

# Extension of the Yellowstone plateau, eastern Snake River Plain, and Owyhee plateau

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## ABSTRACT

Formation of the late Cenozoic volcanic province comprising the Owyhee plateau, eastern Snake River Plain, and Yellowstone plateau has been accompanied by east-northeast-directed crustal extension. A new vector of 45 mm/yr, N56°E for the migration of silicic volcanism across the volcanic province is calculated. If migration of volcanism reflects west-southwest continental drift over a mantle plume, a zone of crustal extension must separate the volcanic province from the more slowly moving North American craton. Space-time relations of basin fill in the adjacent Basin and Range province provide evidence for a zone of extension, about 125 km wide, coincident with and east of coeval silicic volcanism. Since 16 Ma, the zone of extension has migrated along with silicic volcanism, maintaining its position between the province and the unextended craton.

## INTRODUCTION

The Owyhee plateau, eastern Snake River Plain, and Yellowstone plateau form a linear, late Cenozoic volcanic province (Fig. 1) characterized by thick successions of rhyolitic tuffs, intercalated alluvial and lacustrine sedimentary rocks, and overlying basalt (Leeman, 1982). Silicic

eruptive centers become younger to the east (Armstrong et al., 1975), supporting the hypothesis of Morgan (1972) that the volcanic province marks the trail of a mantle plume beneath the southwestward-migrating North American plate. If the volcanic province is the trace of a mantle plume, the rate and path of migration of volcanism should reflect the absolute plate vector for it during this time. Using the ages and locations of silicic volcanic centers we calculated this vector and compared it with independent measurements of the absolute plate motion of the North American craton. The two vectors are significantly different in magnitude, possible evidence that the volcanic province has extended. We suggest that extension in the volcanic province was coeval and coincident with extension in the adjacent Basin and Range province, and propose a quantitative model to estimate the amount of extension.

## EVIDENCE FOR EXTENSION OF THE VOLCANIC PROVINCE

### Absolute Plate Vectors

Armstrong et al. (1975) derived the age-distance trend and a rate of 35 mm/yr for the migration of volcanism across the volcanic province by estimating that volcanic centers and facies shifted eastward 1° of longitude every 2 m.y. This was appropriate for the limited stratigraphic and volcanological data that existed then, but such an approach is less than ideal for several reasons. First, the path of volcanism is N56°E, not due east as implied by rates calculated using degrees of longitude. Second, recent volcanologic studies (see Table 1<sup>1</sup>) provide better locations for major silicic vents. Third, rhyolitic volcanism at a given location is diachronous. We believe that the emplacement of the first voluminous, anhydrous silicic ash-flow tuff at each eruptive center reflects widespread basalt-induced melting of the continental crust (Leeman, 1982), and therefore marks the inception of plume-related volcanism. Silicic volcanism prior to plume passage may reflect pre-plume crustal extension, and volcanism subsequent to plume passage is readily explained by residual heat in the crust and upper mantle.

For the reasons given above, a more accurate estimate of the migration rate of volcanism can be obtained by plotting the distance of rhyolitic eruptive centers along the volcanic province against the age of the earliest anhydrous rhyolite erupted from the volcanic center. Relevant data are given in Table 1 (see footnote 1), and results are shown in Figure 2A. For the past 16 m.y. the volcanic province has drifted 45 mm/yr, S56°W relative to the underlying plume.

The vector for the volcanic province should match independent estimates of the North American plate vector at Yellowstone. Minster and Jordan (1978) calculated a Holocene plate vector of 24 mm/yr, oriented S56°W, measured with reference to oceanic plumes beneath the Pacific plate. With reference to oceanic plumes beneath the African plate, Engbreton et al. (1985) calculated a mid-Miocene to Holocene plate vector of

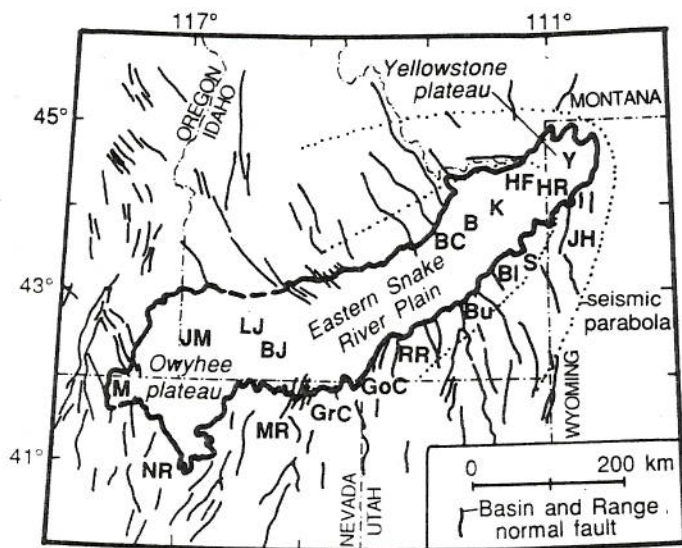


Figure 1. Late Cenozoic bimodal volcanic province comprising Owyhee plateau, eastern Snake River Plain, and Yellowstone plateau. Major rhyolite eruptive centers in volcanic province: McDermott (M), Juniper Mountain (JM), Little Jack's (LJ), Bruneau-Jarbridge (BJ), Blacktail (B), Blue Creek (BC), Kilgore (K), Henry's Fork (HF), Huckleberry Ridge (HR), Yellowstone (Y). Normal faults north, west, and south of volcanic province indicate extent of Basin and Range province. Specific basins and rifts south of volcanic province: northern Nevada rift (NR), Mary's River (MR), Grouse Creek (GrC), Goose Creek (GoC), Raft River (RR), Buckskin (Bu), Blackfoot Mountains (BI), Swan (S), Jackson Hole (JH). Parabolic zone of historical seismicity after Anders et al. (1989). Unextended craton is north and east of seismic parabola. Sources of data listed in Table 1 (see Footnote 1).

<sup>1</sup>Table 1, Data for Age-Distance Relations, GSA Supplementary Data 9028, available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

11 mm/yr, oriented S54°W. Although the directions are similar, the rates are significantly less than the 45 mm/yr rate given by age-position relations along the volcanic province. If relative movement between the oceanic plumes and the Yellowstone plume is negligible (Engebretson et al., 1985), then the difference between rates derived by the two methods represents previously unrecognized extension between the volcanic province and the North American craton. Relative to the craton, the vector of extension is 21 mm/yr, S56°W using the data of Minster and Jordan (1978), or 34 mm/yr, S57°W using the data of Engebretson et al. (1985).

### Basin Fill in the Northeastern Basin and Range

The volcanic province is bordered by the northeastern Basin and Range province, where Tertiary extension is recorded by fault geometries, sedimentary basins, and magmatic activity. Although Basin and Range extension north of the volcanic province has not been precisely dated, south of the volcanic province much is known about the age span of extension. Using the ages of earliest extension from four localities in north-central Nevada, southern Idaho, and western Wyoming, Allmendinger (1982) recognized a pulse of extension that migrated east through time, leaving mature Basin and Range topography in its wake. He calculated a migration rate for this pulse of extension of about 65 mm/yr across Nevada during the middle Miocene, 35 mm/yr across southern Idaho during the late Miocene, and 17 mm/yr across easternmost Idaho during the Pliocene to Holocene. Since the analysis by Allmendinger (1982), new ages of basin fill south of the volcanic province have become available (Table 1; see footnote 1). These new data confirm the trend recognized by Allmendinger (1982), but by using the mean age of basin fill at each locality, we calculate an average migration rate of 37 mm/yr during the past 16 m.y. (Fig. 2B). At any given time, Basin and Range extension occurred in a zone approximately 125 km wide, from the locus of volcanism to the east-northeast (Fig. 2C). At any one place, basin filling and thus extension lasted for about 4 m.y. (Fig. 2C).

Further evidence of the coeval development of the volcanic province and adjacent Basin and Range is given by the composition of rocks in the basins. Basin fill generally contains two components: clastic sediment derived from adjacent horsts, and silicic tephra and volcanoclastic rocks derived from the volcanic plateau. In each basin, the influx of volcanogenic sediment records the passage of plume-related volcanism. In at least two basins, the Raft River and Buckskin (Fig. 1), the lower halves of basin fill are predominantly siliciclastic sedimentary rocks, and the upper halves contain significant amounts of volcanoclastic rocks and/or ash-flow tuff (Williams et al., 1982; Kellogg and Marvin, 1988). We interpret these basin fills to indicate that early basin subsidence occurred east-northeast of plume-related volcanism, when only horst-derived sediment was delivered to the subsiding basin. During the later stages of basin subsidence, plume-related volcanism had migrated east-northeastward, to a position where volcanic sediment could be delivered to the basin.

### Petrology

The bimodal magma types of the volcanic province and their inferred mode of emplacement are indicative of an extensional tectonic setting, as is true throughout the Basin and Range province (Christiansen and Lipman, 1972). Leeman (1982, 1989) postulated that basalt was injected into the lower crust, silicic magma was generated by convective heat transfer, and lower crust-derived rhyolite rose to the upper crust. Erupted basalt and rhyolite are largely uncontaminated by middle to upper crustal rocks (Doe et al., 1982), indicating ascent by injection, not assimilation. The volumes of erupted magma (which for many individual eruptions exceeded 1000 km<sup>3</sup>) are only a fraction of magma volumes at depth (R. L. Smith and Shaw, 1978), suggesting that for each plume-related rhyolite eruption, several thousand cubic kilometres of rhyolite remain in the middle and upper crust as silicic batholiths. To make room for basalt at lower crustal depths and rhyolite at middle and upper crustal depths, the crust must have thickened (Sparlin et al., 1982) and/or extended.

### Structural Geology

Structural trends in the volcanic province indicate west to west-southwest extension. On the Yellowstone plateau, fault-plane solutions (R. B. Smith and Lindh, 1978) show that normal faulting is occurring, and geothermal systems and silicic volcanic vents are localized along north-striking normal faults. On the eastern Snake River Plain, Quaternary extension is indicated by north-northwest-striking volcanic rift zones (Kuntz et al., 1988) and north-northwest-striking basaltic dikes (R. P.

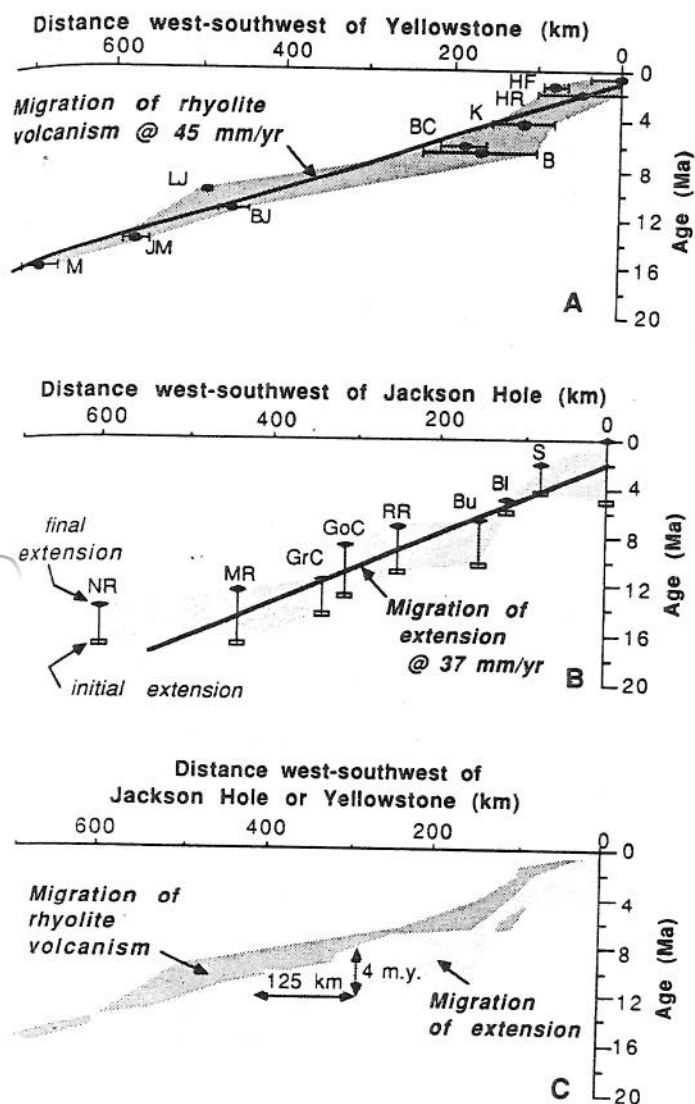


Figure 2. Graphs showing migration of volcanism and extension across northeastern Basin and Range province. Data and sources listed in Table 1 (see Footnote 1). Abbreviations of eruptive centers, rifts, and basins as in Figure 1. A: Ages of 10 major ash-flow tuffs plotted against distances of their eruptive centers from Yellowstone caldera, Wyoming. Best-fit line has slope of 45 mm/yr, interpreted to be average migration rate of volcanism. B: Age span of basins south of volcanic province and age of earliest extension in north-central Nevada, plotted against their distance from Jackson Hole, Wyoming. Best-fit line using mean ages of extension at each locality has slope of 37 mm/yr, interpreted to be average migration rate of extension. C: Comparison of location and migration rates of volcanism and extension through time. In general, basins have formed about 125 km east-northeast of coeval volcanism, and basins subside for about 4 m.y.

Smith et al., 1989). Near the plain to the north and south, trends of ranges and basins do not change as they might if dragged along a strike-slip zone separating extended from unextended crust. On the Owyhee plateau, north- to northwest-striking Tertiary and Quaternary normal faults are present (Bonnichsen, 1982; Coats, 1987).

## DISCUSSION

We propose the following model of late Cenozoic crustal extension in the northeastern Basin and Range (Fig. 3). As North America drifted west-southwest over a mantle plume, the crust beneath and east of the locus of volcanism extended. Extension was localized in a zone ca. 125 km wide (east-west), and since at least the Pliocene the zone has formed a V-shaped or parabolic pattern, symmetrically distributed about the volcanic province (Anders and Geissman, 1983; Scott et al., 1985; R. B. Smith et al., 1985; Anders et al., 1989). East of the locus of plume-related volcanism, sedimentary basins formed and were filled by horst-derived clastic detritus. Basins east-northeast of the locus of volcanism were progressively obliterated as the continent drifted over the plume, but basins south of the path of volcanism were preserved. Over the plume, the crust extended by normal faulting at very shallow levels and magma injection at depth. North and south of the plume, the crust continued to extend by faulting and ductile attenuation, resulting in basins filled with plume-derived volcanic detritus. West of the plume, minor extension in the volcanic province was accommodated by the injection of basalt dikes and by rare normal faults.

The geometry of late Cenozoic crustal extension proposed above can be used to estimate the extension factor across the volcanic province and northeastern Basin and Range. Figure 4 shows a migrating, parabolic zone of extension symmetrically distributed about the migrating volcanic plateau. The extension direction is assumed to be parallel to the direction of parabola migration, as suggested by the trends and tilts of ranges and average seismicity and geodetic measurements in the region (Eddington et al., 1987). The relation between the extension factor and the extension rate, derived and graphed in Figure 4, shows that of the two extension rates inferred from plate motions, 34 mm/yr would produce an impossibly high extension factor, whereas a rate of 21 mm/yr would yield an extension factor of 3.2. This exceeds the inferred factor of 2 for the northern Basin and Range (Wernicke et al., 1988). The disparity may reflect an underestimate of extension in the northeastern Basin and Range, or the migration rate of North America during the past 16 m.y. If an extension factor of 2 is accurate, then, according to this model, during the past 16 m.y. the average extension rate has been about 15 mm/yr, and the average rate of North American plate motion has been about 30 mm/yr.

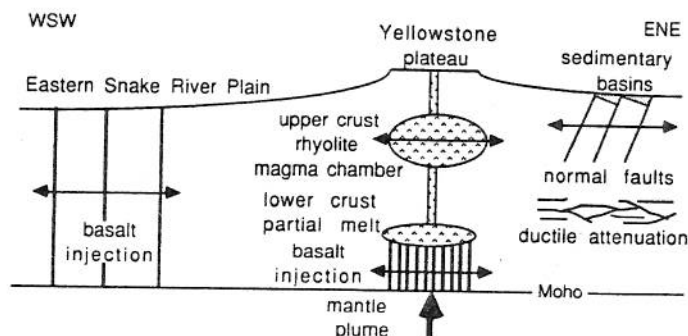


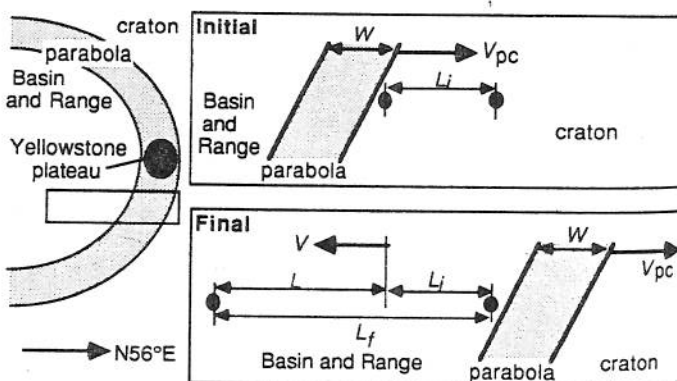
Figure 3. Different styles and locations of extension in volcanic province. Not to scale. See text for discussion.

## Implications and Further Research

1. Migration of North America over the Yellowstone plume cannot be used to derive the plate vector of cratonal North America. If extension is associated with other continental plumes, then plate vectors derived from them will not represent the entire plate, only the region under extension.

2. Thinning by extension of continental lithosphere may be necessary for mantle plumes to penetrate it. Thus, the Yellowstone plume did not penetrate until the 17 Ma initiation of Basin and Range extension.

3. The east-migrating pulse of extension shown in Figure 2B was the earliest Cenozoic extension to affect the region east of Raft River basin,



| Variable  | Definition                                          |
|-----------|-----------------------------------------------------|
| $W$       | width of parabolic extension zone                   |
| $L_i$     | initial width, northeastern Basin and Range         |
| $L_f$     | final width, northeastern Basin and Range           |
| $L$       | extension amount ( $=L_f-L_i$ )                     |
| $\beta$   | extension factor ( $=L_f/L_i$ )                     |
| $V$       | extension rate                                      |
| $V_{pc}$  | parabola migration rate with reference to craton    |
| $V_{pbr}$ | parabola migration rate measured in Basin and Range |

## Equations

The extension rate equals the extension amount divided by the time needed to extend the distance  $L_i+W$ :

$$V = L / [(L_i+W)/V_{pc}] \quad (1)$$

Substituting  $V_{pc} = V_{pbr} - V$  and simplifying:

$$\beta = 1 / [1 - \{1+W/L_f\} \{V/V_{pbr}\}] \quad (2)$$

Setting  $L_f = 600$  km,  $W = 125$  km, and  $V_{pbr} = 37$  mm/yr, the relation between  $\beta$  and  $V$  is:

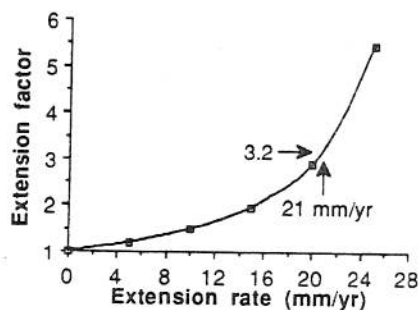


Figure 4. Model developed to relate extension factor to extension rate in volcanic province and adjacent Basin and Range province. Not to scale. Widths of northeastern Basin and Range and parabolic zone from Figure 1 and Figure 2C. Migration rate of parabolic zone from Figure 2B.

indicating that the northeastern Basin and Range has expanded eastward since 10 Ma.

4. The rate of mid-Miocene to recent extension in the northeastern Basin and Range may exceed previous estimates. More precise measurements of the cratonic North American plate vector will better constrain the rate and amount of extension in the northeastern Basin and Range, as will detailed structural analyses of fault geometries.

5. Extension will have a significant effect on the isostatic equilibrium of the crust. Brott et al. (1981) modeled the subsidence of the Snake River plain using only thermal contraction. Effects of crustal extension and a faster rate of migration need to be incorporated into their model.

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