

## Reassessment of the sources and space-time patterns of Late Cretaceous and younger magmatism, Colorado

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Late Cretaceous to mid-Tertiary igneous activity in Colorado, western U.S., can be divided into two discrete pulses, Laramide (~70-55 Ma) and mid-Tertiary (35-25 Ma). Most workers link both episodes of continental interior magmatism to subduction of oceanic lithosphere beneath North American continent, although the exact relationship between subduction and either magmatic event is enigmatic. Laramide magmatism was restricted to the SW-NE trending Colorado Mineral Belt (COMB), which consists largely of alkaline intrusive igneous rocks at its southern and northern end and calc-alkaline intrusive rocks inbetween. Mafic lower crust has been invoked as the source of the magmas parental to the COMB igneous rocks, but new isotopic data from Laramide volcanoclastic clasts in the Front Range demonstrate that mafic magmas generated at this time ranged to  $\epsilon_{Nd} \sim 0$  and  $^{87}Sr/^{86}Sr \sim 0.7045$ . These isotopic compositions do not overlap the isotopic compositions of mafic lower crust in this region as directly determined from "high"  $(La/Yb)_N$  mafic xenoliths entrained in Devonian age kimberlite diatremes in the Front Range ( $\epsilon_{Nd}(65 \text{ Ma}) \sim -6$  to  $-10$ ). The isotopic data suggest that the COMB parental magmas were mantle-derived and were not solely the products of lower crustal anatexis. The trigger mechanism for mantle melting is unknown but one speculative possibility is that melting occurred in response to local convective upwelling of asthenospheric mantle along the northern margin of a "flat slab" segment of subducted oceanic lithosphere.

Mid-Tertiary magmatism in Colorado was dominated by silicic magmatism that spatially overlapped, but was not confined to, the position of earlier COMB igneous activity. Many workers have attributed the magmatism to melting during slab rollback of mantle metasomatized during the early Tertiary by slab derived fluids. The large volumes of mid-Tertiary magmas produced (10,000 km<sup>3</sup> of silicic magma in the San Juan volcanic field alone) require either "dynamic" melting in upwelling asthenosphere, or "static" melting of recently hydrated lithosphere over a large area. The latter possibility could account for the wide spacing (~300 km) between major mid-Tertiary silicic volcanic centers in the southern Rocky Mountain area.

## Post-Laramide Tectonomagmatics of the U.S. Cordillera

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Arc magmatism was nearly continuous through most of the Mesozoic until the Laramide (~70-55 Ma), when the arc ceased in most of the Western U.S. Contractual orogenesis spread to the stable interior as the subducting plate flattened and lithospheric thickness doubled.

A basalt-poor subalkalic continental-interior andesite-rhyolite association dominated between about 55 and 17 Ma in the southeast U.S. Cordillera and in transverse belts that migrated episodically from the northern and southern margins of the Laramide magmatic gap toward its center; tectonic extension was locally extreme in these belts. Arcs were active adjacent to the migrating belts, and small alkalic centers dotted the interior forelands.

Beginning about 17 Ma regional extension became widely distributed and dominant regional magmatic associations changed to basaltic and bimodal, typically alkalic or tholeiitic but in places calcalkalic. Greatest magmatic productivity has been in the northwest, including the northern Great Basin, Columbia Plateau, and Snake River Plain-Yellowstone regions. Flood basalts of the Columbia Plateau and adjacent areas erupted from dike swarms adjacent to the cratonic margin, beginning near a prong of thick Archean crust, then propagating north and south, followed by widespread bimodal volcanism. Many interpret this as reflecting the head of a deep-mantle plume; alternatively, it might reflect edge convection and incipient back-arc separation of relatively thin, warm, and weak accreted terranes from the older, colder, and stronger cratonic interior.

Since about 12 Ma voluminous caldera-forming rhyolitic volcanism has propagated about 600 km into the craton along zone of lithospheric weakness from near the initial flood-basalt locus, accompanied by uplift, enhanced extension, a gradually subsiding trace, and a major discontinuity in amounts of extension on opposite sides of the zone. This Eastern Snake River Plain-Yellowstone zone, often regarded as the trail of a plume tail overrun by the North America plate, alternatively might reflect thermal feedback following inception of upper-mantle flood-basalt melting by edge-convection, consequent enhanced melting near the base of the lithosphere, crustal intrusion and partial melting, and voluminous volcanism to unload the source region and promote cyclic replenishment of fertile mantle and further partial melting.

## **The curious decoupling of Cenozoic magmatism and plate tectonics in western North America: A NAVDAT analysis**

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Since the widespread acceptance of plate tectonics, magmatism in the western U.S. has been explained by subduction along the west coast of North America and destruction of the subduction system by development of the San Andreas transform fault system. However, re-analysis of space-time patterns of magmatism in western North America calls many of these inferred patterns of magmatism into question. Animation of space-time patterns found in the developing NAVDAT dataset ([navdat.geogrid.org](http://navdat.geogrid.org)), demonstrates that: (1) subduction-type volcanism is poorly linked to the subduction system; (2) there is little evidence that slab windows controlled magmatism; (3) magmatism was clearly migratory, but not in ways that can be explained by plate-tectonic processes; and (4) magmatism was migratory at length scales ranging from 1000s of km (continental) to 10s of km (county).

Several space-time patterns are evident in the NAVDAT animations, including: (1) a sweep from Montana into Nevada from 50 to about 20 Ma; (2) a clockwise sweep around the Colorado Plateau from New Mexico to southern Nevada, from about 30 to 15 Ma; (3) a burst of magmatism at about 16 Ma in northern Nevada, followed by outward sweeps to Yellowstone, central Oregon, and the Sierra Nevada; (4) a burst of magmatism in the Sierra Nevada at 3.5 Ma; and (5) several local migrations, including from Phoenix north onto the Colorado Plateau and from the San Francisco Bay area north to the Geysers geothermal field.

Some of these patterns have been tied to specific events (e.g., impingement of the Yellowstone plume and Pliocene delamination), but the others are difficult to relate to plate-tectonic events. They may be caused by local tectonic events (propagating rifts?), minor convective rolls in the asthenosphere, lithospheric delamination, or delamination of a flat Laramide slab.

## **Puzzling aspects of Cenozoic Cordilleran magmatic activity: Do we need a new paradigm?**

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Attempts to explain space-time-composition patterns of Cordilleran Cenozoic magmatic activity within a plate tectonic framework have not been very successful. The widely quoted paradigm of early to middle Tertiary, intermed. to silicic, "subduction-related" magmatism progressively replaced by bimodal or basaltic "rift-related" magmatism inboard of the growing transform ( $\pm$  "plume-related" magmatism in the Pacific Northwest) is difficult to reconcile with several observations:

(1) Spatial and temporal patterns of early to mid- Tertiary volcanic activity do not resemble modern "Andean" arcs. Instead, belts of isochronous volcanic activity extended up to 1000 km inboard and migrated erratically, often parallel to the trench.

(2) The character and major and trace element compositions of pre- and post- subduction volcanic rocks at any particular latitude are often not very different, suggesting primary control by lithospheric processes rather than ultimate source region or melting mechanism.

(3) Cenozoic magmatism appears to be distinctly episodic, with distinct peaks in activity ranging from early Eocene to late Miocene and Quaternary. Some episodes (e.g. middle Miocene) affected the entire Cordillera from southern Mexico to Canada.

(4) A close spatial and temporal association of magmatism and local tectonism (e.g., extension) is evident in many places, regardless of the plate tectonic setting.

These patterns of Cordilleran magmatism attest to an unstable mantle under western North America during much of the Tertiary. Explanations for this instability (e.g. subduction, rifting, slab rot, slab windows, plumes, delamination) remain speculative; Some nicely account for magmatic histories in some areas, but fail to account for nearly identical histories in distant areas.

The magmatic/tectonic histories of 3 areas (southern Sonora, central California, and eastern Nevada) are used to illustrate some of these complexities.

## Miocene magmatic transition in the northern Basin and Range province, western United States

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In the northern Basin and Range province, a change from andesite-dacite-rhyolite to bimodal eruptions of basalt and rhyolite occurred about 20 million years ago. The earlier magmas are dominantly magnesian, alkali calcic andesite to rhyolite; no basaltic magma erupted. Silicic magmas ranged to high SiO<sub>2</sub> rhyolite but most of the rhyolites had low Fe/Mg, high Rb/Nb, and low Rb similar to volcanic arc granites. Beginning about 25 Ma, more mafic magmas started to appear. The oldest known true basalts erupted after about 20 Ma; they are silica-undersaturated and lack significant Nb anomalies. Other mafic magmas also erupted at this time, but most are too potassic to be true basalts and these potassic rocks have negative Nb anomalies. Gradually, the gap between mafic and silicic magmas widened. A-type rhyolites and granites first appeared about 21 Ma.

This sequence is probably the result of the progressive foundering of a shallowly dipping subducting slab that began in the Eocene. This produced widespread dehydration of the subducted lithosphere and generated voluminous arc-like magma which intruded, hybridized, and differentiated in the crust to make the ignimbrite flareup. Compensating inflow of asthenospheric mantle beneath the Great Basin, along with the development of a transform boundary and lithospheric extension, resulted in decompression melting of asthenospheric and lithospheric mantle. A fraction of this mafic magma stagnated in the lower crust, then remelted and differentiated to create subalkaline and peralkaline silicic magmas of anorogenic affinity.

## The Columbia River basalts

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We interpret the Columbia River basalts (CRBG) in terms of a mantle plume (17- 6 Ma) impinging on a long-lived intermontane zone of back-arc extension behind the Cascade subduction zone. Diversion of the plume head northwards against the thicker cratonic lithosphere to the east created an elongate dome within the thinner lithosphere of the accreted oceanic Blue Mountains province. N-S fissures at the base of the crust, enhanced by fractures along the dome, provided the outlet for mafic magma stored in large reservoirs at the base of the crust.

The huge volume of tholeiitic magma erupted through the Chief Joseph dike swarm (approximately 220,000 km<sup>3</sup> in 1.5 m.y.) was derived from an OIB-like mantle source. Variable degrees of fractional melting, crystal fractionation, lower crust assimilation, and magma mixing can be demonstrated for each CRBG formation using the chemical and isotopic data available.

Smaller and subsequent eruptions (Picture Gorge Basalt, the high alumina olivine tholeiites (HAOTs) and silicic volcanics along the Brothers Fault Zone) are a consequence of the expanding severed mantle plume head with increasing components from depleted mantle and lower crustal sources. The severed plume tail, transgressed by the North American plate, formed the eruptions of the eastern Snake River Plain and the Yellowstone hot spot.

## **Heterogeneity in Columbia River Basalt Group dikes and the flows they feed: Implications for significance and time scale of magma processes**

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Heterogeneity in flood-basalt flows and their feeder dikes can provide insight into magma processes, and the time scales of those processes. Columbia River Basalt Group dikes that can be physically correlated to flows they feed appear to fall into three categories: 1) dikes and flows with homogeneous compositions, 2) dikes with heterogeneous compositions that feed homogeneous flows and, 3) dikes and flows with heterogeneous compositions. Dikes-flows with homogeneous compositions typically occur when there are significant time gaps between eruptions (e.g. Saddle Mountains Basalt). Heterogeneous dikes that feed homogeneous flows typically are zoned. The central portion of the dike correlates to the flow but the selvage and margins are much more evolved than the main dike. No surface eruption counterpart to the evolved compositions are found which suggests that the evolved compositions were of minor volume and represent the initial eruption of a slightly zoned magma chamber. These dikes occur both when there are significant time gaps between eruptions, and when many eruptions are occurring close in time. Dikes that have heterogeneous compositions and feed heterogeneous flows tend to be very complex. As an example, one Grande Ronde Basalt dike is zoned from an evolved composition at the margins to a significantly less evolved central portion. The dike fed three lava flows that have a combined volume of nearly 4,000 km<sup>3</sup>. The volume of each eruption increases with time and corresponds to a zone in the dike. The first two eruptions were nearly simultaneous and eventually mixed together over 100 km from the vent to form a complex single flow; the third and largest erupted a short time later. This implies that the magma chamber underwent very rapid (months?) changes in composition with each change resulting in the eruption of large volume of a relatively homogeneous magma.

## **The calc-alkaline paradox of the inland Pacific Northwest**

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The main phase of Columbia River flood-basalt volcanism (~16.6-15.0 Ma) was followed by bimodal volcanism along two age-progressive trends: eastward along the Snake River Plain (SRP) and westward along the Oregon High Lava Plains (HLP). Both trends contain tholeiitic basalt but lack intermediate rock types. Superimposed midway between the SRP and HLP, however, is a north-south belt composed largely of partly contemporaneous, intermediate, calc-alkaline to mildly alkaline rocks, which are associated with graben formation extending from the Northern Nevada Rift (NNR) in the south, broadening northward to include the Oregon-Idaho graben, and terminating at the La Grande graben in northeastern Oregon.

Most of these rocks show the lack of Fe-enrichment that defines the calc-alkaline trend. Traditionally, such trends are attributed to the high water content of subduction-related magmas, which depresses plagioclase as a liquidus phase and promotes the crystallization of hornblende and magnetite. However, such a scenario cannot be applied to the eastern Oregon calc-alkaline belt, which lies well east of the Cascade volcanic chain. Others have suggested instead that these rocks are the product of back-arc extension, consistent with both their geographic position and their association with extensional structures. However, there is a lack of empirical evidence for the genesis of calc-alkaline rocks in back-arc environments, which are more typically dominated by mafic rocks with tholeiitic or alkalic compositions.

This apparent paradox in the genesis of these calc-alkaline lavas suggests that there is something unique about the back-arc environment east of the Cascades. We present chemical and petrographic data demonstrating that the calc-alkaline lavas are the product of crustal contamination and/or magma mixing of high-temperature mafic magmas with high-silica, low-Fe granitic sources. This north-south zone of mixing and contamination coincides with the apparent north-south crest of the Yellowstone mantle plume head in Miocene times. Elevated temperatures provided by the plume, in an environment of back-arc extension, generated a unique environment conducive to such mixing.

## Revisiting the tectonomagmatic implications of Oregon Plateau basaltic volcanism

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Mid-Miocene volcanism on the Oregon Plateau initiated at ~16.5 Ma with the onset of the Steens flood basalt episode. The contemporaneous Columbia River flood basalts were emplaced to the north as part of this same regional episode. This period of substantial intraplate crustal formation and modification lasted up to 2.5 m.y. followed by volumetrically minor and geochemically distinct eruptions extending the age of Steens-Columbia River activity to ~11 Ma. These 16.5 to 11 Ma lavas and associated dikes typically are high-Fe basalts to basaltic andesites, although small volumes of little differentiated low-K, high-Al olivine tholeiite (HAOT) magma were erupted prior to 11 Ma. HAOT magmas dominate the Oregon Plateau basalt record from 11 Ma to the present, with aggregate volumes far less than those associated with the mid-Miocene flood basalt episode. The HAOT magma type is restricted to a relatively narrow latitudinal band across the Oregon Plateau, is encountered from west of the modern Cascade arc to the Yellowstone region, and intimately is associated with extension at the time of eruption. Combined elemental and Sr, Nd, Pb, O, and Os isotope data suggest that similar petrologic conditions but heterogeneous mantle reservoirs are responsible for HAOT magma generation and evolution. In the context of the above and of previously proposed regional tectonomagmatic models, the following important observations will be discussed: (1) At ~16.4 Ma HAOT and Steens magmas were erupted in close spatial association at the northern end of the Northern Nevada Rift, (2) In the southeastern portion of the Oregon Plateau, Steens basalt eruptive loci are widely distributed, do not define simple age patterns, and fringe a broad area defined as the Owyhee Plateau, (3) Chemically and isotopically diverse monogenetic basalt systems (11 to 0 Ma) characterize the Owyhee Plateau region and their isotopic characteristics are age dependent, and (4) Regardless of age, location, volume or bulk composition the 16.5 to 0 Ma Oregon Plateau basalts provide evidence of primary inputs from two to three geochemical reservoirs; depleted mantle (DMM), subduction modified DMM, and subcontinental lithospheric mantle.

## Lithospheric vs. asthenospheric contributions to basaltic magmatism in the Snake River Plain - Yellowstone (SRPY) hot-spot track

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Volcanism along the SRPY hot-spot track comprises (1) early large-volume, age-progressive rhyolitic magmatism, and (2) later basaltic volcanism that emerged late in local rhyolite cycles and persisted intermittently across much of the province. Whereas the rhyolites appear to represent largely crustal melts, their formation requires a significant heat - presumably from even more voluminous mafic intrusions. Origin of the basalts, and the implied production rates and timing are enigmatic and bear on the validity of a mantle plume model as a driving mechanism.

*Compositions.* Although SRPY basalts are variably evolved, the most primitive slightly Fe-rich olivine basalts (up to 10% MgO, 150 ppm Ni, 200 ppm Cr; Mg#  $\leq$  60) are characterized by 'evolved' Sr-Nd-Pb isotopic compositions unlike those found in most oceanic settings. Also, sharp isotopic discontinuities along the northern and western boundaries of the SRP attest to involvement of distinct lithospheric source domains. And all analyzed basalts have REE patterns consistent with melting of shallow (spinel lherzolite) mantle. These features cannot generally be explained by crustal contamination. Rather, melting of aged (ca. 2.5 Ga) lithospheric mantle is implied. On the other hand, samples spanning the province have high  $^3\text{He}/^4\text{He}$  values (Ra > 11) that are characteristic of oceanic hot-spot basalts. Together these observations imply that heat and volatiles may originate in part from sublithospheric depths, but that melting dominantly occurred within an compositionally distinct lithospheric mantle keel.

*Melt production.* Significant and early melting of lower lithospheric mantle can result from Basin and Range style extension (cf. Harry & Leeman, 1995, JGR) if the mantle contains easily fusible (i.e., eclogitic or pyroxenitic) veins or 'impurities' or is hydrated by earlier subduction processes. However, this process must be augmented by additional heat inputs to account for anomalously high melt production in the SRPY province compared to adjacent regions. Heating from below by ascending plume-like asthenosphere is implied. Melting of the latter material could be repressed by presence of an initially thick (> 100 km) lithospheric lid.

## On the enigmatic basalts of the Eastern Snake River Plain, Idaho

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Quaternary, dominantly mafic, volcanism of the Eastern Snake River Plain (ESRP) has persisted across southern Idaho in the wake of time-transgressive Tertiary-Quaternary bimodal magmatism (basalt-rhyolite) associated with the Yellowstone hotspot. Isotopic characteristics of the ESRP basalts suggest a connection to both lithospheric and plume source reservoirs, making it perplexing to define the melting and fractionation conditions for this widespread magmatism.

Sr, Nd, and Pb isotope signatures for the basalts require contributions from enriched crust or mantle sources. Pb isotope signatures in olivine-hosted melt inclusions ( $^{208}\text{Pb}/^{206}\text{Pb} = 2.058\text{--}2.170$ ) expand the range delimited by their host rocks by a factor of  $\sim 2$ . This heterogeneity is not adequately explained by crustal contamination alone and requires melting of enriched, possibly lithospheric, mantle. In contrast, olivines from magnesian ESRP basalts collected within 200 km of the main locus of activity at Yellowstone caldera have  $^3\text{He}/^4\text{He}$  ratios  $>15 R_a$ . Such elevated ratios are unexpected of enriched mantle and are normally attributed to mantle plumes. Additionally, the ESRP basalts exhibit a range in  $^{230}\text{Th}/^{232}\text{Th}$  that varies from ratios typical of depleted mantle ( $^{230}\text{Th}/^{232}\text{Th} > 1.1$ ) to enriched mantle ( $^{230}\text{Th}/^{232}\text{Th} < 0.8$ ) sources. Activities of  $^{230}\text{Th}$  generally exceed those of  $^{238}\text{U}$  and the associated Th excesses vary by a factor of  $>10$ . Collectively, the range in Th isotope ratios is better explained by extraction of melts from different depths and sources rather than by decay of  $^{230}\text{Th}/^{232}\text{Th}$  during hundreds of k.y of basaltic magma storage.

Possible sources for the ESRP basalts include a deep-seated mantle plume, Proterozoic to Archean-aged lithosphere, and/or depleted upper mantle. Covariations among the isotope ratios, while much more complicated than simple two component mixing, are probably best explained if the basalts are derived from plume-metasomatized subcontinental lithosphere.

## Geochemical evidence for multiple, chemically-evolved mafic magma reservoirs beneath the eastern Snake River Plain (ESRP)

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Geochemical and physical volcanological studies of the ESRP imply a system with variably evolved magma batches and possibly several magmatic sources. Chemical variability is extensive ( $\text{MgO} = \sim 11.2 - 4.6$  wt. %;  $\text{La} = \sim 8 - 60$  ppm) in over 500 analyses of samples representing  $\sim 40$  individual eruptions. Petrologic modeling suggests that early magmas in the sequence form (layered?) sub-volcanic mafic intrusions that fractionate to evolved compositions. Later mafic magmas commingle with these earlier-derived intrusions, partially melt and assimilate late-stage fractionates, and erupt with chemically evolved, but isotopically unevolved compositions. Olivine equilibrium temperatures range  $\sim 1210 - 1068$  °C, and the most mafic magmas in the system are tightly constrained to temperatures above 1200 °C, suggesting separation of magma from upper mantle regions and little, if any, interaction with pre-Neogene crust. Samples representing lower temperature magmas typically have the highest LIL elements and diktytaxitic textures made up of coarse interlocking plagioclase crystals and large pore spaces. Textures are apparently related to high volatile contents obtained during magma evolution in crustal reservoirs. Temperature and oxygen fugacity ( $f\text{O}_2$ ) measurements indicate a close adherence to the QFM buffer, at least within  $\sim 0.5$  log units. Geochemical models and  $f\text{O}_2$  measurements further suggest concomitant increase in volatiles with increasing incompatible elements and decreasing Mg. Oxide equilibria temperatures ranging  $\sim 750 - 1040$  °C indicate possible protracted conditions of final cooling and ripening. These results suggest that an extensive system of small mafic intrusions was, and perhaps still is, recently active beneath the ESRP. A vertical series of evolving magmas, in which magmas undergo extensive fractionation and “autoas-similation”, may be similar to the magmatic columns evident in other chemically variable mafic systems.

## The Yellowstone hotspot in space and time: Evidence from silicic volcanism

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We have compiled a record of over 165 explosive silicic eruptions from the Yellowstone hotspot ranging in age from 16 Ma to the Quaternary. Throughout the history of the hotspot, Nd and Hf isotopic ratios co-vary and span the range of most terrestrial samples, reflecting mixing of crustal and mantle sources, with the *minimum* mantle component in silicic magmas varying between 20 - 40%. Early silicic volcanism was contemporaneous with eruption of Columbia Plateau Basalts. Between 16-15 Ma, silicic centers were widely distributed across SE Oregon and N Nevada, and large eruptions were frequent with over 35 events preserved in the tephra record. Earliest erupted silicic magmas were hot (up to 1080 °C), relatively less evolved (high Fe), and have Nd isotopic ratios within the range of Columbia Plateau flood basalts. Dramatic shifts in epsilon Nd from +4 to -11 and epsilon Hf from +10 to -10 mark the west to east transit of the hotspot across the lithospheric boundary between accreted oceanic terrain and the Precambrian craton. The hotspot was centered on the boundary at 15.2 Ma. The duration of the transit constrains the cratonic lower crustal magma source to a diameter of ~60–80 km in contrast to broadly distributed sources to the west of the lithospheric boundary. The timing and distribution of explosive silicic volcanism is consistent with an upper mantle plume defined by a region of low velocity beneath Yellowstone that extends to the 660 km mantle discontinuity (Jordan et al., 2004). Early, broadly distributed silicic volcanism, contemporaneous with flood basalts is consistent with the arrival of a plume. After approximately 1 million years, the plume head may have been sheared off from its conduit by thicker Precambrian crust, resulting in a focused source of silicic volcanism from 15 Ma to the present.

### Reference

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## Patterns of rhyolitic volcanism along the track of the Yellowstone hotspot

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The track of the Yellowstone hotspot developed over the last 16 m.y., as a bimodal volcanic province in response to the SW movement of the North American (NA) plate over a melting anomaly. Volcanism, dominated by eruptions of explosive high-silica rhyolite, represents some of the largest eruptions known. Basaltic eruptions signal the final stages of volcanism and cap the voluminous rhyolite. Volcanism progressed from SW to NE in successive volcanic fields comprised of nested caldera complexes. Most caldera-forming eruptions within a field are separated by 0.2 to 1 m.y., similar to the present-day Yellowstone Plateau volcanic field. Volcanic fields may be separated in time and space by as much as 2 m.y. and 50-150 km from center to center. Passage of the NA plate over a melting anomaly resulted in uplift, regional tectonism, massive explosive eruptions and caldera subsidence followed by basaltic volcanism. Southwest of Yellowstone, the Heise volcanic field has four large-volume rhyolitic ignimbrites, constituting a time-stratigraphic framework of late Miocene to early Pliocene volcanism. Field relations and high-precision <sup>40</sup>Ar/<sup>39</sup>Ar ages establish that these regional ignimbrites erupted from the Heise volcanic field. The Heise Group includes the Blacktail Creek Tuff (6.62± 0.03 Ma), Walcott Tuff (6.27± 0.04 Ma), Conant Creek Tuff (5.51± 0.13 Ma), and Kilgore Tuff (4.45± 0.05 Ma). These units erupted from separate calderas, each with a set of discrete vents. Major eruptions are separated in time and space while less voluminous minor rhyolitic eruptions are less systematic and fill in the spectrum. Large caldera-forming eruptions and development of individual volcanic fields are related to the rate of movement of the NA plate, amount of material available in crust for melt, the degree of crustal depletion, and flow dynamics in the upper crust.

## Systematic geochemical variations in single eruptions of primitive basalts: Tectonic implications

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Basalt geochemical variations over  $10^1$ - $10^3$  km length scales or Myr time scales are often used to interpret large-scale tectonic processes. Major element variations over  $10^2$  km scales, for example, have been used to model asthenospheric upwelling and lithospheric depths in the western U.S. In addition, isotopic and trace element shifts over Myr timescales have been used to suggest shifts from lithospheric to asthenospheric sources during slab rollback. These approaches implicitly assume that basalt chemical variations on much shorter time and length scales are either small or irrelevant to larger scale trends and their tectonic controls. However, if chemical variations of similar style and magnitude were observed within single eruptions, they would be difficult if not impossible to attribute to large-scale tectonic processes, and thus would raise questions about such interpretations.

Here we show an example of systematic, large-magnitude, temporal-compositional trends in a single monogenetic eruption of primitive basalts erupted over a  $10^0$ - $10^2$  yr timescale in the Big Pine Volcanic Field of southern CA. This eruption produced basalts with a high and constant Mg# of  $69 \pm 1$ , decreasing (by a factor-of-two) incompatible element concentrations, increasing  $\text{SiO}_2$  from 45 to 48 wt.%, decreasing  $^{87}\text{Sr}/^{86}\text{Sr}$  from 0.7063 to 7055, and increasing  $\epsilon_{\text{Nd}}$  from -3.5 to -1.0. REE patterns require residual garnet in at least one source. These trends cannot be due to fractional crystallization or partial melting of a single source, and crustal contamination models are difficult to reconcile with nearly constant, high Mg#, small Ni and Cr variations, inverse correlations between  $\text{SiO}_2$  and incompatible elements, and the presence of abundant mantle xenoliths.

If interpreted in terms of pressures of melting variations such as might be caused by lithospheric thickness variations, these chemical variations would require unreasonably large ranges (i.e., 2-6 GPa) for a single eruption. These single-eruption variations also extend far across compositional cut-offs that have been proposed to represent a lithosphere to asthenosphere transition, indicating that similar variability is evident at much smaller time and length scales.

## Mineralogy and geochemistry of Table Legs Butte and Quaking Aspen Butte, Eastern Snake River Plain (ESRP), Idaho

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### Links between Geomorphology and Geochemistry

Tholeiitic basalt shields on the ESRP generally consist of pahoehoe flows with low-angle ( $1$ - $2^\circ$ ) slopes. Based on topographic profiles, shields with significant relief on the ESRP have been grouped into three geomorphic categories: low-profile, dome-shaped, and shields with caps. Table Legs Butte (TLB) and Quaking Aspen Butte (QAB) are capped shields that exhibit gentle ( $4$ - $6^\circ$ ) medial slopes and a sharp transition to steep ( $20^\circ$ - $30^\circ$ ) proximal slopes. Hypotheses that may explain this geomorphology relative to low-profile shields are: (1) a geochemically evolved, higher viscosity magma, (2) increase in crystal content/abundance from distal to summit regions, or (3) a different petrologic evolution compared to other tholeiitic shields on the ESRP. TLB and QAB were evaluated in detail by petrographic microscopy, INAA, ICP-AES, and EMPA and then compared to published literature on other ESRP basalts.

### Results and Conclusions of study

Relative to low-profile shields, TLB displays high crystal abundance (~ 25% plagioclase), overall steeper shield profile, and a coarse (up to 1cm) diktytaxitic texture. QAB has low (~ 4%) crystal abundance, a less-pronounced summit cap, and poorly developed diktytaxitic texture. Neither shield displays changes in crystal content or abundance from proximal to distal regions. Bulk major- and trace-element chemistry depicts two distinct batches of magma that lie on a single fractionation trend, with TLB being more evolved than QAB. Trace elements vary widely in both shields, with TLB showing 2X to 3X enrichment in incompatible elements and QAB showing no enrichment relative to other low-profile tholeiitic shields. No apparent connection can be made between different shield types and degree of geochemical evolution. Isotopic and EMPA work in progress will be applied to petrologic modeling techniques (MELTS and QUILF) for final results.

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## Mid-Miocene basalt driven volcanic field development in the Pacific Northwest, USA

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Mid-Miocene volcanism in the Pacific Northwest initiated at ~16.5 Ma with the onset of regional Steens-Columbia River flood basalt volcanism. During the duration of flood basalt activity, numerous, dominantly silicic eruptive loci and volcanic fields formed (e.g. Santa Rosa-Calico; SC). SC activity initiated at ~16.4 Ma and lasted ~2 Ma. In the SC, a complex volcanic history is recorded by a diverse volcanic assemblage and eruptive history. SC eruptive loci and shallow intrusive bodies are dominantly found in N-S trending zones, parallel to regional mid-Miocene structural trends (e.g. the northern Nevada rift) and illustrate the presence of multiple SC magmatic systems. Additionally, field evidence demonstrates that the SC was characterized by a paucity of caldera-forming silicic volcanism, unlike other contemporaneous volcanic fields. Texturally, SC intermediate and silicic products are characterized by abundant disequilibrium textures, including xenoliths of local granitoid crust and mafic units. Chemically, SC eruptive products and shallow intrusive bodies span a compositional spectrum from basalt through high-Si rhyolite. Most SC mafic units chemically are identical to Steens Basalt, with the exception of a high Mg#, high Ni, low LIL and HFSE suite that resembles regionally exposed HAOT. Mafic units isotopically are identical to Steens Basalt ( $^{87}/^{86}\text{Sr}_i < 0.7040$ ). The SC intermediate units are subalkaline to calc-alkaline and exhibit more diverse isotopic compositions than SC mafic units ( $^{87}/^{86}\text{Sr}_i = 0.7045-0.7056$ ). Silicic units also are chemically diverse and exhibit trace element variations along separate evolutionary paths suggesting open-system differentiation in multiple magmatic systems. These silicic units also are isotopically diverse ( $^{87}/^{86}\text{Sr}_i$  up to 0.7070) and resemble local granitoid crust ( $^{87}/^{86}\text{Sr}@16 \text{ Ma} = 0.7045$  to 0.7058 and 0.7061 to  $>0.7070$ ). These physical, chemical, and isotopic variations reflect a complex set of open-system petrogenetic processes facilitated by upwelling Steens basaltic magma and localized lithospheric extension. Accordingly, the evolution of the SC is a direct result of the availability of mafic magma, its tectonic setting, the pre-SC lithospheric structure and composition, and mid-Miocene petrogenetic processes. These observations suggest that the development and styles of volcanism found within other Pacific Northwest mid-Miocene volcanic systems may also be complex and highly dependant on local basaltic input and tectonism.

## The noble gas character of mantle fluids associated with Cenozoic volcanism in the SW USA

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Noble gases, and the  $^3\text{He}/^4\text{He}$  ratio in particular, provide critical information about the character and processes controlling the mantle volatile source. We present here new noble gas data that provides a unique insight into the volatile character of the sub continental lithospheric mantle sourcing the Cenozoic volcanism in the SW US. While some volcanic localities allow local mantle  $^3\text{He}/^4\text{He}$  to be determined from xenoliths, suitable samples are not always available, and air contamination of this sample type precludes resolution of the heavy mantle-derived noble gases. Magmatic  $\text{CO}_2$  well gases provide a new and exciting resource that enables the  $^3\text{He}/^4\text{He}$ , heavy noble gas isotope and relative abundance determination of the mantle source (Ballentine et al., 2005).

Magmatic  $\text{CO}_2$  well gases from three systems to the east of the Colorado Plateau uplift, and two systems from within the uplift area have been collected. To the east of the uplift full data sets now exist for Bravo Dome (Harding Co, NM) (Ballentine et al., 2005) and Sheep Mountain (Huerfano Co, CO). Bravo Dome is associated with basaltic Cenozoic volcanism from the Raton-Clayton volcanic field. Sheep Mountain is associated with intermediate to acidic lacoliths.  $^3\text{He}/^4\text{He}$  of the Bravo dome mantle source (5-7Ra) is similar to convecting mantle values of  $8 \pm 1\text{Ra}$  (where Ra is  $^3\text{He}/^4\text{He} = 1.4 \times 10^{-6}$ ), and the resolved mantle noble gas elemental abundance pattern is indistinguishable from MORB. In contrast, resolved Sheep Mountain mantle  $^3\text{He}/^4\text{He} \sim 2\text{Ra}$ , pointing to a more evolved mantle source. Importantly, resolved mantle  $^4\text{He}/^{40}\text{Ar}$ ,  $^3\text{He}/^{22}\text{Ne}$  and  $^4\text{He}/^{21}\text{Ne}$  are also indistinguishable from both Bravo dome and MORB. This requires that the process modifying the  $^3\text{He}/^4\text{He}$  (either U+Th enrichment or gas loss) cannot significantly fractionate the magmatic volatile system during regional evolution of the Cenozoic volcanism.

Completion of data sets for McCallum, (Jackson Co, north CO) and St Johns and McElmo  $\text{CO}_2$  gas fields, both from within the Colorado Plateau uplift region, will provide further insight into the regional tectonic control of the mantle volatiles associated with the Cenozoic volcanism.

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## Geochemistry of basaltic volcanism in and around the Bruneau-Jarbidge eruptive center, Southwest Idaho

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The Bruneau-Jarbidge eruptive center (B-J) is a large structural basin at the southwest end of the Eastern Snake River Plain (ESRP), formed by passage of the Yellowstone hot spot *circa* 12.5 Ma. Basaltic lavas (8Ma) postdate the rhyolites.

Twenty-four volcanic vents are found within the eruptive center, along with numerous vents that lie outside the structural basin. Vents within B-J are located along three distinct NW trends; vents outside the eruptive center are subparallel to the trend of the Western Snake River Plain (WSRP).

Sixty-eight samples were analyzed using XRF, microprobe, and ICP-MS. Basalts consist of plagioclase and olivine phenocrysts set in a groundmass of plagioclase, clinopyroxene, opaques, and glass. B-J eruptive center basalts have Mg# = 38.5 - 61.3, with TiO<sub>2</sub> = 1.2 - 2.4 wt%; FeO = 10.1 - 14.0 wt%, and P<sub>2</sub>O<sub>5</sub> = .06 - .42 wt%. Trace element abundance's are: Nb = 6-16 ppm, Sr = 153-356 ppm, Zr = 67-261 ppm, La<sub>N</sub> = 22-65, and (La/Lu)<sub>N</sub> = 2 - 3.5. Non B-J basalts have Mg# = 38-42, TiO<sub>2</sub> = 3.2-4.2 wt%, FeO = 13.9-16.7 wt.%, P<sub>2</sub>O<sub>5</sub> = 0.14-0.88 wt.%, Nb = 25-38 ppm, Sr = 267-373 ppm, Zr = 302-396 ppm, La<sub>N</sub> = 125, and (La/Lu)<sub>N</sub> = 6.7. Differences in REE slopes indicate distinct source regions. B-J basalts are consistent with ESRP basalts. Non B-J basalts are similar to basalts from the WSRP. Forward modeling of the trace elements suggests distinct sources

## Shevlin Park Tuff: Welding features of an intermediate composition ash-flow tuff

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The Shevlin Park Tuff is a 260,000-year-old ignimbrite deposit in central Oregon that is unusual because of its range in bulk and glass compositions. Bulk composition of Shevlin Park Tuff pumice is bimodal, ranging from 55 to 62 and 64 to 68 wt% SiO<sub>2</sub> (Conrey, 2001). Matrix glass shows a similar compositional range, reflecting the near aphyric nature of the Shevlin Park magma.

Lower flow units within the tuff contain only dacitic pumice clasts with porosities of 71-87% and have a limited spatial distribution. Upper flow units contain both dacitic and basaltic andesite pumice clasts, with larger average sizes, a wider porosity range (52 to 82%), abundant lithic clasts, and broader spatial distribution. Distal upper units are generally welded, whereas lower units are welded only where in contact with an overlying welded unit. However, the thickest, most proximal section is only welded in a thin portion near the base. Permeability-porosity relations of these welded rocks show that permeability decreases continuously with decreasing porosity. Similar relationships are seen in obsidian domes, whereby once a connected pathway forms, it is maintained as the pore volume reduces (Rust and Cashman, 2004) and may be critical in permitting welding to occur. Quantification of pore-space using 3-D imaging and conductivity measurements will assess the role of pore tortuosity on permeability and welding progress.

Welding experiments on Shevlin Park ash were conducted to determine the relative roles of temperature and composition on welding. Although, experimental temperatures (900-950°C) were sufficiently high to induce crystallization of glass walls not seen in naturally welded samples, we find that non-crystallized dacite deforms ductily, whereas basaltic-andesite deforms brittly. Additionally, mafic pumice is more porous (less deformed) than dacitic counterparts after experimental welding.

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## The fluid compositions of lherzolite xenoliths in Eastern China and Western American

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The occurrence of fluids in the mantle is of crucial importance in interpreting the mechanisms and geochemical effects of mantle evolutions, the fluids trapped in mantle-derived xenoliths have provided unique and important constraints on the chemical composition of the mantle fluids.

### Experiment and Results

In present study fresh lherzolite xenoliths, which are regarded as relict refractory mantle (Menziés, 1987; Zhang, 2004), have been collected from Dixiasenlin, Liuhefangshan, Xilong, Dayangcao in eastern China and Dish Hill, San Carlos in western American, the fluid compositions of lherzolite xenoliths have been investigated by vacuum step-heating MAT 271 mass spectrometer.

The fluids in lherzolite xenoliths were released by stages and formed two releasing peaks at about 400°C (low temperature peaks, LTP) and 800°C (high temperature peaks, HTP) in vacuum step-heating experiments, the fluid compositions of two releasing peaks in lherzolite xenoliths in eastern China and western American are list in Table 1.

Table 1 The fluid compositions in lherzonite ( $\mu\text{l}\cdot\text{STP/g}$ )

Peak	Locality	H <sub>2</sub>	CH <sub>4</sub>	H <sub>2</sub> S	CO	N <sub>2</sub>	CO <sub>2</sub>	SO <sub>2</sub>
LTP	E-China	0.57	0.39	0.00	1.20	0.08	12.79	0.24
	W-USA	0.21	0.17	0.00	1.64	0.04	5.26	0.00
HTP	E-China	5.89	0.24	0.01	1.87	0.60	18.17	7.26
	W-USA	13.08	0.29	0.01	7.25	0.23	8.05	1.18

### Conclusion

Fluids of HTP are formed by the bursting of early stage of fluid inclusions (close to their homogenization temperature) which represent the primitive mantle fluids (Zhang, 2004), fluids of LTP are derived from the late stage fluid inclusions which reflect the fluid of mantle evolutions. There are significant differences in chemical compositions of the primitive mantle fluids (except the fluid of mantle evolutions) between eastern China and western American.

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