inferred to be roughly the same as the cone diameters, although we allow for the fact that fissures could be as long as the diameter of the entire volcano (cone and lava flows), as indicated by dashed lines. Makani volcano was erupted along a small fissure

[*Valentine et al.*, in review], the length of which can be directly measured from a geologic map. Fissure length has generally decreased from as long as 5 km during Pliocene times to lengths on the order of a few hundred meters for the younger volcanoes (Figure 2).

The final characteristic plotted in Figure 2 is the lava effusion rate. This is estimated from *Walker's* [1973] graphical relationship between lava flow length and effusion rate based upon a large number of eruptions around the world. *Walker* [1973] argued that effusion rate is the primary control on lava flow length, with viscosity and topographic slope only having secondary effects. The Pliocene-Pleistocene lavas in the volcanic field discussed here have a relatively limited range of composition [*Fleck et al.*, 1996; *Perry et al.*, 1998] such that their viscosities would have likely been within one order of magnitude of each other. Also, the lavas all flowed across relatively flat or gently sloping terrain. These observations reinforce the argument that flow length within this field is primarily a function of effusion rate. Note that explosive phases of eruptions might have had higher magma volume flux, but this cannot be determined due to erosion of the resulting pyroclastic deposits. The effusion rate data reflect an evolution in overall eruptive style during the time frame of interest. The earliest Pliocene volcano, Thirsty Mountain, erupted with a relatively high effusion rate that fed lava flows at least 6 km long. The volcano is a small shield with a central remnant of near-vent pyroclastic deposits near its summit, but lavas apparently vented from a ~5 km long, NE-SW trending fissure. The Pliocene Crater Flat eruptions were fed by a N-S trending fissure system. The eruptive products are mainly lavas that flowed distances of at least 4 km, with coarse, welded pyroclastic material only preserved in the immediate vicinity of localized vents along the fissure system. The Pliocene Crater Flat products probably formed a low shield volcano that was subsequently disrupted by normal faults. Buckboard Mesa consists of a prominent remnant of a cone composed of pyroclastic deposits, but lavas erupted along a N-NW trending fissure and flowed as far as 7.3 km. Overall, the Pliocene volcanoes have characteristics indicative of Hawaiian eruption styles, with sustained lava effusion and poorly fragmented pyroclastic fountains associated with long fissures. Younger volcanoes are, in contrast, characterized by products indicative of Strombolian (poorly fragmented, discrete eruptive bursts) to violent Strombolian (sustained, well-fragmented eruption columns) explosive eruptive styles [*Valentine et al.*, 2005, in review]. Lava flows associated with these volcanoes tend to have limited extents (typically around 1.5 km long) and appear to have been emplaced as multiple small flow pulses [*Valentine et al.*, in review]. Additionally, all eruptive products from each Pleistocene volcano erupted from the area of the volcano's main cone, rather than from longer fissures as in the older volcanoes.

4. Interpretation and Implications

We infer that the decrease in fissure length with time in this waning basaltic field reflects a decrease in dike length at depth. The exact relationship between the two depends upon the shape of a dike along its plane. Experimental studies [e.g., *Menand and Tait*, 2002] indicate that vertically-rising dikes have curved upper surfaces, concave downward with the highest point representing the centerline of the dike. In real geological situations it is likely that the upper surfaces are irregularly shaped due to heterogeneities in host rock properties, but the curved shape is likely a good first-order approximation. Eruptive fissure length may therefore be shorter than the length of the dike at depths of hundreds of meters, but it is unlikely that the difference is more than a factor of 2-3 (note that this pertains to a vertically rising dike, not a laterally-propagating bladed dike). This is supported by the fact that two of the Pleistocene volcanoes erupted on local topographic highs (Little Black Peak and Hidden Cone). If their dike lengths were much longer than the footprint of the volcanoes themselves, the feeder dikes would have first intersected the surface at lower altitudes and volcanic vents would have formed there [*Gaffney and Damjanac*, submitted]. Therefore, we expect that the Pliocene volcanoes were fed by dikes on the order of 5-10 km long (at depth), while the Pleistocene volcanoes were fed by dikes ranging from 0.5-2 km long. These dike lengths reflect, in turn, differences in the length scale of the magmatic source zone – the magmatic footprint - in the mantle for the volcanoes. Eruptive volume and systematic differences in incompatible trace-element concentrations suggest that Pliocene volcanoes represent larger degrees of partial melting than Pleistocene volcanoes [*Perry and Crowe,* 1992; *Fleck et al.*, 1996; *Perry et al.*, 1998]. A hypothetical ~5% partial melting to produce the source magma for Thirsty Mountain (Pliocene) would tap a volume of mantle with a length scale of ~4 km. 1% partial melting of the mantle to produce the trachybasaltic magmas at the late Pleistocene Lathrop Wells would tap a volume with a length scale of ~1 km. This decreasing length scale (footprint) is consistent with the differences in inferred dike lengths. The notion of decreasing magmatic footprints is consistent with observations at the Reveille Range volcanic field [*Yogodzinski et al.*, 1996], ~100 km NNE of the volcanoes we describe, where volcanism focused into successively smaller portions of the field as overall volume flux waned. Crustal magma reservoirs that might be associated with each of these small volcanoes (evidenced by the geochemistry and petrology of the eruptive products, which commonly record significant fractionation [*Perry et al., 1998*]) are expected to have had lateral extents within the magmatic footprints.

There are two important ramifications of the above conclusion. The first pertains to estimating the likelihood of formation of a new volcano at a given location within a volcanic field. Dikes that feed the volcanoes will only be affected by shallow structural or topographic features within their magmatic footprints. During a high volume flux phase of a basaltic field the lengths of feeder dikes are likely to be several kilometers. Such dikes can be "captured" by structures such as faults (e.g., *Valentine and Krogh* [2006]) or by topographic variations (forming vents at topographically low points) on the same length scale. If the overall volume flux is waning, volcano formation would be increasingly less likely to be affected by such long-wavelength topography. In the volcanic field described here, several of the younger volcanoes formed in the topographic basin of Crater Flat (Figure 1). We maintain that this does not reflect topographic control on dike ascent, but rather the location of the source zones in the mantle (of course, it is possible that the tectonic processes that produced the basin and the processes that produce small length-scale mantle melting are related, c.f. *Connor et al.* [2000]). If melting occurs beneath a topographic high during waning volcanism, the resulting volcano will form on that high, as demonstrated here for two of the eight Pleistocene volcanoes. Most basaltic dikes that we have observed at eroded Miocene volcanoes in the Southwestern Nevada Volcanic Field occupy normal faults [e.g., *Valentine and Krogh*, 2006], and based upon field and geophysical data it is likely that the Plio-Pleistocene volcanoes all erupted along pre-existing faults. Therefore fault capture is an important mechanism for shallow dike ascent but only affects vent location if a fault is within the magmatic footprint. In order to estimate the probability of formation of a new volcano at a given location, the size and location of potential magma source zones are primary determining factors, while shallow structure and surface topography are secondary. It is also important to note that while decreasing volume flux of a volcanic field results in decreasing magmatic footprints and volumes of individual volcanoes, the frequency of formation of new volcanoes and their explosivity may increase. This may reflect increasing volatile contents of magma batches as degree of partial melting decreases [e.g., *Condit and Connor*, 1996; *Perry et al.*, 1998]. Note that SW Little Cone and Lathrop Wells volcanoes had estimated water contents as high as 4.6 wt% [*Nicholis and Rutherford*, 2004].

A second implication is that a waning basaltic volcanic field, where the magmatic footprints of volcanoes decrease with time, may provide a systematic sampling of different length scales of compositional heterogeneity in the mantle source region. Other studies of mantle source heterogeneities have focused on variations in high magma production areas such as the Hawaiian hot spot [*DePaolo*, 1996] or mid-ocean ridges [*Spiegelmann*, 1993], where new (asthenospheric) mantle material is constantly upwelling into the magma source region. For a waning continental volcanic field, the decreasing magmatic footprint samples a range of length scales in a relatively stationary (lithospheric) mantle source.

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Figure Captions

Figure 1 – Digital elevation model (DEM) showing distribution of Pliocene-Pleistocene basaltic volcanoes in the Southwestern Nevada Volcanic Field (not including known or inferred buried volcanoes). Pliocene volcanoes (magenta) include Thirsty Mountain (TM), Pliocene Crater Flat (PCF), and Buckboard Mesa (BM). Pleistocene volcanoes (red) include Makani (MC), Black Cone (BC), Red Cone (RC), SW and NE Little Cones (both labeled together as LC), Little Black Peak (LBC), Hidden Cone (HC), and Lathrop Wells (LW). Solid lines represent margins of Miocene silicic calderas [*Wahl et al.*, 1997]. Crater Flat and Jackass Flats are major structural basins (note that most linear

ridges and range fronts in the DEM coincide with normal faults). Inset shows location with respect to the southwestern United States.

Figure 2 – Plot of eruptive volume (circles sized in proportion to cube-root of volume) fissure length (lines), and lava effusion rate (dots) for Pliocene-Pleistocene volcanoes of the Southwestern Nevada Volcanic Field. Note that age determinations do not allow discrimination of relative ages amongst the five Pleistocene volcanoes in Crater Flat, therefore they plotted in random order around 1 Ma. The eruptive products of SW and NE Little Cones are largely buried by alluvium and mapped by aeromagnetic anomaly [*Valentine et al.,* in review]; their volumes are lumped together in this plot.

Table 1. Ages, Volumes, and Eruptive Characteristics of Pliocene-Pleistocene Volcanoes in the Southwestern Nevada Volcanic Field

Volcano	Age (Ma)	Rock type[a]	Volume (km^3)	Fissure length (km)	Lava flow length (km)	Maximum lava effusion rate[b] (m^3/s)	**Brief description**
Thirsty Mountain	4.63±0.02[c]	Basaltic trachyandesite	2.28	5[d]	6	80	Broad shield volcano consisting of stacked lava flows and a central remnant of pyroclastic (near vent) deposits.[c]
Pliocene Crater Flat (a.k.a. Southeast Crater Flat)	3.73±0.02[c]	Basalt	0.56	3.6	4	40	Low shield volcano, now broken by normal faults and partially buried by alluvium, with multiple lavas and pyroclastic vent facies exposed.
Buckboard Mesa	2.87±0.06[c]	Basaltic trachyandesite	0.84	2.5	7.3	100	Large lava field with remnant of a main pyroclastic cone in northern part, fissure inferred from ridge of lava and pyroclastics that extends SE from main cone.
Black Cone	0.986±0.047[c]	Trachybasalt	0.06[e]	0.6 (1.8)[f]	1	0.9	Pyroclastic cone remnant preserving Strombolian and violent Strombolian facies, and two lava fields that vented from the base of the cone.[e]

Red Cone	0.977±0.027[c]	Trachybasalt	0.06[e]	0.5 (1.6)[f]	1.4	3	Pyroclastic cone remnant preserving Strombolian and violent Strombolian facies, and two lava fields that vented from the base of the cone.[e]
SW Little Cone	1.042±0.045[c]	Trachybasalt	0.03	0.3 (0.8)[f]	0.7	0.4	Pyroclastic cone remnant, open to the south, with single lava field mainly buried by alluvium.[e]
NE Little Cone	1.042±0.045[c]	Trachybasalt	Included with SW Little Cone	0.2 (1.8)[f]	1.8	4	Pyroclastic cone remnant, open to the south, with single lava field mainly buried by alluvium.[e]
Makani volcano (a.k.a. Northernmost)	1.076±0.026[c]	Trachybasalt	0.002[e]	0.4	0.4	0.1-0.2	Small lava mesa with pyroclastic deposits marking location of short fissure.[e]
Little Black Peak	0.323±0.027[c]	Basalt to trachybasalt	0.014	0.4 (1)[f]	1.3	2	Pyroclastic cone with lavas that extend from its base.
Hidden Cone	0.373±0.042[b]	Basalt to trachybasalt	.03	0.3 (0.8)[f]	1.6	4	Pyroclastic cone on side of butte with two lava field extending from its base.
Lathrop Wells	0.076±0.005[g]	Trachybasalt	0.09[h]	0.8 (1.8)[f]	1.6	4	Single pyroclastic cone with two lava flow fields that vented from the base of the cone.[h]

[a] Classification of *Le Bas et al.* [1986] as determined by *Fleck et al.* [1996]

[b] Maximum lava effusion rate estimated from Figure 4 of *Walker* [1973].

[c] Weighted mean values of *Fleck et al.* [1996]

[d] Inferred from geophysical data [*Grauch et al.,* 1997] and geologic map [*Minor et al.*, 1998]

[e] *Valentine et al.* [submitted]

[f] Value provided represents diameter of main cone, which is the source for all preserved eruptive material [*Valentine et al.*, submitted], representing the expected value. Value in parentheses is the total length that could be buried by all eruptive deposits, representing the maximum possible value.
[g] Age of Ql_2 flow, *Heizler et al.* [1999].
[h] *Valentine et al.* [2005]. Note that loose pyroclastic deposits, including a fallout tephra deposit that extends up to 20 km from the cone, is preserved at Lathrop Wells volcano due to its young age. This results in a larger estimate of volume than at older volcanoes such as Red Cone and Black Cone, which are otherwise similar in size.

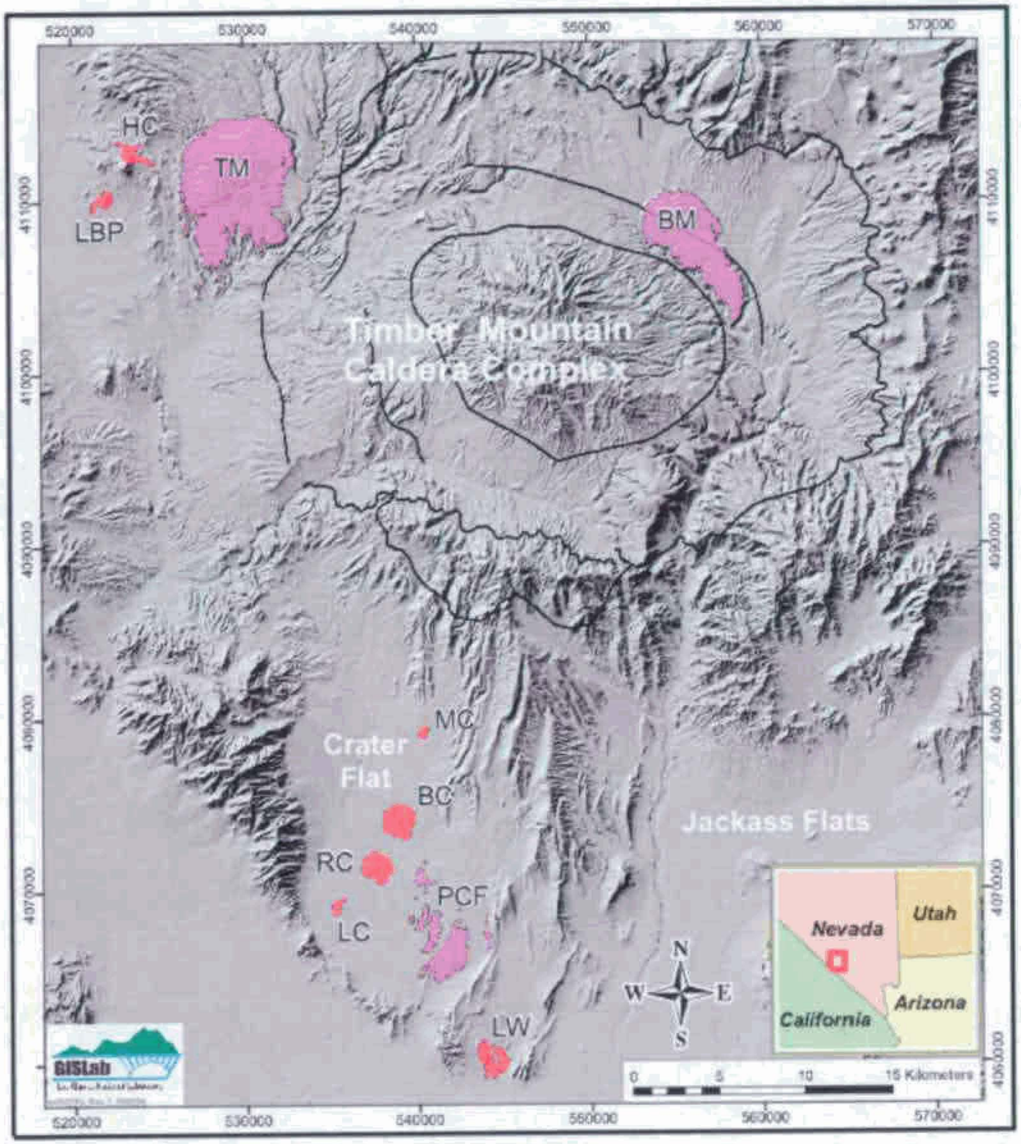
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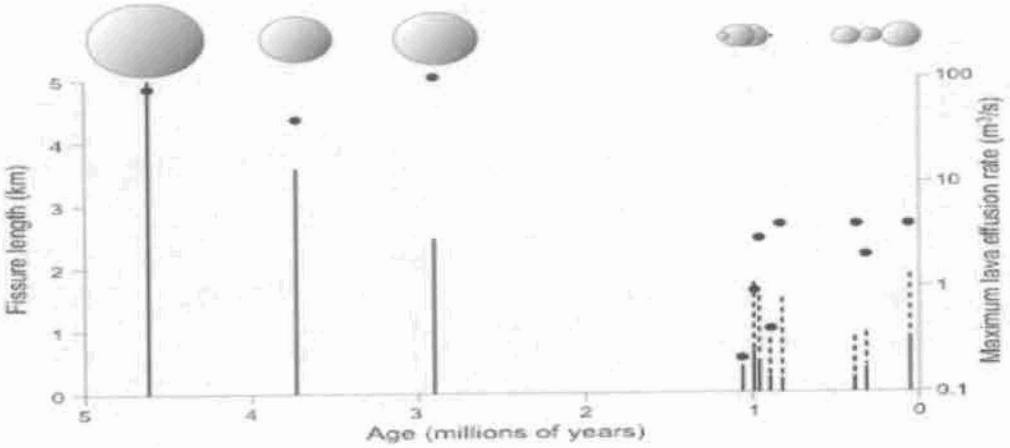
Figure 1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Age (millions of years)

Figure 2