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Neogene Basaltic Volcanism in the Southern Owens Valley, CA: Implications to Tectonics of the ECSZ

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Abstract

Neogene basaltic volcanism occurs at four locations in the Owens Valley; the Big Pine field south of Independence, the Darwin field 40 miles to the southeast on the Darwin Plateau, the Coso field north of Ridgecrest, CA and the Ricardo field in the El Paso Mountains. Big Pine basalts range in composition from *ne* normative alkali basalt to *Q* normative tholeiitic basalt. Basalts of intermediate composition (olivine tholeiites) are rare. Olivine and its alteration product, iddingsite, are rare phenocrystic phases. Darwin basalts span a similar range in composition, but are characterized by a larger population of olivine tholeiites. Olivine is a common modal mineral, as is iddingsite. The Coso field is characterized by bimodal basalt-rhyolite volcanism. Basalts are primitive *ne/ol* normative alkali basalts with prominent phenocrysts of olivine. The Ricardo volcanic field is also bimodal, but the basalts are *Q* normative tholeiites. Iddingsite and calcium siderite have replaced olivine, leaving only scattered remnants of the latter.

Owens Valley magmatism spans the transition from the late Miocene-Pliocene "Basin and Range" extension to Pliocene-Recent dextral shear with tectonic setting having a significant influence on basalt composition. Basalts that are the products of extension (Ricardo) are tholeiites while those emplaced in regions of transtension or oblique-slip related to dextral shear (Coso) are dominantly alkali basalts. The Big Pine volcanics underwent a compositional change from older tholeiites to Recent alkali basalts. This may be related to changes in the regional stress pattern from Basin and Range extension to the current regime of right-oblique slip. Darwin basalts do not fit the established pattern. Isotopic and trace element data suggest Coso magmas reached the surface quickly utilizing conduits created by transtension and did not interact with continental crust. In contrast, Ricardo volcanics were emplaced during a period of pure extension resulting in tholeiitic basalts. The more evolved and silica-saturated basalts (Ricardo) represent assimilation of crustal rocks during periods of ponding at shallow levels within the crust.

Introduction

The Eastern California Shear Zone (ECSZ), a broad region of crustal deformation that has accommodated both Neogene dextral shear and Basin and Range extension. The Owens Valley has undergone intermittent volcanism coincident with tectonic deformation.

This research examines four basaltic volcanic fields in the Owens Valley (Fig. 1). The Big Pine volcanic field straddles US 395. Basalts outcrop from the base of the Sierra Nevada Mountains to the west, to the Inyo Mountains to the east. The field encompasses an area of approximately 150 mi^2. Volcanism dates from 1.2 Ma to as recently as 25 ka (Manley, et al., 2000) (Fig. 2). Basalts dominate, but a small outcrop of rhyolite is present to the west of the Poverty Hills. The Independence fault (dip-slip, east side down), Fish Springs fault (right-oblique slip) and White-Inyo fault (right-oblique slip) were important conduits for basaltic magmas as evidenced by alignment of flows and cones along the faults. Sense of motion for the White-Inyo fault is controversial . Bellier and Zoback, (1995) argue that the current right-slip regime began at 288 ka; prior to that movement was dominantly dip-slip, west side down.

The Darwin volcanic field lies atop the uplifted block of the Darwin Plateau, 1000 feet above the Owens Valley to the west and 4000 feet above the Panamint Valley to the east. The field covers an area of 300 mi^2, much of it draped over the southern flank of the Inyo Mountains. Limited age dating suggests basaltic volcanism occurred between 8 and 4 Ma (Larsen, 1979). Schweig (1989) concludes that magma extrusion began shortly after the onset of Basin and Range extension (7-8 Ma) and continued after the initiation of dextral shear at 4-6 Ma.

The Coso volcanic field lies just east of the Sierra Nevada Mountains, 13 miles north-northwest of Ridgecrest, CA. The field is comprised of an arcuate array of Pliocene to Quaternary rhyolite domes and basalt cinder cones and flows covering 150 mi^2. The volcanics were emplaced during two events; an early phase from a 4.0 to 2.5 Ma and a more recent phase (1.0 Ma-Recent). Weaver and Hill (1979) suggest that volcanism and deformation within the Coso Range is due to a transtensional environment created by a releasing bend in a dextral strike-slip fault system. Monastero, et al., (2005) place the principal boundary faults of the strike-slip system as the Little Lake fault in Indian Wells Valley to the southwest and in the Wild Horse Mesa area on the northeast. Duffield, et al., (1980) point out that many Pleistocene basaltic cinder cones lie astride arcuate dip-slip faults representing the surface expression of transtensional extension.

The Ricardo volcanics lie within the El Paso Mountains in an area encompassed by Red Rock Canyon State Park. The Garlock fault lies 1-3 miles to the south. The Ricardo Group is comprised of the Cudahy Camp and Dove Spring Formations. Basalt is the dominant volcanic rock, but rhyolite is common. The Dove Spring Formation, the focus of this research, has experienced basaltic volcanism during the late Miocene (11.7-8.1 Ma). Loomis and Burbank (1988) conclude extrusion of the Dove Spring basalts was coincident with the onset of sinistral slip along the Garlock fault and the initial phase of east-west Basin and Range extension.

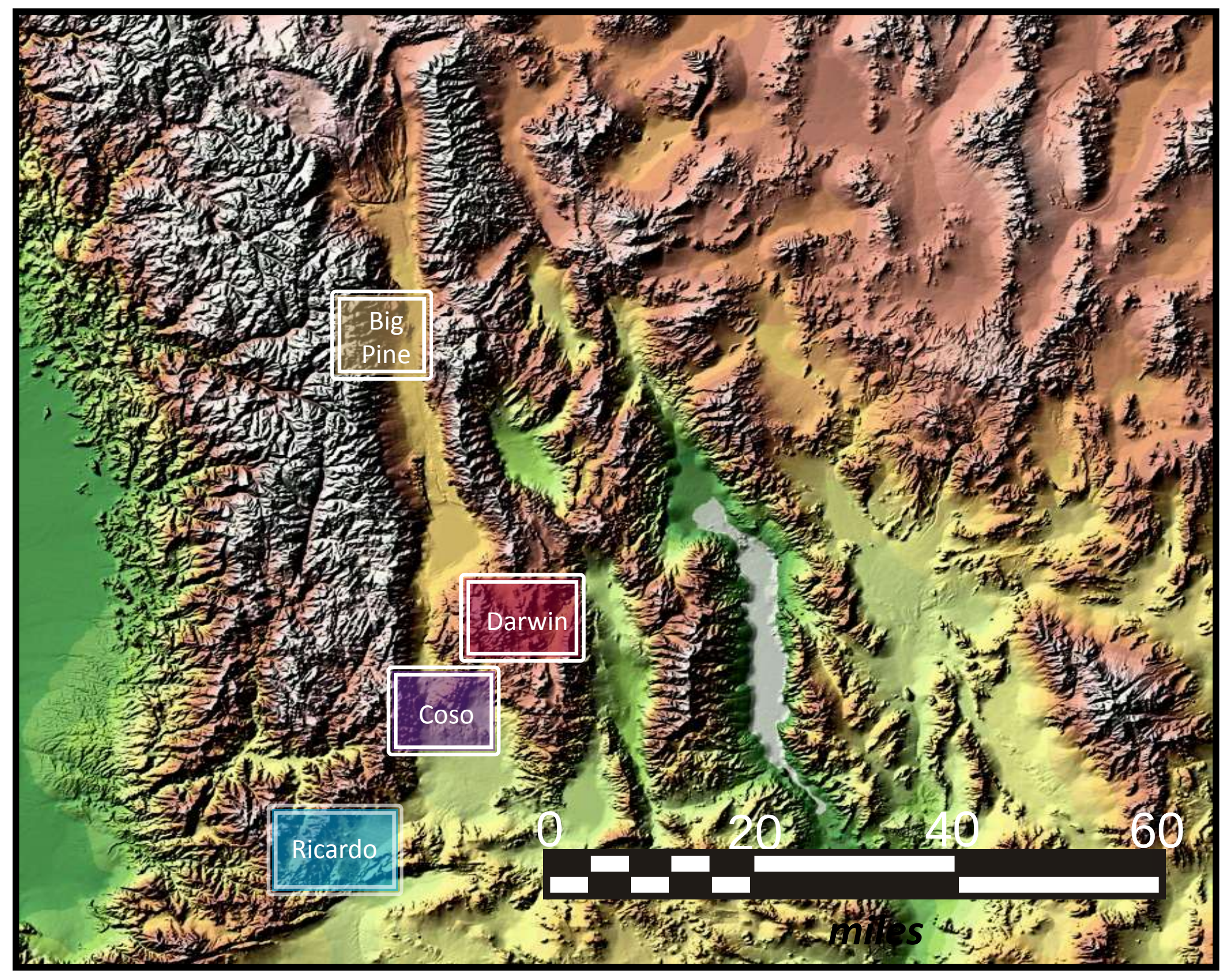


Figure 1. Index map showing the locations of Neogene Owens Valley volcanic fields.

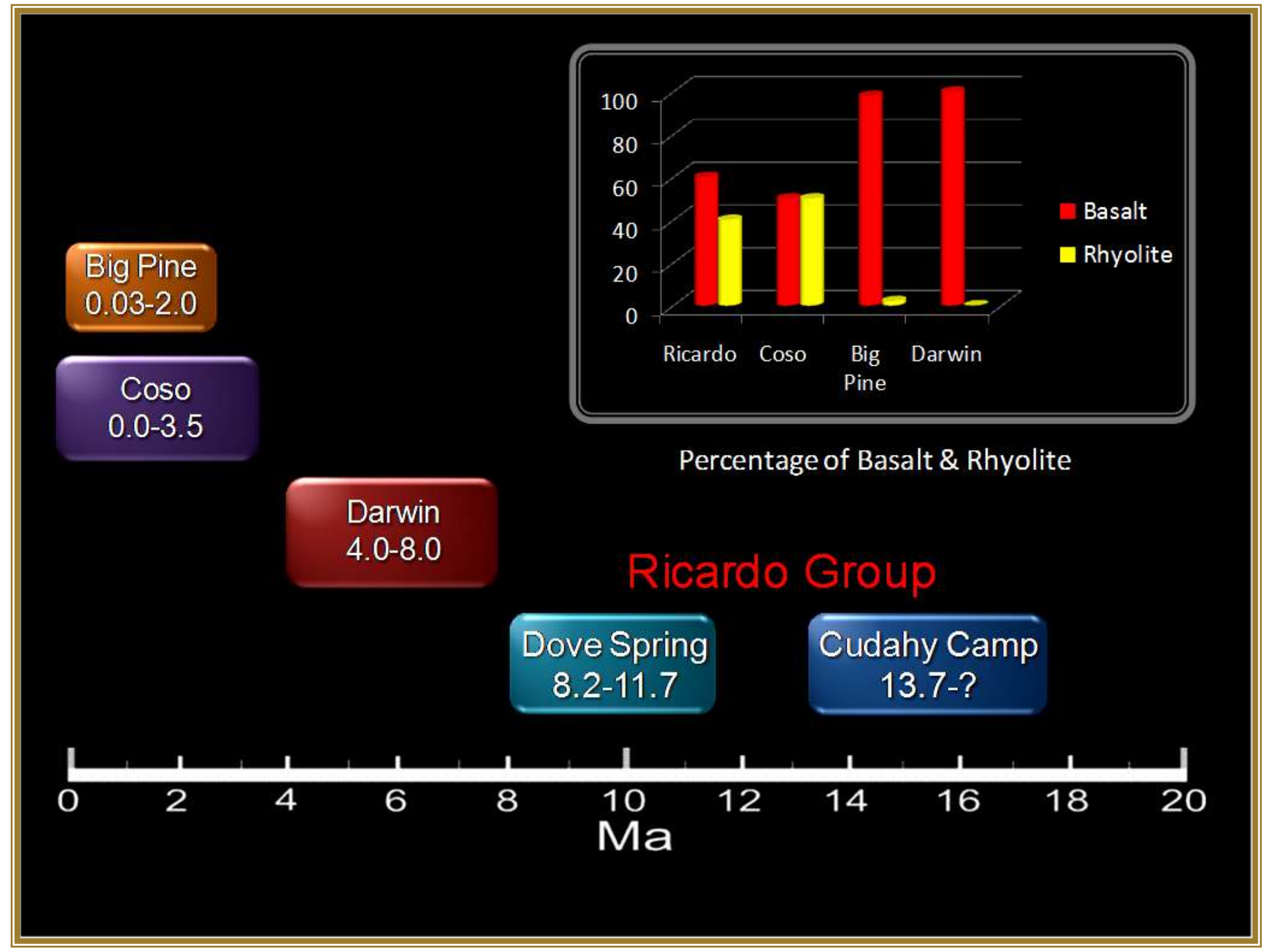


Figure 2. Geochronology and lithology of Owens Valley volcanic fields.

Results

Figure 3 presents XRF whole rock analyses of basalts from the four fields. Basalts from the Ricardo volcanic field are generally *Q* normative tholeiites while those from the Coso volcanic field are *ol* and *ne* normative alkali basalt. Basalts from the Big Pine and Darwin fields span the compositional spectrum, however, Big Pine basalts are clustered into two discrete groups; older tholeiites and younger alkali basalts.

Figure 4a is a spider diagram. It presents average trace element concentrations normalized to a MORB standard. The most incompatible trace elements lie near the left center of the diagram (K, Rb, Ba, Th) and the most compatible (Sm, Ti, Y, Yb) to the right. The trend for the Coso volcanic field (blue diamonds) mimics the classic oceanic island basalt (OIB) trend thought to represent melts of "fertile" mantle. In contrast, the other fields display varying degree of incompatible element enrichment.

Figure 4b is an E-neodymium diagram for data from the Big Pine and Coso volcanic fields (isotopic analyses were not available for Darwin and Ricardo). Coso basalts plot on the Mantle Array indicative of magmas extracted from a primitive mantle source. In contrast, Big Pine samples plot outside the Mantle Array and along the EMII trend (EMII is a reservoir created from melting average continental crust), requiring crustal contamination of the magmas.

Thin section analysis reveals that Ricardo basalt phenocrysts consist of iddingsite and calcium siderite that have replaced and pseudomorphed olivine. Big Pine and Darwin contain both unaltered olivine and iddingsite (Fig.5) while Coso basalts phenocrysts are unaltered olivine. Textures and field relationships suggest that olivine alteration to iddingsite occurred at elevated temperatures during the latter stages of magma crystallization and was not a product of weathering.

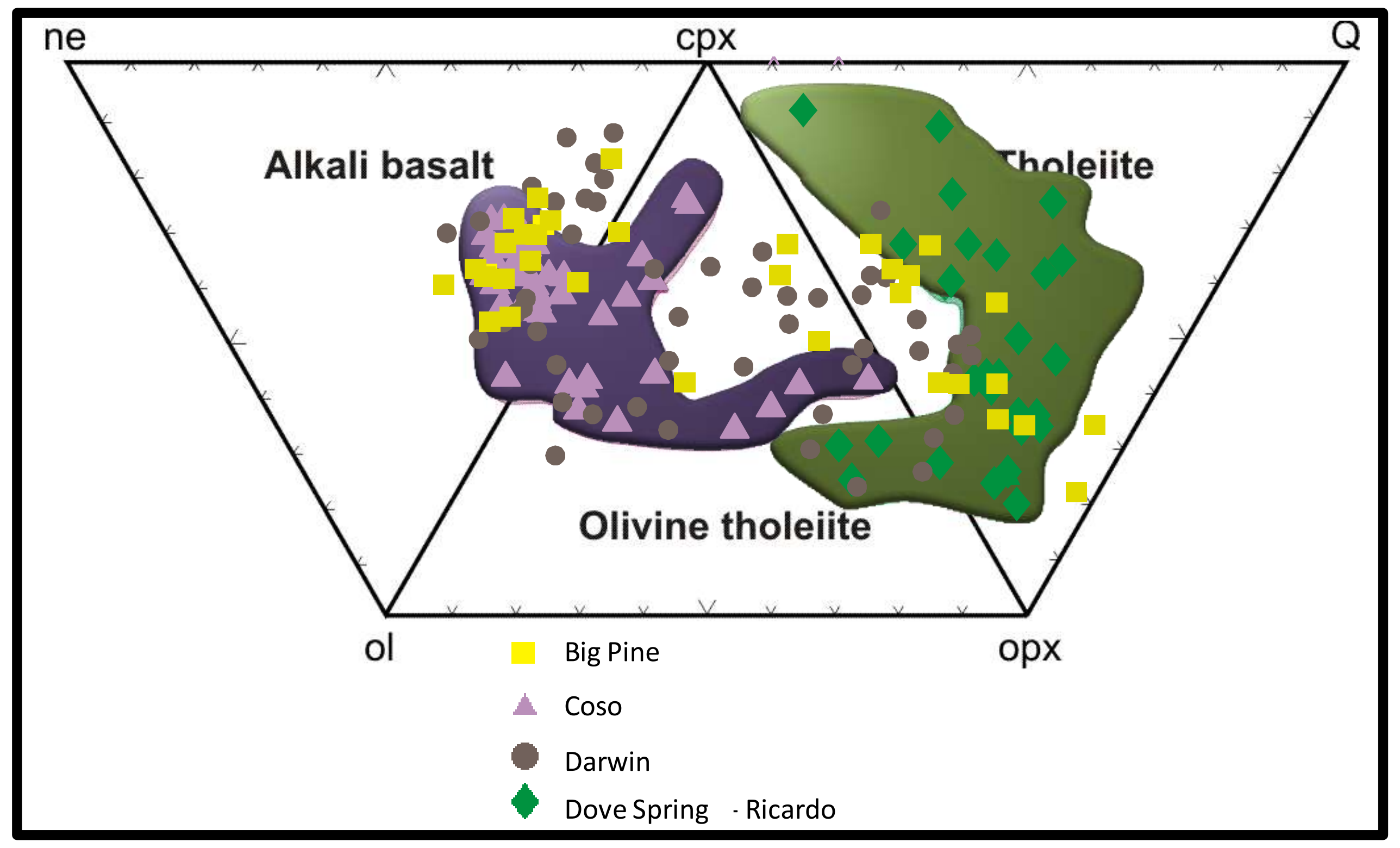


Figure 3. Basalt tetrahedron for the Owens Valley volcanic fields. Some data for the Coso volcanics from Groves (1996).

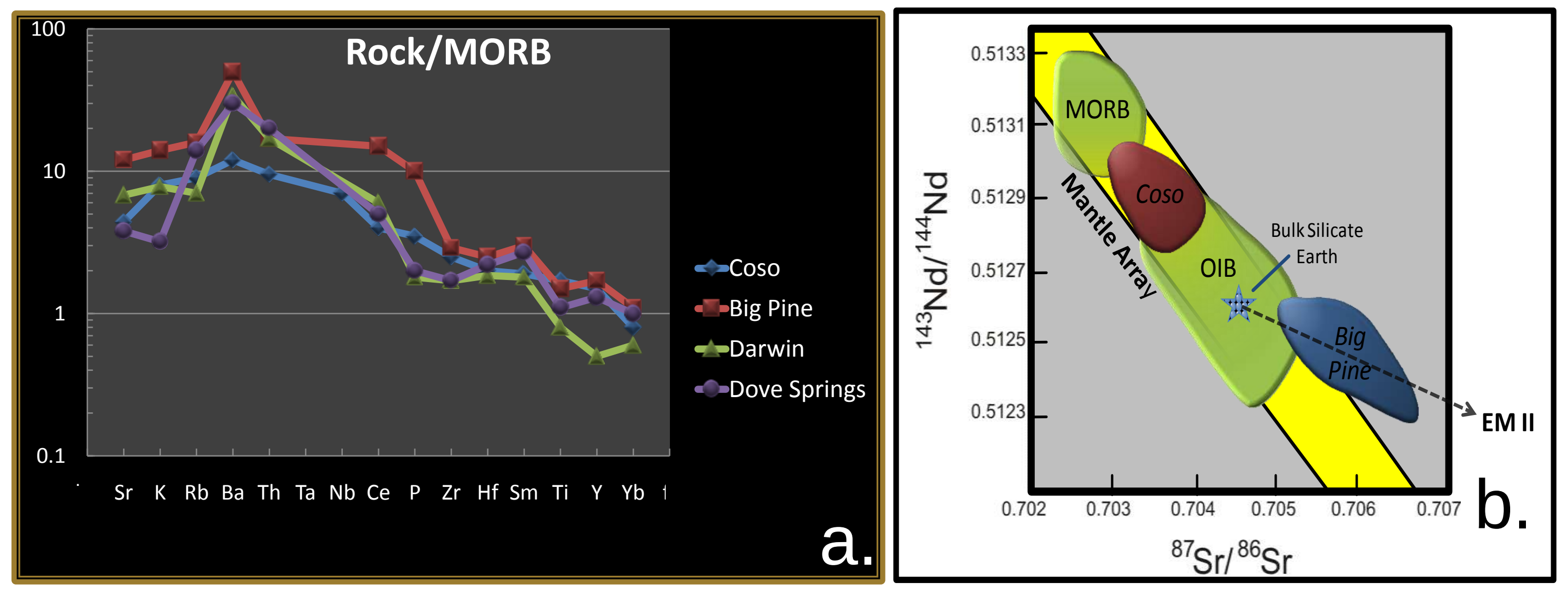


Figure 4a.Spider diagram for average basalt trace element concentrations (MORB standard) 4b. Epsilon neodymium diagram for samples from the Big Pine and Coso basalt s (Data from the NAVDAT database).

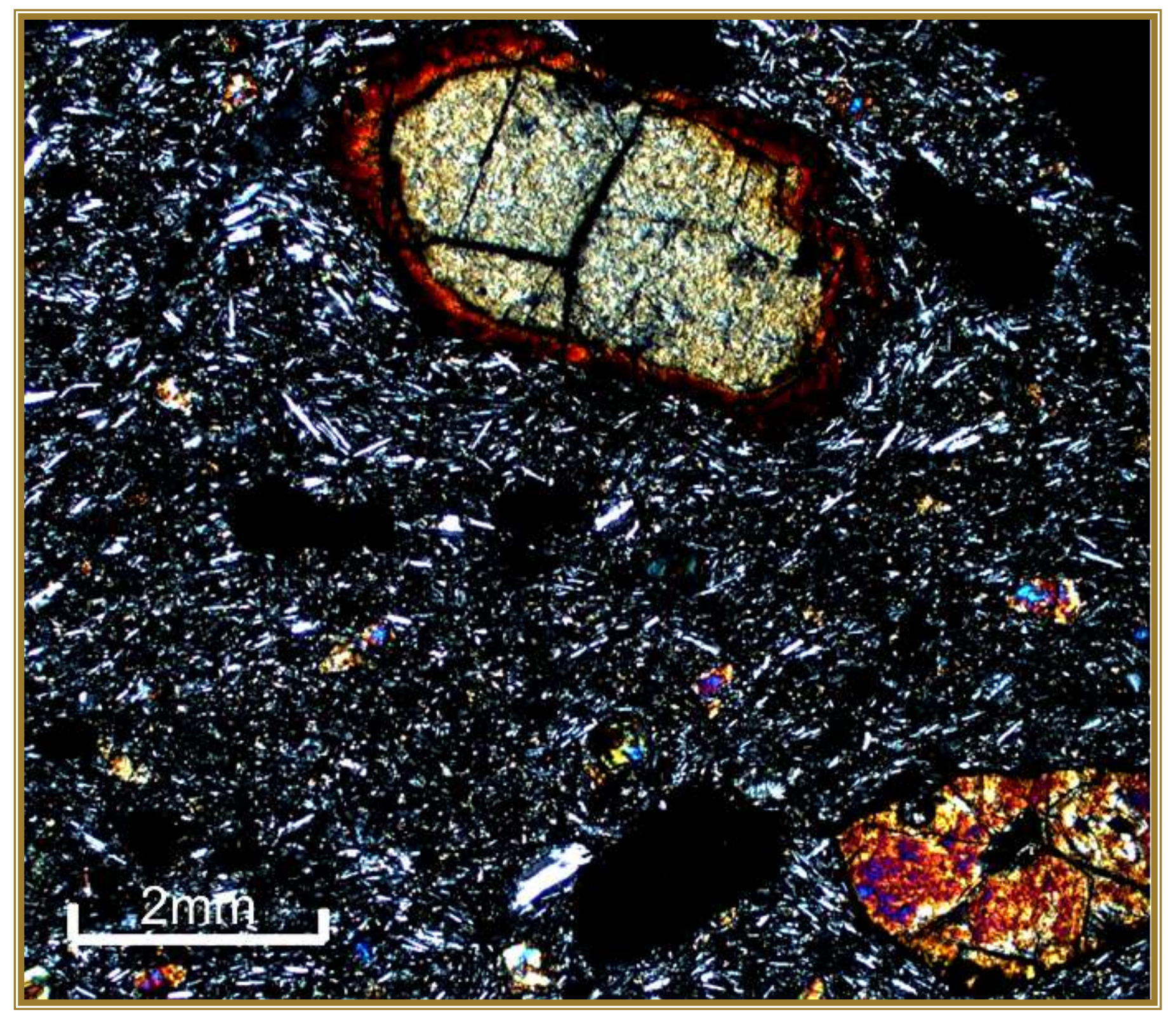


Figure 5. Iddingsite reaction rim enclosing olivine. Darwin volcanic field.

Discussion

The presence of iddingsite places constraints on any model. Textural relationships for the Ricardo and Darwin basalt fields indicate that iddingsite formed during the latter stages of magma crystallization due to changes in oxygen fugacity within the magma chamber, perhaps resulting from an encounter with circulating groundwater. This does not, however, account for the significant compositional variation between tholeiitic and alkali basalt in the Owens Valley. While meteoric water may oxidize iron and destabilize olivine, it will have limited effect on bulk rock chemistry. Large differences in rock chemistry require either magma mixing or assimilation. The former is attractive, but mixing of mafic and felsic magmas presents chemical and physical challenges due to density and viscosity disparities. This is evidenced by the abundance of basalt and rhyolite at Coso and Ricardo, but the near absence of their mixed product, andesite. Assimilation requires a ponding of the basaltic magma at depth with heat from the magma melting and assimilating crustal rocks. The ponding would occur when the mafic magma became gravitationally stable. While ponded, assimilation of country rock would occur until an open conduit presented itself and the basaltic magma would escaped to the surface. Evidence to support the assimilation hypothesis comes from both trace element and isotopic data (see previous section).

The Ricardo volcanics were extruded during the onset of Basin and Range extension. Rates of vertical crustal displacement during the Miocene are uncertain, but the current rate of extension in the eastern Sierra Nevada is around 0.1-0.2 mm/yr (Le, et al, 2007). In contrast, the Coso volcanic field formed in a transtensional basin created by dextral shear along the Owens Valley fault zone. Estimates of right-slip motion range from 3 to 8 mm/yr (Frankel, et al, 2008), an order of magnitude greater than the rate of vertical displacement. As the rate of motion is much greater for the Coso field, faults serving as conduits for magma would tend to remain open. However, in the Ricardo and Big Pine fields, Basin and Range extension results in much slower rates of displacement causing the periodic ponding of magma and assimilation of crustal rocks.

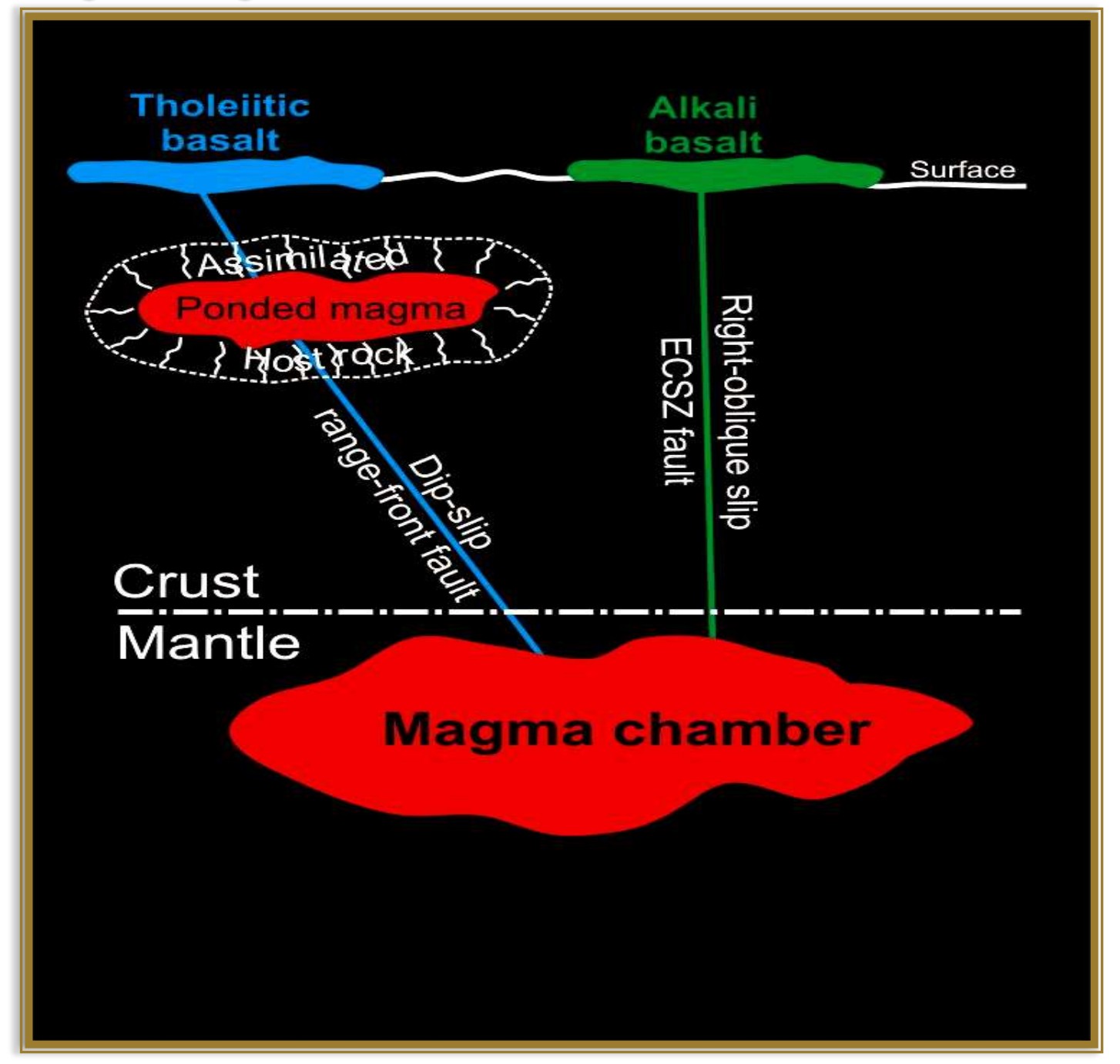
Model

- Alkaline basaltic magma was generated within the mantle/lower crust and rose to the surface.
- Coso basalts reached the surface with little/no interaction with the crust.
- Ricardo magmas were ponded, increasing $\mathcal{F}O_2$ converting olivine to iddingsite, while heat from the magma chamber melted and assimilated continental crust.
- Big Pine basalts are hybrids. Early volcanism mimics that of Ricardo while more recent volcanism is compositionally similar to Coso.
- Darwin basalts do not fit the established model.

Tectonic Implications

1. *Ricardo volcanics (Dove Spring) coincide with a period of Basin and Range extension.*
2. *Coso volcanism is related to dextral shear and transtension.*
3. *Big Pine records two episodes of volcanism, suggesting strain has been partitioned over time, between episodes of dip-slip and right-oblique slip.*
4. *Rates of motion on range front faults are generally an order of magnitude less than those related to dextral shear. This causes ponding of magmas and assimilation of crustal rock.*

Cartoon Model for Basaltic Volcanism



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