Palinspastic restoration of NAVDat and implications for the origin of magmatism in southwestern North America

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[1] Simultaneous palinspastic restoration of deformation and volcanism illuminates relationships between magmatism and tectonics in western North America. Using ArcGIS, we retrodeformed the NAVDat (North American Volcanic Database, navdat.geongrid.org) using the western North America reconstruction of McQuarrie and Wernicke (2005). From these data sets we quantitatively compare rates of magmatism and deformation and evaluate the age, composition, and migration of Cenozoic volcanism from 36 Ma to present. These relationships are shown in a series of palinspastic maps as well as animations that highlight migrating extension and volcanism with time. Western North America is grouped into eight different regions with distinct relationships between strain and volcanism to evaluate competing hypotheses regarding the relationship of extension to continental magmatism. A first-order observation from this study is that magmatism throughout the Basin and Range appears to be primarily driven by plate boundary effects, notably subducting and foundering slabs as well as slab windows. Exceptions include the Yellowstone hotspot system along the northern border of our study area and late-stage (<8 Ma) passive, extension-related asthenospheric upwelling along the eastern and western margins of the Basin and Range. The palinspastic reconstructions presented here highlight that the classic, high-angle, Basin and Range faulting that comprises most of the physiographic Basin and Range Province commenced during a magmatic lull. More broadly, with the exception of the Rio Grande rift we find that pulses of magmatism lag the onset of extension. These observations largely contradict the active rifting model where magmatism triggers Basin and Range extension.

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1. Introduction

[2] The tectonic processes that gave rise to the voluminous Cenozoic magmatic centers in western North America, and in particular the relationship of extension to continental magmatism as well as the magma source (asthenosphere or lithosphere) remains unresolved even after 40 years of active research [e.g., *Christiansen and Lipman*, 1972, *Lipman et al.*, 1972; *Ormerod et al.*, 1988; *Gans et al.*, 1989; *Armstrong and Ward*, 1991; *Best and Christiansen*, 1991; *Leeman and Harry*, 1993; *Axen et al.*, 1993; *Metcalf and Smith*, 1995; *DePaolo and Daley*, 2000; *Wang et al.*, 2002; *Dickinson*, 2002]. The great width and areal extent of volcanism throughout the western US has led to scientific debate regarding the relative roles of plate boundary, i.e., subduction, slab steepening, and expanding slab windows, versus intraplate, i.e., active or passive rifting, processes. Interpretations of the volcanic history of western North America are critical for relating mantle structures imaged today to these various tectonic processes [e.g., *Bunge and Grand*, 2000; *Schutt and Humphreys*, 2001; *Schmid et al.*, 2002; *Sigloch et al.*, 2008; *Moucha et al.*, 2008; *Roth et al.*, 2008; *Zandt and Humphreys*, 2008]. A full understanding of Cenozoic volcanism in western North America must account for dramatically changing plate tectonic boundary conditions. Prior to mid-Tertiary time (36 Ma), this boundary was convergent, with the Farallon plate subducting eastward beneath the North American plate. By ca. 30 Ma, the Pacific-Farallon ridge came in contact with the North American plate [*Atwater*, 1970], initiating a transtensional Pacific-North America plate boundary. The conversion from a subduction margin to transtension continues to the present through northward migration of the Mendocino Triple Junction [e.g., *Atwater and Stock*, 1998].

[3] Space-time patterns of volcanism in North America have been used to argue for various relations between magmatism and tectonics. While large portions of western North America were still inboard of a subducting oceanic plate, a long narrow region of tectonically thickened continental crust underwent large-magnitude extension concurrent with

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southwestward sweeping volcanism in the north and northwestward sweeping volcanism in the south [*Coney and Harms*, 1984; *Coney and Reynolds*, 1977; *Wernicke et al.*, 1987; *Armstrong and Ward*, 1991; *Gans et al.*, 1989; *Axen et al.*, 1993; *Dickinson*, 2002; *McQuarrie and Wernicke*, 2005, and references therein]. This continental-scale pattern of magmatism has been variously attributed to roll-back of a once flat subducting Farallon plate [*Coney and Reynolds*, 1977; *Dickinson and Snyder*, 1978; *Best and Christiansen*, 1991; *Spencer et al.*, 1995; *Dickinson*, 2002], active, perhaps rift-induced upwelling of hot asthenosphere and the resulting influx of basalt into the lower crust [*Gans et al.*, 1989; *Harry et al.*, 1993; *Hawkesworth et al.*, 1995; *Hooper et al.*, 1995; *Leeman and Harry*,1993], passive rifting of a thickened crust and lithosphere [*Sonder et al.*, 1987; *Wernicke et al.*, 1987; *Coney and Harms*, 1984] and volcanism that developed above an expanding slab window as the Mendocino Triple Junction migrated northward [e.g., *Dickinson and Snyder*, 1979; *Severinghaus and Atwater*, 1990]. As the Pacific-North America boundary grew, the distribution of lithospheric extension in the Basin and Range province has widened from ~16 Ma to present [*Dickinson*, 2002; *McQuarrie and Wernicke*, 2005]. This latter period of extension is associated with increasing amounts of basalt as well as evidence for increasing amounts of asthenospheric source material [*Christiansen and Lipman*, 1972; *Lipman et al.*, 1972; *Fitton et al.*, 1991; *DePaolo and Daley*, 2000; *Wang et al.*, 2002].

[4] *Gans et al.* [1989] argued that plate boundary interactions inadequately explained patterns of magmatism through western North America; (1) space time patterns bear little resemblance to inferred plate margin configuration (particularly the wide W-E arc and southwestward sweep of magmatism), (2) extension predated the termination of subduction and is broadly synchronous with volcanism and (3) there is no obvious switch from calc-alkaline to bimodal volcanism associated with the northward migration of the triple junction. Counter arguments contend that the change from Laramide flat slab subduction to Pacific-North America plate motions required large-scale foundering of the Farallon plate [e.g., *Humphreys*, 1995; *Sigloch et al.*, 2008] which may lead to patterns of migrating volcanism that are not easily reconciled with the western boundary of the continent [e.g., *Dickinson*, 2002].

[5] Although time-space-composition patterns of igneous rocks have contributed greatly to our understanding of the links between petrology and tectonics, none thus far have considered patterns of magmatism on a fully palinspastically restored base. Admittedly, at the scale of the entire Pacific margin, palinspastic restoration may be secondary to the patterns of magmatism revealed. For example, the remarkable compilation of Cordilleran magmatism by *Armstrong and Ward* [1991] documented the temporal and spatial association of magmatism and metamorphic core complexes. At a larger scale, simultaneous reconstruction of deformation and volcanism over time is needed to fully interrogate the relationship of the plate boundary and intra-plate deformation to volcanism. With the advent of publicly available volcanic data compilations (e.g., the North American Volcanic and Intrusive Rock database [*Glazner*, 2004; *Walker et al.*, 2004]) and the growth in the power of GIS (Geographic Information System) visualization and data manipulation tools, continental scale high-resolution (1–2 Ma) joint reconstructions of magmatism and tectonism are now feasible.

[6] We integrate two new large GIS-based datasets to create palinspastic restorations of extension and volcanism. These palinspastic restorations allow us to readdress the relationship between plate-boundary deformation, intra-plate extension and magmatism in western North America. The first new data set is the tectonic reconstruction of western North America by *McQuarrie and Wernicke* [2005] (hereafter referred to as MW2005). This data set compiles the amount, timing, and direction of displacement and rotation of crustal blocks across the North American-Pacific plate boundary since 36 Ma. Geologic observations were compiled along three main transects through the northern (40°N), central (36°N–37°N), and southern (34°N) portions of the Basin and Range Province. The regions where kinematics are known constrain adjacent regions where the kinematics are not well defined. Extension and strike slip deformation were sequentially restored over 2 Myr intervals from 0–18 Ma and 6 Myr intervals from 18–36 Ma. In detail, the reconstruction highlights misalignments, overlaps, or large gaps in each incremental step, particularly in the areas between data transects, indicating that our knowledge of incremental displacements throughout western North America is still incomplete. However, the first-order components of the model – amount of extension across the region, westward motion of the Sierra Nevada/ Great Valley block from 36–12 Ma and the northwestward motion from ~12–0 Ma – as well as timing of extension in the data rich regions are robust.

[7] The second data set is NAVDat [*Glazner*, 2004; *Walker et al.*, 2004], a web-accessible repository for age, chemical and isotopic data from Mesozoic and younger igneous rocks in western North America. The database allows a continent-wide look at complex space-time patterns of magmatism. At the time of this research, NAVDat contained 59,209 samples, 17,473 of which fall within the boundary of the tectonic model of MW2005 in both space and time. This is the largest thinning of the dataset. Spatially, the NAVDat points needed to be <50 km from a given polygon in the reconstruction and temporally the samples range in age from 42 Ma to −0.0020 Ma (negative numbers indicate ages of samples after 0 AD). NAVDat lists ages of volcanic samples as a calculated age, calculated maximum age and calculated minimum age. The table also provides the age technique as well as the mineral used to obtain an age when available. Age techniques range from regional correlation to high precision $^{40}Ar/^{39}Ar$. For age constraints we used the calculated age (or mean age) from the NAVDat table. Regional correlation data can have errors as large as ±7 Myr. Analytical errors on dated minerals range from ±2 Myr to ±100 kyr. For approximately 4,000 of the samples used in our reconstruction, the original data source is unknown. We have removed low temperature cooling ages (specifically fission track ages on plutonic rocks) from the NAVDat data set to focus on ages that are close to age of emplacement. Some samples, however, represent far-traveled air fall tuffs. These analyses have not been filtered from the record. A bias inherent to the NAVDat database is that each datum represents an individual age analysis, and does not reflect the volume of erupted material. Thus the number of age analyses may be a poor proxy for the magnitude of volcanism. This bias is particularly evident in high number of Quaternary volcanic rocks

included in the database. Excluding this obvious Quaternary bias, the first-order distribution of age data appears to adequately capture the spatial and compositional pattern of volcanism since 36 Ma.

2. Methods

[8] We developed procedures in ArcGIS to palinspastically restore arbitrarily positioned point data in western North America according to the reconstruction of MW2005. These authors published a series of vector position and rotation tables for individual range- and block-polygons in western North America. The thirteen original time-steps were differenced and summed to yield two new incremental motion and rotation columns that have been added to the original table published by MW2005 (auxiliary material Table S1).[1]

[9] Palinspastic restoration of arbitrary point-based data was accomplished through association of individual points with the polygons reconstructed by MW2005. Points were then restored via incremental translation and rotation about their associated polygon centroid. Prior to restoration, we projected the volcanic database from geographic latitude and longitude into the Albers conic projection used by MW2005. The database was then sequentially restored from present-day coordinates through to the 36 Ma time step, for the original thirteen time-steps of MW2005. We then interpolated between time steps to restore the NAVDat database spatially every 1 Myr. We also constructed a 50 km-spaced strain grid and associated these grid points with the 36 Ma reconstruction. This grid was then forward-deformed to the present in order to visually highlight extension magnitudes through time. The forward deformation was limited to the original thirteen time-steps.

[10] In detail, the process of associating points with polygons can lead to ambiguous cases where more than one candidate polygon exists, leading to multiple possible restoration pathways for such points. For the case of restoration of NAVDat back through time, no polygons overlap in the initial time step. Thus those points that fall within range- and block-polygons are uniquely associated with one restoration pathway. However a significant number of points fell outside of the polygons of MW2005. Many of these are younger volcanic centers or isolated outcrops of older rocks that lie within alluviated basins of the Basin and Range Province. In order to restore these points, 1 km-width buffer-zones were constructed around the polygons and unassociated points were re-evaluated with the new, buffered polygons. This process was repeated with buffer zones at 2, 5, 10, 20, and 50 km in order to capture all of the available NAVDat data. In many cases, this process led to multiple polygon assignments to a point. For these, all candidate restoration pathways were used and the resulting positions were averaged together at each time step. This method yields restored point positions that lie between the associated polygons - a result that is reasonable at the scale of ranges and blocks in the MW2005 reconstruction.

[11] We used the same technique, in reverse, to forward-deform the 50 kilometer grid from 36 Ma to present. Multiple polygon assignments were more common when associating grid points with the 36 Ma reconstruction of MW2005. For example, a number of range blocks restore beneath the Colorado Plateau on the eastern margin of the Basin and Range. The few grid points that fell outside of polygons were associated using buffer zones, as described for the NAVDat points. As in the NAVDat case, grid points assigned to multiple polygons were restored along all possible pathways and their positions averaged. By later points in the reconstruction (i.e., younger time steps), this caused some of the interpolated grid points to lie well outside of the boundaries of the polygons on MW2005. This is particularly evident in the opening of Gulf of California and the California Continental Borderland.

[12] In two cases, grid points could not be restored due to gaps in the reconstruction of MW2005. One of these is in the U.S. - Mexico border region of Arizona. Here discrepant extension directions documented north and south of the border lead to opening of a substantial gap by 36 Ma. One strain grid point that fell within this gap was >50 km distant from the polygons of the 36 Ma reconstruction. This point was excluded from the reconstruction in order to remove spurious strain calculations that result from the closing of this gap. Another gap occurs in the northwestern corner of the Basin and Range Province. This gap occurs here because of extensive late Cenozoic cover of basalt and because the range blocks that would restore here lie outside of the reconstruction domain, further to the northwest. As deformation proceeds, some parts of the strain grid become highly distorted, especially across the trace of the San Andreas Fault and along the coast where very large offsets and rotations occur between blocks.

[13] Eight, larger irregular polygons are defined to compare rates of extension to volcanism. Polygon vertices are tied to ranges within the reconstruction of MW2005 and retrodeformed sequentially to 36 Ma. Six of these regions represent portions of the Basin and Range extensional province. From north to south, these are the Northern Basin and Range, Central Basin and Range, Death Valley, Colorado Extensional Corridor, Mojave, and Southern Arizona regions. One region defines the Rio Grande rift, and one region encompasses the eastern California shear zone, eastern Sierra Nevada, and the southern Cascades. Region boundaries do not overlap except for the eastern California shear zone, which overlaps the western portions of the northern Basin and Range, central Basin and Range, and Death Valley polygons.

[14] Rates of extension are calculated over each time step from the change in area of each cell of the deformed grid and each region polygon. The areal stretching factor is defined as,

$$\beta = \frac{A_1}{A_0},$$

where A_0 and A_1 are the areas of the polygon before and after a time step, respectively. A constant areal strain rate, $\dot{\varepsilon}_\beta$, is calculated over each time step,

$$\dot{\varepsilon}_\beta = \frac{1}{\Delta t}\int_{A_0}^{A_1} \frac{da}{a} = \frac{1}{\Delta t}\ln\left(\frac{A_1}{A_0}\right) = \frac{\ln\beta}{\Delta t}.$$

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009JB006435.

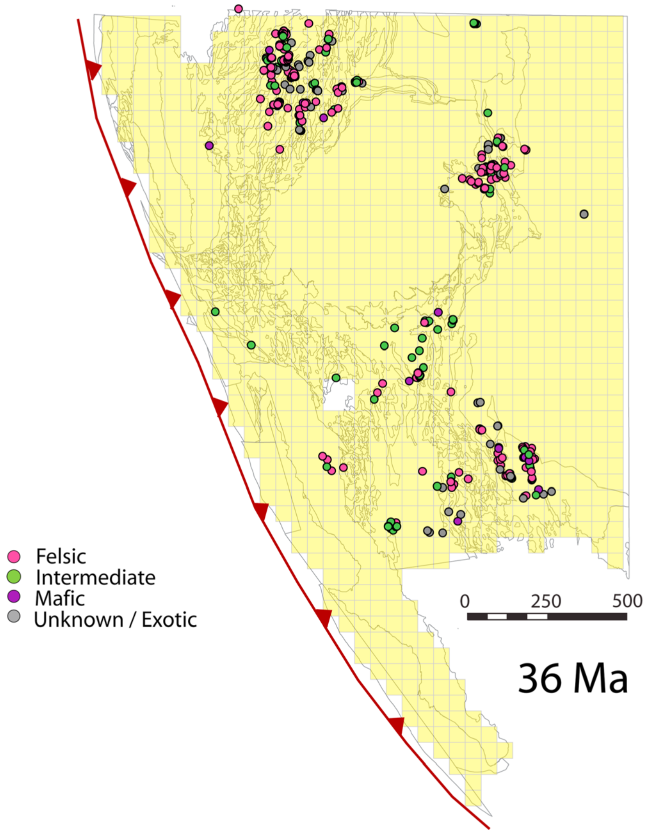

Figure 1. Map view reconstruction of western North America at 36 Ma from MW2005. Overlain on the reconstruction is a 50 km grid shaded yellow. This yellow grid is a base line grid that is linked to the palinspastic reconstruction of MW2005 and subsequently deformed from 36Ma to present in Figure 2. Dots represent NAVDat volcanic analyses from 42–36 Ma. Red barbed line is the subduction zone between the Farallon and North American plates.

Negative strain rates represent areas under compression. Strain values for highly deformed portions of the grid are retained for illustration purposes only. A much finer resolution grid, based on a more detailed reconstruction than MW2005, is required to quantify deformation in these regions. Note that this highly deformed plate boundary zone lies largely outside of the region polygons used to compare extension rates to volcanism. The boundaries of the Mojave region were defined so as to avoid large strains across the San Andreas fault.

[15] To compare strain rates to volcanism, it is most appropriate to consider rates of lithospheric thinning. Absolute rates of thinning would require *a priori* knowledge of thickness of the lithosphere during extension. Lacking this information we instead note that the vertical stretch, λ_z, may be calculated by assuming that the volume of crust is conserved in each box. At constant volume the product of the principal stretches,

$$\lambda_x \lambda_y \lambda_z = 1.$$

Because $\beta = \lambda_x \lambda_y$, we find that $\lambda_z = \beta^{-1}$ and thus that vertical strain rate, $\dot{\varepsilon}_z = -\dot{\varepsilon}_\beta$. Note however that the constant-volume assumption employed here may be violated by significant erosion or deposition, magmatic underplating [*Gans et al.*, 1989], regional lower crustal flow [*Block and Royden*, 1990], or large-magnitude simple shear extension [*Wernicke*, 1985].

3. Visualization and Analysis

[16] We present three different visualizations of the palinspastically restored NAVDat and co-located strain field: (1) interpolated animation of the entire data set from 36 Ma to the present (Animation 1), (2) time-slices corresponding to the reconstructions of MW2005 (Figures 1 and 2 and Animation 2), and (3) strain rate and histograms of volcanic analyses for eight selected regions of the reconstruction (Figures 3 and 4).[2] All three visualizations subdivide volcanism by composition (mafic, intermediate, felsic, and unknown/exotic, as identified in the NAVDat tables), and in general show a close association of volcanism with deformation. Each of these visualization schemes emphasizes aspects of the relationship of volcanism to continental deformation and the evolving Pacific-North America plate boundary.

[17] The animated reconstruction (Animation 1) is built upon the animation from MW2005. The NAVDat points are restored to their paleolocations in 1 Myr increments. Trends in compositional and age change every 100kyr. To enhance visualization of these trends, the NAVDat data points are each displayed for a 1 Myr period starting 500 kyr prior to the reported sample age. The volcanic points on the western edge of the animation are animated to move with the background polygons, which due to the integrated displacement, travel most rapidly. Because of complications due to the number of overlapping points and uniquely identifying each point in a flash-based vector animation, volcanic points in the east do not move over the 1 Myr time window they are shown. The animation fully conveys spatial and temporal relationships between volcanism and deformation, but in a largely qualitative manner. Although not shown quantitatively, deformation is conveyed by the motions of the points, ranges and blocks according the underlying palinspastic reconstruction.

[18] Time-slices of the reconstructed NAVDat overlain on the reconstruction of MW2005 permit a more quantitative view of the relationship of volcanism to extension rate. Each time slice summarizes volcanism and extension rates from the preceding interval (i.e., the 2 Ma time step shows strain rates and volcanism from 4 Ma to 2 Ma). Because of the break in intervals at 18 Ma, the 36, 30, 24, and 18 Myr time-slices show a longer span of volcanism and extension rate (preceding 6 Myr) than the younger time steps (preceding 2 Myr). Figure 1 shows the extent of the model domain as reconstructed at 36 Ma. At this time step the 50 km grid is undeformed. Overlain on this time step are the preceding 6 Myr of volcanism, from 42 Ma to 36 Ma. Subsequent time steps are shown in Figure 2, each with volcanism from the preceding interval. Progressive deformation of the grid is apparent from comparison of the time-slices. This progressive deformation is also shown quantitatively by shading the deformed grids by the extension rate described in section 2. These time-slice reconstructions of NAVDat and extension (Figures 1 and 2) are also animated in a flashcard movie

[2]Animations are available in the HTML.

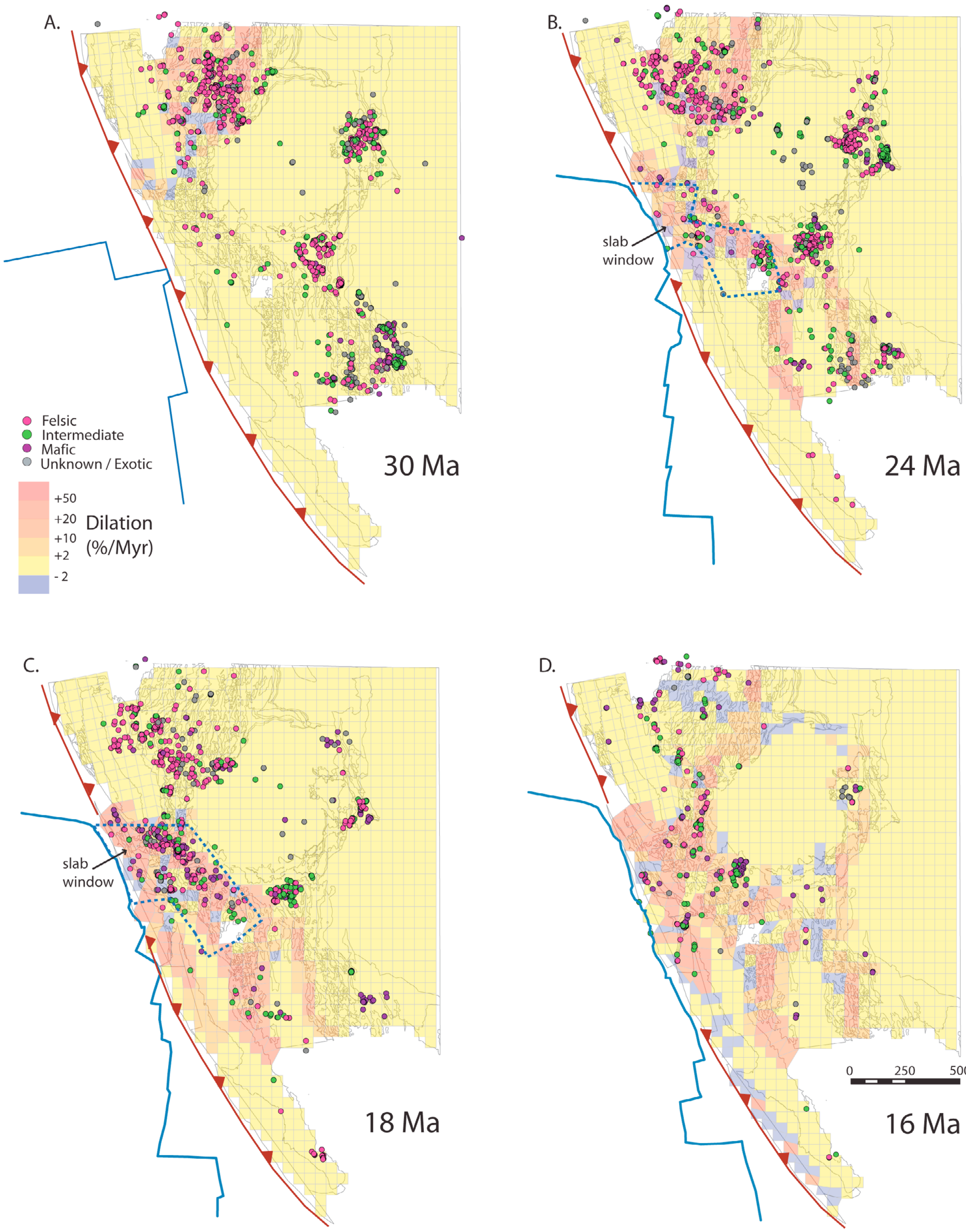

Figure 2. Reconstructed paleogeographic maps of extension and volcanism from 30 Ma to present. Dots represent NAVDat volcanic analyses, and grid is shaded to represent the magnitude of strain rate calculated from the second invariant of the strain rate tensor, undeformed grid in east is 50km. Each time slice summarizes volcanism and strain rates from the preceding interval. Red barbed line is the subduction zone between the Farallon and North American plates while the blue line indicates the Pacific-Farallon plate boundary (Figures 2a–2d) or the western edge of North America (Figures 2e–2l). Dashed region on Figures 2b and 2c outlines the map-view extent of the slab window. The northern edge of this slab window lies directly east of the Mendocino Triple junction. Slab windows from ~18 Ma onward (not shown) underlie essentially all of the study region south of the triple junction [*Atwater and Stock*, 1998].

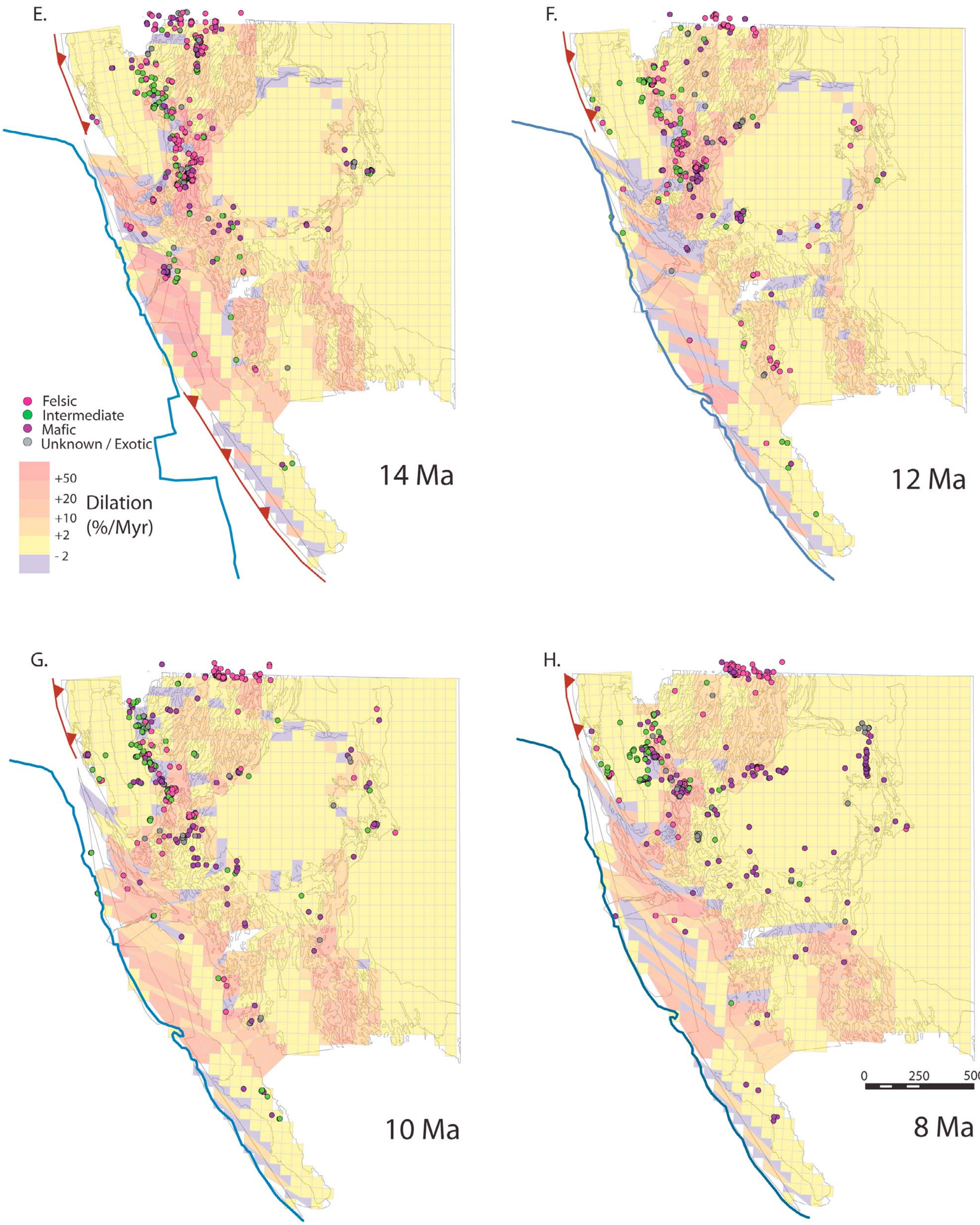

Figure 2. (continued)

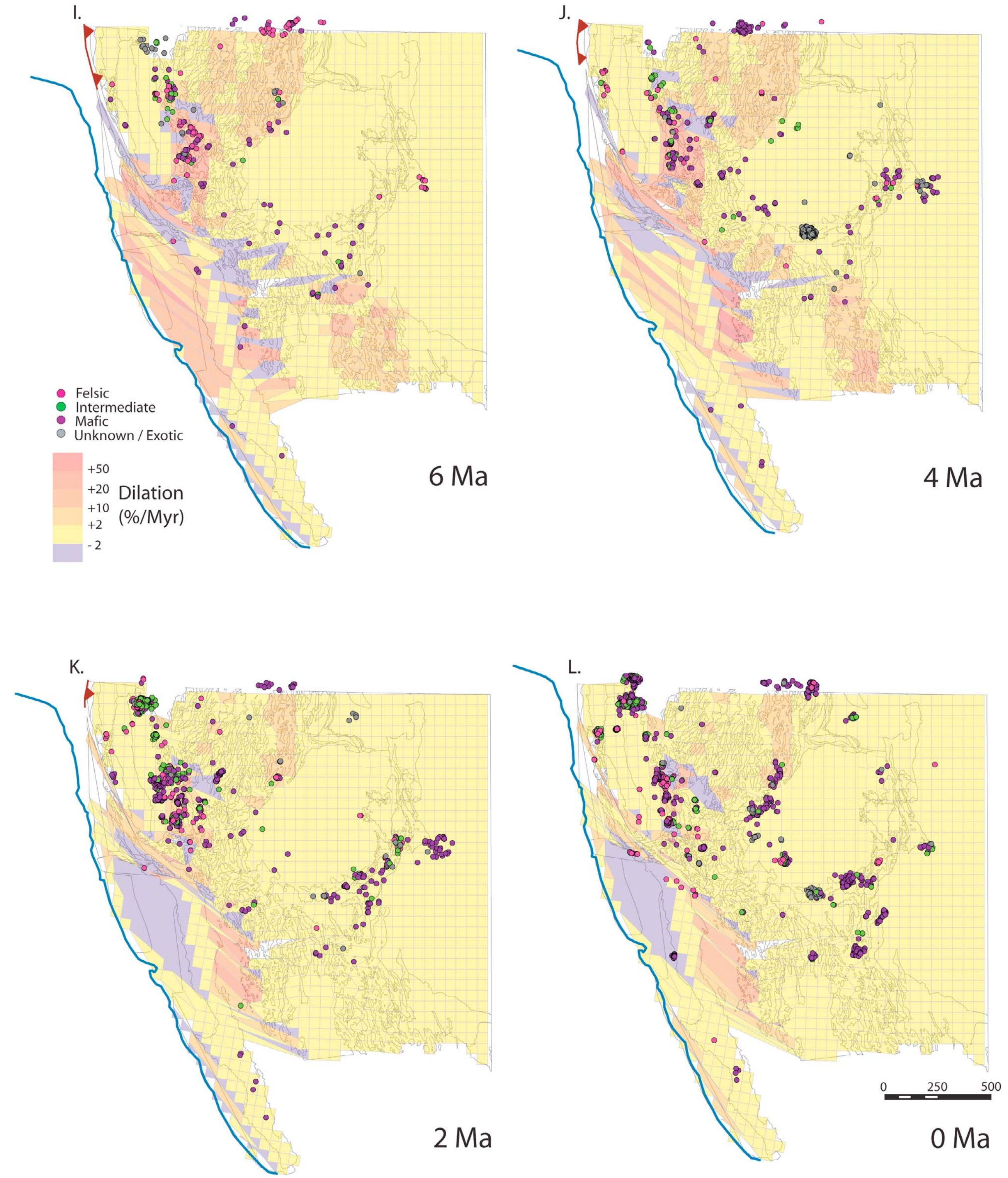

Figure 2. (continued)

(Animation 2). The abrupt but sequential view of each time step enhances changes (patterns of volcanism and extension) that happen more gradually in the continuous animation (Animation 1).

[19] Graphs of extension rate and the frequency of volcanism quantitatively express their relationship but at the expense of spatial resolution (Figure 4). Eight regions of the tectonic reconstruction (Figure 3) were selected to (1) highlight the relationship of extension and total extension rate to volcanic output and (2) illustrate the large-scale migration of volcanic activity across the model domain through comparison of adjacent regions. Volcanism was binned into the time

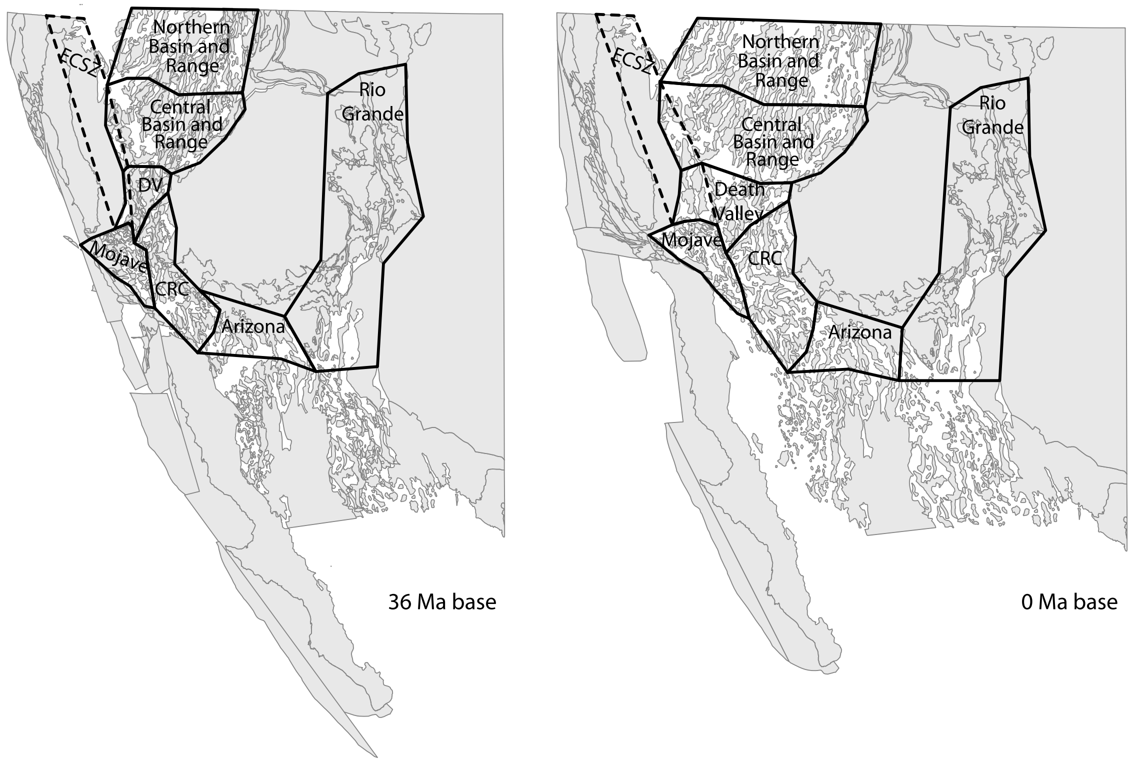

Figure 3. Index map for regions used to compare strain rate and the frequency of volcanism (Figure 4). Black boundaries represent the eight subregions of the tectonic reconstruction over which strain rate and volcanism are averaged. Due to overlap the eastern California shear zone-Walker Lane region (ECSZ) is outlined in black dashed line. The boundaries are highlighted on both the undeformed (36 Ma) and fully deformed (0 Ma) grid.

intervals defined by the reconstruction of MW2005, e.g., 2 Myr windows from 0 Ma to 18 Ma, and 6 Myr windows from 18 Ma to 36 Ma. The frequency of analyses in each region is normalized by the area of that region at the middle of each time step. Though extension rate is calculated from the change in area of the entire region (Figure 3), in detail strain is not homogeneous in space and time in any region (Figure 2). Three regions closest to the San Andreas fault (Mojave, Colorado River Corridor, and Southern Arizona) undergo a transition from extension to mostly contraction in the late Miocene (Figure 4). This transition arises largely due to the onset of significant right shear through portions of these regions. In the MW2005 model, the transition to contraction occurs at ~6 Ma in the Mojave region, significantly later than ca. 18 Ma as indicated from some geologic data [e.g., *Bartley et al.* 1990]. The highly uncertain position of the western bounding edge of the Mojave (i.e., the exact paleolocation of the San Andreas fault) complicates determining the exact extensional history of this region.

4. Discussion

4.1. Patterns of Magmatism

[20] Although palinspastically restored NAVDat points represent analyses and not eruptive volume, space-time patterns highlighted by NAVDat data still reflect the migration and intensity of volcanism through time. Even without palinspastic restoration, several space-time patterns are evident in the broader NAVDat data set [*Glazner*, 2004]. These include: (1) A southward magmatic sweep from Montana into Nevada from ~55 to about 20 Ma. (2) A clockwise sweep around the Colorado Plateau from New Mexico to southern Nevada, from about 36 to 18 Ma. (3) A burst of magmatism at about 16 Ma in northern Nevada, eastern Oregon and Washington, followed by outward sweeps to Yellowstone and southwestern Oregon. (4) A burst of magmatism in the Sierra Nevada at 3.5 Ma. In the following section we discuss these patterns of magmatism and extension on palinspastically restored North American frames. By retrodeforming the NAVDat and comparing this to plate-boundary and plate-interior deformation we provide new perspective on the origin of these overarching patterns (Figures 1–4 and Animations 1 and 2).

4.1.1. Northern Magmatic Sweep: Basin and Range and Rio Grande Rift

[21] At 36 Ma, magmatism extended from northwest Nevada across the northern Colorado Plateau to the northern Rio Grande region. This NW to SE trending band sweeps southwest from 36 Ma to 24 Ma and stalls at its southern most location from 24–18 Ma [*Dickinson and Snyder*, 1978; *Best and Christiansen*, 1991; *Lipman*, 1992; *Christiansen and Yeats*, 1992]. Although the largest number of NAVDat samples is located in Nevada and the northern Rio Grande Rift area (particularly at 36 Ma), by 24 Ma magmatic centers have formed across the Colorado Plateau to link the northern volcanism into one continuous belt (Figure 2b). The NW-SE

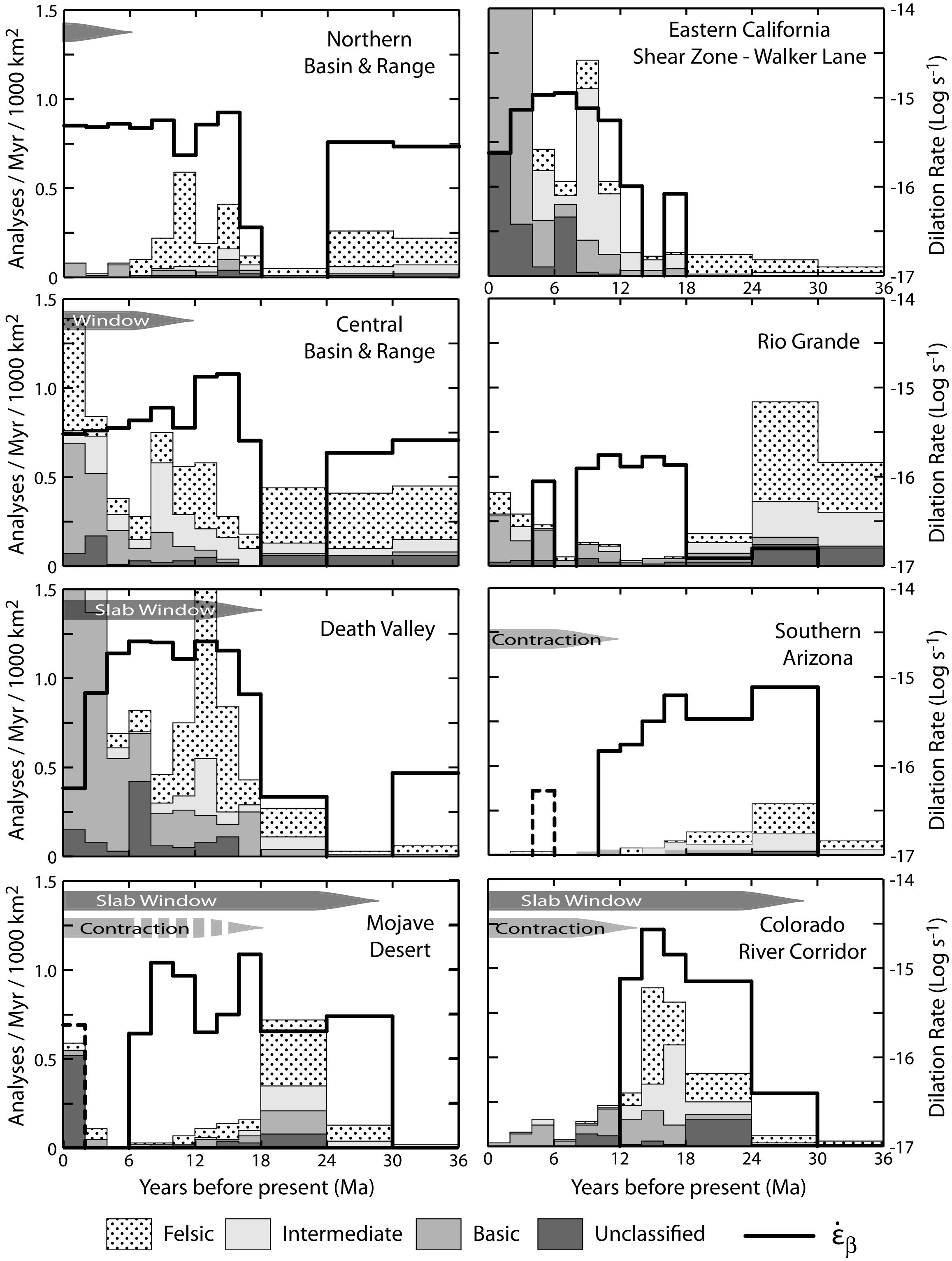

Figure 4. Frequency plots of volcanism shaded by composition overlain with spatially averaged areal extension rate, $\dot{\varepsilon}_\beta$. Transition to volcanism above slab-window shown by dark grey band. Light grey band demarcates brief periods of contraction (area decrease) associated with Pacific-North America plate-boundary right-shear. The dashed grey band in Mojave from ca. 18 Ma–6 Ma indicates a period of local to potentially regional contraction supported by geologic data [e.g., *Bartley et al.*, 1990] that is in contrast to the extension indicated by the model. This discrepancy may arise from the highly uncertain position of the San Andreas fault bounding the Mojave region on the southwest. Dashed black lines denote extension that may be spurious due to uncertainties in the reconstruction of MW2005.

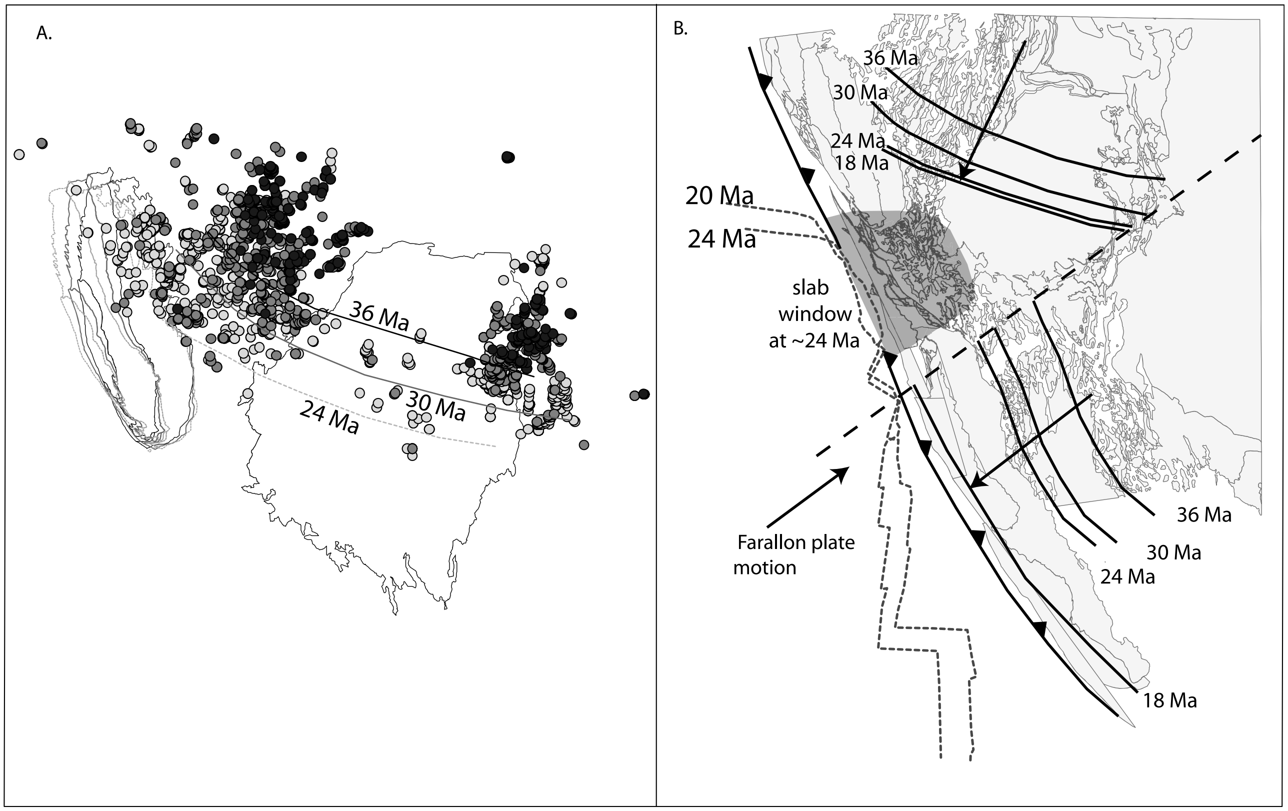

Figure 5. Compilation maps illustrating plate boundary volcanism from 36–18 Ma. (a) Southwestward migration of magmatism in the north from 36–24 Ma. Colorado Plateau and Sierra Nevada-Great Valley regions are outlined in black at 36 Ma. The Sierra Nevada-Great Valley block is also shown at 30 Ma (grey line) and 24 Ma (light grey dashed line). Dots represent NAVDat volcanic analyses and lines represent the volcanic front as defined by the southern extent of >= 98% volcanic analyses at 36 Ma (black); 95% analyses at 30 Ma (grey) and 99% analyses at 24 Ma (light grey and dashed). (b) Map illustrating plate boundary volcanism from 36–18 Ma. The base map is the tectonic reconstruction at 24 Ma. Black lines are southern extent of the majority of volcanic analyses at the specified time period. Black barbed line is the subduction zone between the Farallon and North American plates while the dark grey, dotted line indicates the Pacific-Farallon plate boundary. Grey shaded region is the area above the slab window from ~24 Ma to 18 Ma. Dashed black line represents the proposed tear in the Farallon slab that facilitated different slab steepening histories and geometries from 36 Ma to 18 Ma.

extent of this magmatic belt is a 1000 to 1500 km (as noted by previous studies) however, perpendicular to the trend of magmatism the width is ~250–300 km.

[22] Accompanying the southwestward sweep in volcanism is a westward expansion of the continental margin and counter-clockwise rotation of the Sierra Nevada [*Wernicke*, 1992; *McQuarrie and Wernicke*, 2005]. Extension is focused in relatively narrow north south trending zones of core complexes or other locally highly extended areas [e.g., *Coney and Harms*, 1984; *Axen et al.*, 1993]. The magnitude of extension diminishes southward, tying the southern Sierra Nevada to the Colorado Plateau in a region that does not start to extend until ~15 Ma. This strain gradient forces a counter clockwise rotation of the Sierra Nevada outward toward the subduction margin [*McQuarrie and Wernicke*, 2005] (Figure 5a).

[23] Graphs of strain rate against the number of volcanic analyses (Figure 4) show coeval extension and magmatism in the northern Basin and Range continuing southward into the central Basin and Range. The end of early (pre-24 Ma) extension also coincides with the end of southwestward sweeping volcanism (Figure 2 and Animation 1). As visible in the 18 Ma time slice (Figure 2c), from 24–18 Ma there is pronounced pause in extension while magmatism continues in approximately the same position within the central Basin and Range province as the preceding 6 Myr. (Figures 2b and 4) [*Best and Christiansen*, 1991]. After 18 Ma, extension picks up again and is widespread throughout the classic Basin and Range (i.e., the physiographic Basin and Range of *Stewart* [1980]). This is visible as a pronounced increase in extension rates in Figure 4 for the Basin and Range as well as for the adjacent Death Valley region. In all three regions, the ramp-up in extension rates occurs during a period of relatively low magmatic output (as recorded by the frequency of age analyses). Magmatism subsequently picks up in frequency in the Central Basin and Range and Death Valley regions. A smaller pulse of magmatism in the Northern Basin and Range is localized to the northern edge of that region, nearest to the path of Snake River Plain volcanism, and is probably unrelated to the post-18 Ma increase in extension rate across the region as a whole.

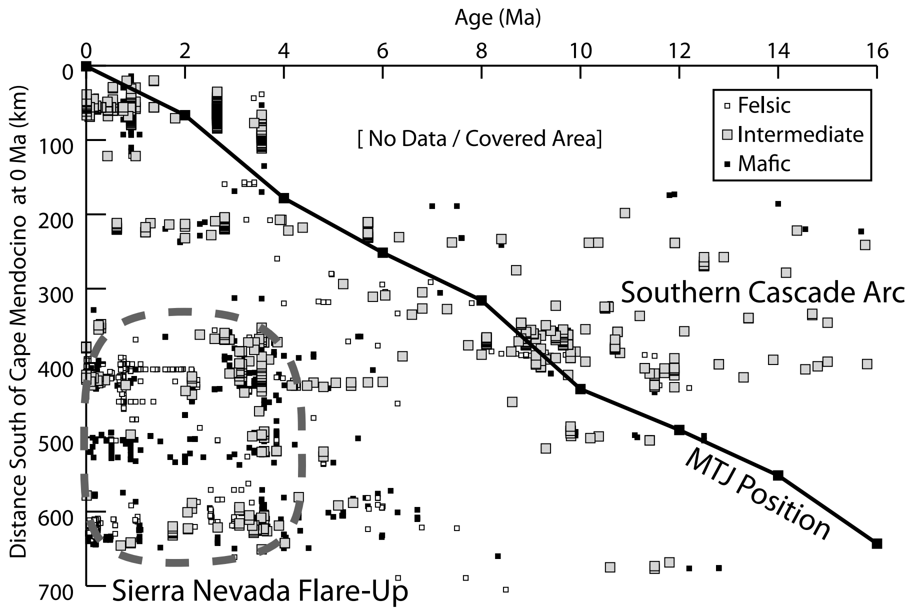

Figure 6. Graph of volcanic analyses from Eastern California Shear Zone as a function of age versus distance from present (0 Ma) position of the Mendocino Triple Junction. See Figure 3 for outline of the Eastern California Shear Zone. Grey dashed line encircles volcanism associated with the Sierra Nevada flare-up post 3.5 Ma.

[24] The only region to show a significant pulse of magmatism that clearly precedes the onset of extension is the Rio Grande rift. Here the peak in volcanism precedes the onset of extension by ~10 Myr (Figure 4).

4.1.2. Southern Magmatic Sweep: Southern Arizona to the Mojave

[25] In the southeastern portion of the Basin and Range province, magmatism ca ~30 Ma trends broadly north-south, parallel to the margin from the Mogollon-Datil volcanic center on the southern Colorado plateau southward to western Texas and Chihuahua, Mexico. This alignment of magmatic centers sweeps westward from 36 Ma to 18 Ma [*Coney and Reynolds*, 1977; *Dickinson*, 2002] (Figure 5). Due to a lower number of analyses in Mexico, trends are harder to discern. However, by 18 Ma, magmatism had migrated to western Sonora and eastern Baja California. Earlier compilations of magmatic patterns displayed a SE to NW sweep in magmatism that converges with the NE to SW sweep discussed in the previous section at ~36° N. [*Armstrong and Ward*, 1991; *Lipman*, 1980; *Christiansen and Yeats*, 1992; *Humphreys*, 1995; *Dickinson*, 2002]. The directional change in this sweep from SE to NW as noted in the earliest papers on magmatic patterns, to the E-W sweep illustrated on our palinspastic maps, is a function of both including a greater number of samples from Mexico (also noted by *Dickinson* [2002]), as well as the projection of samples on a palinspastically restored base. It is notable that at 24 Ma the reconstruction visually separates the magmatism into three trends: a NW to SE northern trend in the north, (section 4.1.1) a N-S trend in the south (section 4.1.2), and a flare-up of magmatism in the far western (Mojave) region directly east of the growing Pacific-North American Plate boundary (Figure 2b).

[26] In southern Arizona and the Colorado River corridor (CRC) the peak of extension coincides well with the westward sweep of magmatism. This relationship is seen in both the animation and in the graphs of extension versus volcanic analyses (Figure 4). The graphs illustrate that the extension starts early (~30 Ma), and volcanism sweeps east to west, showing up early in Arizona (30–24 Ma), and later (24–14 Ma) in the CRC [*Coney and Reynolds*, 1977; *Christiansen and Yeats*, 1992; *Spencer et al.*, 1995]. The arrival of magmatism in the Mojave region, peaking from 18 to 24 Ma (Figure 4), has been attributed to a continuation of the SE-NW sweep of magmatism [*Dickinson*, 2002; *Armstrong and Ward*, 1991; *Christiansen and Yeats*, 1992]. However this magmatism, which lies well to the west of other portions of the Basin and Range province, also corresponds to the region underlain by a growing window in the subducted Farallon slab [*Atwater*, 1989; *Atwater and Severinghaus*, 1989; *Dickinson*, 1997; *Atwater and Stock*, 1998; *Dickinson*, 2002] (Figures 2b, 2c, and 5).

4.1.3. Western Magmatic Sweep: Mojave, Death Valley, and Eastern California Shear Zone

[27] Palinspastic restoration of NAVDat highlights an intriguing association of magmatism and extension in eastern California with the migrating position of the Mendocino Triple Junction (Figure 6). The association of magmatism with the triple junction location was recognized in non-restored NAVDat by *Glazner* [2004], and a northward migrating volcanic arc north of the triple junction with a trailing slab gap to the south has long been suggested [*Dickinson and Snyder*, 1979; *Atwater*, 1989; *Atwater and Severinghaus*, 1989]. Starting in the Mojave region and CRC at ca. 24 Ma, intense volcanism and extension appear to be localized above this gap. As the slab window expands north into the Death Valley and eastern California shear zone (ECSZ) regions ca. 18 Ma and later, the co-existing magmatism and extension migrates north as well [*Dickinson*, 2002] (Figures 2e and 4).

[28] In the Death Valley region and the adjacent Basin and Range, the 16 to 18 Ma time slice stands apart from the set of palinspastic reconstructions of extension and volcanism. During this time frame magmatism is minimal [*McKee et al.*, 1970], but classic basin and range extension [*Wernicke*, 1992] is active everywhere (Figure 2d). By 14 Ma, magmatism becomes focused along the eastern Sierra Nevada, with predominantly intermediate volcanic rocks north of the Mendicino Triple Junction (Figures 2b and 6), and felsic rocks south (Death Valley region 12–16 Ma, Figure 4). Subsequent frames illustrate the progressive northward migration of predominantly andesitic magmatism conjunction with the triple junction (Figure 6). In the greater Death Valley/central Basin and Range region, the re-established magmatic front hugs the western side of the extending area (almost exclusively) from 14 until 8 Ma, regardless if it is intermediate magmatism (to the north) or more bimodal (to the south) (Figure 2 and Animation 1).

4.2. Tectono-magmatic Relationships

[29] Many of the patterns of magmatism and extension evident from region to region can be attributed to the evolving Pacific-North America-Farallon plate boundary system. Most of these relationships have been previously proposed as possible solutions to the migration of magmatism across western North American. The advantage of palinspastic restoration is that it solidifies spatial relationships among the continental margin, extension, and magmatism. Also, by restoring extension, the palinspastic restoration better resolves magmatic fronts that migrated across the continent.

4.2.1. Trench Retreat, Slab Steepening, and Extension

[30] One of the tectono-magmatic features well illustrated by the palinspastic reconstructions is the southwestward migration of volcanism in conjunction with the westward expansion of the northern Basin and Range Province and counter-clockwise rotation of the Sierra Nevada (Figure 5 and Animation 2). More than any other feature, we argue that this is best explained by a migration of the trench to the west (northern Sierra Nevada) in conjunction with slab steepening to impart extension to the overriding plate, as suggested by *Dickinson* [2002]. This southward sweep of magmatism has been variously attributed to roll-back of a once flat subducting Farallon plate [*Dickinson and Snyder*, 1978; *Best and Christiansen*, 1991; *Dickinson*, 2002], active, perhaps rift induced upwelling of hot asthenosphere and the resulting influx of basalt into the lower crust [*Gans et al.*, 1989; *Harry et al.*, 1993; *Leeman and Harry*, 1993] as well as buckling and foundering of a flat Farallon slab, that may be completely detached from an actively subducting Farallon plate [*Humphreys*, 1995]. Both slab steepening and foundering of a detached slab expose previously "protected" lithosphere to hot asthenosphere and cause pressure release melting as the asthenosphere rises to fill the vacated space. In order to explain simultaneous northward- and southward-sweeping volcanism identified in previous compilations of magmatic patters [*Armstrong and Ward*, 1991; *Lipman*, 1980; *Christiansen and Yeats*, 1992], *Humphreys* [1995] proposed that the slab buckled and foundered along an east-west axis centered at ~36° N. In this model, two bands of volcanism trail the slab as it pulls away from the base of the lithosphere. This is in contrast to earlier models of slab steepening that would predict a single westward-sweeping band of volcanism [e.g., *Coney and Reynolds*, 1977].

[31] Our palinspastic reconstruction highlights two fronts of magmatism, ~200–300 km wide, inboard from an actively subducting Farallon plate. A northern front, orientated west-northwest to east-southeast which sweeps to the southwest from 36 Ma to ~24 Ma, and southern front, orientated more north-south which sweeps to the west. These two bands of magmatism are offset by a northeast southwest trending line (Figure 5). This pattern is not consistent with rollback of a single slab or the buckling model. We suggest instead that the offset could represent a tear in the Farallon plate that separates two separate slabs that steepen independently. A tear in an actively subducting slab, similar to those imaged in the modern Juan de Fuca plate [*Sigloch et al.*, 2008] can accommodate the different directions of magmatic patterns to the north and south of ~36° N. This tear, which may have been correlative in space with the Pioneer Fracture zone, changes subduction dynamics by facilitating the transfer of material from below the retreating slab to above it, enhancing roll back [*Wortel and Spakman*, 2000; *Schellart et al.*, 2007].

[32] It is uncertain how the flat slab and the north to south migration of the volcanism as the slab steepens relates to the ancestral Cascade subduction system that was established at ~40 Ma [*Priest*, 1990; *Du Bray et al.*, 2006] in Oregon and Washington. In this region, north of our reconstruction, the magmatic arc was parallel and close to the subduction zone. This contrasts with volcanism in the Basin and Range and Rio Grande rift that defines an arc oriented oblique to the margin, from northeastern California to southern Colorado. The oblique orientation of the arc with respect to the subduction front offshore California suggests that the Farallon slab was bowed upward beneath the Colorado Plateau, and is consistent with the geometry of flat-slab subduction as proposed by *Saleeby* [2003]. Towards Oregon, the flat slab may have bent to steepen and connect to the ancestral Cascade system. Alternatively, there could have been a discontinuity that separated reestablished steep subduction in the north from the longer-lived flat slab to the south. A tear both north and south of the flat slab could have facilitated the slab to founder in a southward direction, not parallel to the plate margin.

[33] Overall, we interpret the volcanism from 42–18 Ma as a rapidly migrating arc/ backarc system [e.g., *Dickinson*, 2002] and raise the possibility that a slab tear beneath the Colorado plateau facilitated mantle flow around retreating Farallon slab. Such a slab tear (or possibly two tears) removes geodynamical objections to relating 42–18 Ma magmatism to a continuous, steepening Farallon slab [e.g., *Humphreys*, 1995; *Schellart et al.*, 2007]. Steepening slabs in conjunction with trench retreat imparts extension in the overriding plate [*Schellart et al.*, 2007], allowing overthickened crust to gravitationally fail toward the subduction zone [*Dickinson*, 2002]. Thus although the specific location of extension may be focused by previously thickened continental crust and zones of lithospheric weakness [*Coney and Harms*, 1984; *Sonder and Jones*, 1999], trench retreat in conjunction with a steepening slab provided the space for the crust to expand [*Dickinson*, 2002]. This is exemplified in our reconstructions with the counterclockwise rotation of the Sierra Nevada due to early core complex extension to the east (MW2005)

concurrent with a southwestward sweep of magmatism (Figure 5).

4.2.2. Slab Windows and Thermal Failure of the Lithosphere

[34] Magmatism in the CRC and the Mojave has been related to slab steepening, northwestward migration of a volcanic arc, as well as the effects of a slab window trailing the Mendocino Triple Junction. *Dickinson* [2002] argued that only detailed geochemistry could differentiate between the competing processes. We suggest that this is another region that benefits from a palinspastic reconstruction of volcanic centers and extension. Animation 1 clearly shows that volcanism in the CRC and Mojave was confined to the slab window region between migrating triple junctions from 24–18 Ma (Figures 2b and 2c). We also emphasize that at this time extension and magmatism behave differently in this region, compared with the rest of western North America. In the Mojave and CRC, a strong peak in volcanism accompanies the peak in extension. We suggest that the direct overlap of extension and volcanism indicate thermally induced failure of the lithosphere in the region directly above the slab window that developed as the East Pacific Rise spreading ridge encountered the edge of North America. A similar pattern of extension and magmatism may have occurred in the Death Valley region as the triple junction migrated northward (Figures 2e, 2f, and 4).

4.2.3. Decoupling of Magmatism and Basin and Range Extension

[35] As illustrated by the 24–18 Ma time slice, the locus of volcanism and, presumably, the steepening of the Farallon slab stalled in central Basin and Range (previously noted by *Best and Christiansen* [1991]). The palinspastic reconstruction illustrates that this stalling was the first stage of a reorganization of subduction-related magmatism. At ~18 Ma the trend of volcanism was strongly oblique to the continental margin. By 14 Ma the locus of magmatism jumped westward and became aligned with the eastern edge of the Sierra Nevada, parallel to the North American plate margin. At this time the triple junction is at ~37°N. North of the triple junction the volcanism was primarily intermediate while to the south magmatism was predominantly felsic (Figure 2e). We speculate that slab stall, minimal volcanism at 16 Ma, and the re-establishment of a volcanic arc along the eastern Sierra Nevada, particularly north of 37° N at ~14 Ma represents a reorganization of the geometry of the slab and/or a lateral tear which separated the younger, coast parallel subduction system from the older, stalled portion.

[36] The relationship between classic Basin and Range extension and magmatism is illustrated in the 16 Ma time slice (Figure 2d). At this time almost the entire Basin and Range region appears to have been undergoing extension [e.g., *Wernicke*, 1992], excepting for northwestern Nevada where extension begins at ~12 Ma [*Colgan et al.*, 2006]. This same time window appears to be a relative lull in magmatism in the Basin and Range province [*McKee et al.*, 1970]. In detail, dips in the frequency of magmatism appear ca. 16–24 Ma in the northern and ca. 14–18 Ma central Basin and Range regions, whereas the pace of magmatism is picking up in the Death Valley region (Figure 4). The lack of clear association of magmatism with the onset of widespread extension across the Basin and Range and Death Valley (circa 16 Ma) calls into question whether active rifting is a viable tectono-magmatic process for this region. The magmatism prior to 16 Ma we attribute to the foundering Farallon slab. The patterns of magmatism that appear after 16 Ma we attribute to the ancestral Cascade arc or the slab window that followed as the triple junction migrated northward.

4.2.4. Establishment of the Southern Cascadia Arc

[37] The apparent reorganization of subduction at ~16 Ma appears to have led to initiation of a short-lived, southern Cascades volcanic arc along the eastern edge of the Sierra Nevada. A progressive northward switch-off of intermediate volcanism appears to record northward migration of the southern end of this arc with the triple junction (Figure 6). Although an ancestral Cascade arc that was roughly coincident with the modern Cascade arc is well established (i.e., the Eocene–Miocene Western Cascades of *Priest* [1990] and *Du Bray et al.* [2006]), more uncertain is the age and southern extent of a Miocene–Pliocene ancestral Cascade arc in California. The reconstructions presented here support that ancestral Cascade arc magmatism began ~15 Ma from ~42° to 37° N. This arc was a fleeting feature of this region. Due to migration of the Mendocino Triple Junction the southern end of this ancestral Cascade arc migrated rapidly northward [e.g., *Cousens et al.*, 2008; *Busby et al.*, 2008; *Dickinson*, 2002; *Christiansen and Yeats*, 1992; *Dickinson and Snyder*, 1979].

[38] As Figure 2d through 2g illustrate, most of the magmatism in the central and northern Basin and Range province over the 6 Myr period from 16 Ma to ~10 Ma appears to have been related to the establishment of the ancestral Cascadia arc and its northward cessation in conjunction with migration of the Mendocino Triple Junction, as first proposed by *Dickinson and Snyder* [1979]. There is a fairly sharp change in magma composition directly inland of the triple junction from intermediate compositions to the north over the subducting plate to bimodal volcanism (dominated by felsic compositions) immediately over the growing slab window (Figures 4 and 6).

[39] Today the Walker Lane belt is located directly to the east of the Sierra Nevada in the zone once occupied by the ancestral Cascade arc. The combined eastern California shear zone–Walker Lane belt creates a ~120-km wide zone of right-lateral, intraplate transtension that geodetically accommodates up to 25% of the Pacific–North America relative plate motion [*Bennett et al.*, 2003; *McClusky et al.*, 2001; *Miller et al.*, 2001; *Sauber et al.*, 1994]. Combining patterns of deformation with palinspastically restored magmatism illustrates that this shear zone occupies a region weakened by magmatism associated with the southern Cascade arc [*Busby et al.*, 2008], as well as magmatism associated with the slab gap that followed the migrating triple junction. We propose that this thermally weak zone focused transtension within the broader Basin and Range extensional province.

4.2.5. Non-Plate-Boundary Magmatism

[40] Although we argue that most of the tectono-magmatic signal throughout southwestern North America can be directly related to plate boundary effects, some pronounced patterns of volcanism do not appear to be directly related to the plate boundary. Foremost is the magmatism related to the Yellowstone hotspot and Columbia River Plateau. Most of this magmatic event occurred north of our model boundary, however the pulse of volcanism in northern Nevada at ~16–14 Ma includes the southern extent of the

McDermitt caldera and related volcanic centers [*Pierce and Morgan*, 1992; *Colgan et al.*, 2004]. The string of rhyolitic magmatism that migrated east along the northern boundary of our model is the eastward migrating volcanism of the Eastern Snake River Plane/Yellowstone magmatic system [*Pierce and Morgan*, 1992].

[41] Although initial classic Basin and Range extension (~16 Ma onwards) was relatively amagmatic, by ~8 Ma a geochemical fingerprint of this extension appears that is basaltic with a significant contribution from the asthenosphere [*DePaolo and Daley*, 2000]. This magmatism was concentrated along the edges of the Basin and Range Province. The change in the geochemistry of the volcanic rocks suggests that passive rifting induced adiabatic upwelling of mantle material due to lithospheric extension [e.g., *Sengör and Burke*, 1978; *McKenzie and Bickle*, 1988]. This late-stage volcanism is easiest to discern along the eastern margin of the Basin and Range. Along its western margin, the passive rifting signal is intermingled with the evolving Cascade arc-Walker Lane transition that we associate with a widening slab window. We note that the peak in magmatism that followed passage of the slab window lasted about ~6 My in the Mojave and CRC regions. We speculate that a similar slab-window related period of volcanism occurred (~16–10 Ma) in the Death Valley region. The transition from slab-window to passive-rifting induced volcanism provides an alternative explanation for the geochemical transition ca. ~10–8 Ma that *DePaolo and Daley* [2000] associated with magnitude of extension.

[42] The burst of magmatism in the Sierra Nevada Mountains at ~3.5 Ma has been interpreted as the loss of a lithospheric root [*Ducea and Saleeby*, 1996; *Lee et al.*, 2001; *Boyd et al.*, 2004; *Jones et al.*, 2004]. It is intriguing to evaluate this pulse of magmatism in context with the magmatism that has migrated westward adjacent to the Sierra Nevada from ~10–0 Ma (Animation 1). At ~3.5 Ma volcanic centers simply and quickly expand into the Sierra Nevada, suggesting a distinct event that extended for 300 km in a north-south direction (Figure 6).

5. Conclusions

[43] We explore the relationships of magmatism to deformation across the southwestern U.S. through reconstruction of NAVDat with the palinspastic reconstruction of MW2005. By considering patterns of magmatic composition and ages in this restored reference frame, we suggest that magmatism throughout the Basin and Range province was primarily driven by plate boundary effects. Early in the history of the northern Basin and Range province, large-magnitude extension accompanied the westward expansion of the continental margin in conjunction with southwestward migrating volcanism. These patterns are consistent with southwest-directed steepening of a segmented Farallon slab and westward trench retreat. A similar pattern of volcanism and extension in the southern Basin and Range province, although less well defined, is also consistent with slab steepening and possible trench retreat (Animation 1). We suggest that these areas were separated by a tear in the slab that facilitated different steepening directions and transfer of asthenosphere around the slab edge and into the mantle wedge. In both regions the location of extension may have been focused by thickened continental crust but trench retreat provided the space for the lithosphere to extend by permitting the trench to migrate westward.

[44] As the Pacific plate impinged upon North America, a growing slab window began to impart its effects on the tectonothermal evolution of the Basin and Range Province. In areas directly overlying the slab window, peak extension and magmatism closely coincide, suggesting that the lithosphere underwent thermally induced failure. We suggest this thermal failure of the lithosphere is significant both in the Mojave region, where the slab window first developed, and also along the eastern margin of the Sierra Nevada as the triple junction migrated northward. Also at ~15 Ma, a southern ancestral Cascade arc developed along the eastern Sierra Nevada north of the Mendocino Triple Junction, and classic, high-angle normal faulting that comprises most of the physiographic Basin and Range province commenced. In contrast to regions above the growing slab window to the southwest, this Basin and Range extension was not accompanied by a pulse in magmatism. A complex overprinting of effects occurs as the slab window expanded northward. Transtensional shear of the ECSZ-Walker Lane appears to have taken advantage of thinned or weakened lithosphere vacated by the Cascadia arc.

[45] Although most of the magmatism throughout the Basin and Range Province can be genetically linked to plate boundary processes, notable exceptions include the Yellowstone hotspot system along the northern border of our study area, and the late-stage (<8 Ma) transition to basalt-dominated magmatism on the eastern and western margins of the Basin and Range. This latter transition has been attributed to passive, extension related asthenospheric upwelling that accompanied thinning of the lithosphere. Lithospheric delamination underneath the Sierra Nevada appears as an event distinct from volcanism that we associate with the migration of the triple junction. Palinspastic reconstructions presented here largely argue against the role of active rifting, where magmatism triggers extension. Rather, we suggest that overall the Basin and Range Province, pre-conditioned by orogensis and arc-related volcanism, provided a preferred site for extension and magmatism driven by plate boundary effects.

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