The Geological Society of America
Special Paper 553

Cenozoic magmatism and plate tectonics in western North America: Have we got it wrong?

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ABSTRACT

The current tectonic framework for understanding Cenozoic magmatism in western North America was laid out in a series of influential papers in the early days of the plate-tectonics revolution. These ideas, largely developed through deductive analysis, were so revolutionary yet seemingly self-evident that they quickly passed from hypothesis to axiom. These include the following. (1) Inboard and outboard sweeps of magmatism resulted from shallowing and then rapid steepening of a subducted slab. (2) The Oligocene–Miocene ignimbrite flareup resulted from sinking and rollback of a shallow slab. (3) Late Cenozoic basaltic magmatism resulted from opening of a slab window. (4) The current Cascade arc is the remnant of a much more continuous ancestral arc that ran the length of western North America. When tested against current databases of igneous rock ages and chemical analyses, these conjectures largely fail; some are clearly contradicted, whereas others are possible but ad hoc and unfalsifiable. Ironically, the plate-tectonics revolution nicely explains plate-boundary magmatism in much of the world but is less successful in western North America, where many of these links were first developed. It is time for a second revolution.

INTRODUCTION

The 1970s were an exciting time to be a student in geology. Plate tectonics had advanced from being an eccentric idea to being the inspiration for radical new conjectures about the ways in which Earth functions. The kinematic framework of plate tectonics was established from marine geology and geophysics, and soon the basic concepts of plate movement and mantle flow were applied to the continents.

Many fundamental advances in the application of plate tectonics to the continents were developed from observations in western North America in the 1960s and 1970s. In particular, Warren Hamilton and Tanya Atwater placed Mesozoic and Cenozoic magmatism and tectonics into a plate-tectonic context in truly pioneering papers (Hamilton, 1969; Atwater, 1970). Their basic framework—that the magmatic and tectonic history of western North America resulted from subduction of oceanic plates followed by progressive conversion of the continental margin into a transform boundary—inspired many creative new postulates, including the northward retreat of an ancestral Cascade arc, shallowing and then rapid steepening of the subducted Farallon plate to produce sweeps of magmatism, and the opening of slab windows and consequent alkali basaltic volcanism. There seemed to be no end to links between magmatism and plate tectonics, and the ideas of the 1970s pervade the general understanding of these links today.

Numerous papers followed Hamilton and Atwater in the 1970s (e.g., Christiansen and Lipman, 1972; Lipman et al., 1972;

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Glazner, A.F., 2022, Cenozoic magmatism and plate tectonics in western North America: Have we got it wrong?, *in* Foulger, G.R., Hamilton, L.C., Jurdy, D.M., Stein, C.A., Howard, K.A., and Stein, S., eds., In the Footsteps of Warren B. Hamilton: New Ideas in Earth Science: Geological Society of America Special Paper 553, https://doi.org/10.1130/2021.2553(09).

Dickinson, 1975; Coney and Reynolds, 1977; Dickinson and Snyder, 1979), making predictions based on the general framework established earlier. These hypotheses were difficult to test owing to limited data; my undergraduate thesis was designed to fill a hole in the data and to determine the dip of the Miocene subducted slab under southern California from the potassium contents of lavas (ah, youth!). Data had to be hand-compiled on paper, and these studies were necessarily first attempts at reconciling magmatism and plate tectonics.

Three major hypotheses from this era have survived to the present day with little challenge; they are essentially taken as axiomatic. These are: (1) the subducted Farallon slab flattened in the Late Cretaceous and Paleogene and then steepened rapidly and dramatically ca. 40 Ma, causing an in-and-out sweep of magmatism and deformation (Coney and Reynolds, 1977); (2) formation of a slab window inboard of the lengthening transform boundary led to asthenospheric upwelling, extension, and widespread basaltic volcanism (Dickinson and Snyder, 1979); and (3) an ancestral Cascade arc ran down the length of California and western Mexico, and it was progressively shut off as the trailing edge of the subducted Farallon plate moved northward to its present position in northern California (Dickinson and Snyder, 1979). These hypotheses are still widely cited and taken as starting points for interpreting the geologic history of western North America (e.g., Dickinson, 2006; John et al., 2012; Busby, 2013; Best et al., 2016; Copeland et al., 2017).

We can now use the NAVDAT database (Walker et al., 2006), and related data sets available at www.earthchem.org, to test these hypotheses with much greater rigor than we could 40 yr ago. There are ~37,000 igneous samples from western North America in NAVDAT for which geochemical and/or geochronological data are available. The point of this paper is that the hypotheses listed above fail, or at least earn lower-than-average grades, when tested against this data set. There is something deeply incorrect about our understanding of how magmatism and plate tectonics relate in western North America. It is time to rethink this paradigm.

DATA COMPILATION

NAVDAT includes records for ~65,000 igneous rocks in western North America. Another ~8000 Cenozoic ages are present in the U.S. Geological Survey's National Geochronological Database (Sloan et al., 2003). Geochronological compilations for Arizona (Reynolds et al., 1986), New Mexico (Wilks and Chapin, 1997), Nevada (C. Henry, 2003, personal commun.), and northwestern Nevada and northern California (du Bray et al., 2014) were also added.

The resulting data set was cleaned by eliminating the following: (1) nonigneous and altered rocks; (2) all Ar ages on plutonic rocks except those done on hornblende; (3) other low-temperature age determinations on plutonic rocks, such as fission-track ages; and (4) far-traveled rocks (pyroclastic fall deposits and anything marked simply as "tuff"). Samples that were clearly marked as pyroclastic flow deposits (e.g., "ash-flow tuff") and basalt flows were kept, even though some were probably sampled more than 100 km from their sources.

Rocks were classified into four broad compositional groups, exotic (chiefly low-silica alkalic rocks such as leucitite), low-silica, intermediate, and high-silica, using standard silica cutoffs (exotic <45 wt% SiO_2, low-silica 45–52 wt% SiO_2, intermediate 52–66 wt% SiO_2, high-silica >66 wt% SiO_2). Rocks with no chemical data were assigned to one of these groups using their name and average rock compositions listed in LeMaitre (1976) or an ad hoc data dictionary for uncommon rocks. The total number of samples in the cleaned data set ranging from 65 to 0 Ma was ~38,100. An unknown number of these are duplicates, but these do not bias visual patterns because they plot identically.

VISUALIZATIONS

The analyses below are based on temporal animation of the data. Supplemental Material Movie S1[1] was produced by combining 0.2 m.y. time slices at 10 frames per second. Starting 1 m.y. before its age, each point grows to maximum radius at its age and then decays back to zero over the next 2 m.y. Points in the database were screened to include only those with estimated errors (age bracket) of ±2 m.y. For Movie S1, this is ~23,000 points. In this paper, selected time slices are shown (Fig. 1), but the movie is a clearer representation of magmatic patterns.

Greatly simplified plate boundaries were taken from the reconstruction of Atwater and Stock (1998) relative to an unrestored base map of western North America. Because extension was dominantly in a roughly east-west direction (McQuarrie and Oskin, 2010), and because the Mendocino transform fault strikes east-west, this simplification is reasonable at the scale of western North America. In the Atwater and Stock (1998) reconstruction, the Sierra Nevada block restores to a position ~100 km south relative to the Colorado Plateau, but Glazner et al. (2002) argued that 50 km is consistent with observed fault offsets in the Mojave block and with stated uncertainties of the Wernicke and Snow (1998) reconstruction.

TESTING THE HYPOTHESES

Slab Flattening and Steepening

The simple concept of the subducted slab flattening and steepening, with consequent sweeps of the magmatic arc inland and then back toward the coast, is intuitively appealing and lends itself to elegant hand gestures. Coney and Reynolds (1977) linked their hypothesis to recently discovered shallow Wadati-Benioff zones in parts of South America. They plotted a limited data set

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[1] Supplemental Material. Animation of space-time patterns of magmatism in the western United States. Please visit https://doi.org/10.1130/SPE.S.18730106 to access the supplemental material, and contact editing@geosociety.org with any questions.

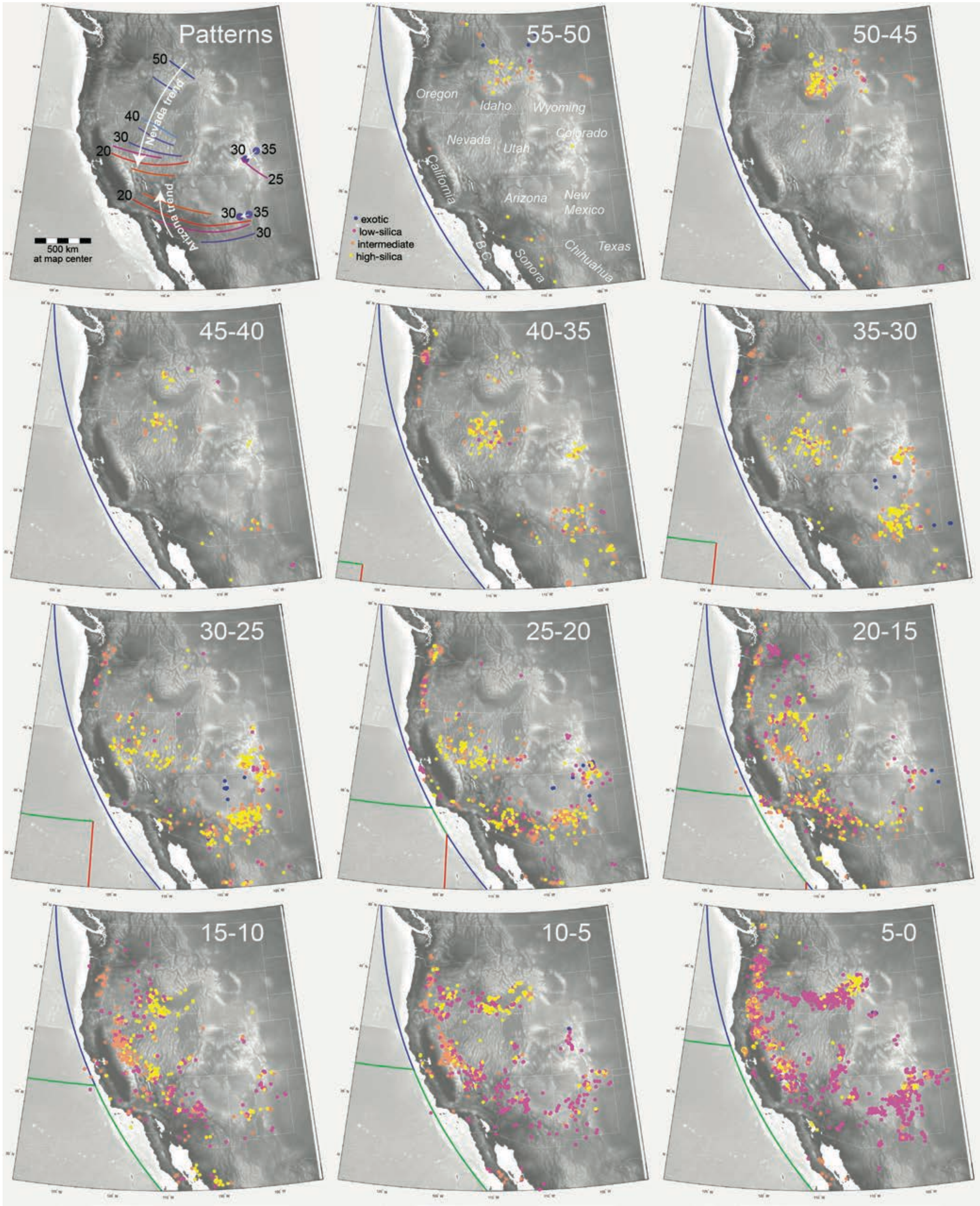

Figure 1. Time slices (ages in Ma) taken from animation of Cenozoic magmatism in the western United States (see Supplemental Material Movie S1 [text footnote 1]). First panel summarizes main patterns discussed in text. Base map is not restored for strike-slip faulting (chiefly right slip along the San Andreas fault) or extension (chiefly east-west across the Basin and Range). Simplified plate boundaries were taken from Atwater and Stock (1998), with positions relative to the Colorado Plateau. Blue—subduction zone, red—spreading ridge, green—transform fault. B.C.—Baja California.

(~450 samples) of predominantly K-Ar ages on an east-west cross section and inferred that the subducted slab shallowed from ca. 120 to 40 Ma, forcing the arc inland to Colorado, and then rapidly steepened, bringing it back to the continental margin.

There is little support in the data for either a systematic inland sweep (not discussed here), or a rapid westward sweep back toward the coast (Fig. 1). In particular, from ca. 25 to 18 Ma, magmatism stretched from the Rio Grande Rift to southern California in an arcuate east-west belt. This belt stretched over 1000 km inland and was essentially perpendicular to the continental margin and strike of the subduction zone.

There are two main patterns seen in the animation and in Figure 1. One, referred to here as the Arizona trend, comprises a broad east-west belt that moved northward with time, reaching the latitude of southern Nevada ca. 15 Ma (Glazner and Supplee, 1982; Glazner and Bartley, 1984). At the same time, a concentration of magmatic activity was moving southward from Montana and Idaho and into Nevada (hereafter the Nevada trend; Axen et al., 1993), reaching southern Nevada at about the same time (15 Ma). If projected onto an east-west cross section as in Coney and Reynolds (1977), weak east-to-west trends are discernible, but these are minor components of dominantly north-south movement.

Ancestral Cascades

The southern end of the present-day Cascade arc is essentially even with the southern end of the Cascadia subduction zone, inboard of the Mendocino triple junction. It makes sense that in past times, the arc would have extended farther south, tracking the Mendocino triple junction as it moved northward and leaving an extinct ancestral Cascade arc behind. This extinct arc has been shown extending deep into eastern California and past the southern tip of Nevada to ~34.5°N latitude on numerous maps (Christiansen and Lipman, 1972; Dickinson and Snyder, 1979; Dickinson, 1997, 2006; Busby et al., 2008).

There is little evidence for such an ancestral arc in this area south of ~38°N (Mono Lake and Yosemite National Park), a reach of >500 km, in the Oligocene and Miocene, either in the data compilation of Figure 1 or in the field. Eastern California has been mapped in exquisite detail, and there are no rocks of the appropriate age there. Miocene lavas north and east of Yosemite National Park have been assigned to the ancestral Cascade arc by numerous authors (Putirka and Busby, 2007; Busby et al., 2008; John et al., 2012; du Bray et al., 2014), but this assignment is questionable because their compositions are unlike other circum-Pacific arcs (see below).

The analysis by Dickinson and Snyder (1979) was deductive, taking the basic framework of Atwater (1970) and predicting what ought to be found. They stated (p. 617–618), "In the latest Oligocene and earliest Miocene…an active magmatic arc extended unbroken parallel to the coastal subduction zone from Canada to Mesoamerica, except for a minor gap centered near southernmost Nevada," and "…the southern end of the Cascade arc retreated through the Neogene in a manner that closely matches behavior predicted by our modified geometric model."

These statements are contradicted by the geology of the southwestern United States, and south of 37°N, the observed magmatic pattern is precisely the opposite of that predicted. Figure 2 shows latitude versus age for rocks east of the San Andreas fault and west of a line from north-central Nevada to southeastern Arizona, the area where an ancestral Cascade arc might have been located (Fig. 2, inset). The blue line, the latitude of the Mendocino triple junction at the coast, marks the time when the tectonic regime at that latitude should have changed from subduction to transform (Fig. 1; Atwater and Stock, 1998) after the Mendocino triple junction formed ca. 28 Ma. However, south of 37°N, there was almost no magmatism when subduction was occurring. In this region, Miocene volcanic rocks sit on weathered Mesozoic and older basement, and commencement of volcanism at a given latitude corresponded to the time when the Mendocino triple junction, the southern limit of subduction, was located to the west (Fig. 2; Glazner and Supplee, 1982). At 36.5°N, this northward-sweeping belt of magmatism (Arizona trend) met the southwestward-sweeping belt (Nevada trend) 10–15 m.y. ago.

Thus, there was no magmatism when subduction was occurring, and a voluminous burst of magmatism started when subduction ended and stretched far inland, perpendicular to the trench. It is tempting to tie this outburst to formation of a slab window (see below), but it started well before the slab window formed, with its distal (eastern) part well over 1000 km from the margin (Fig. 1, 30–15 Ma).

North of 37°N, there are rocks of the proper age to have been the ancestral Cascade arc (du Bray et al., 2014), but their spatiotemporal patterns and compositions call this into question. Oligocene magmatism in northern Nevada was part of the south-sweeping Nevada trend. The parts of northwestern Nevada and eastern California designated as ancestral Cascades by du Bray et al. (2014) and John et al. (2012) include the western end of this sweep, which moved to the southwest and west into California.

Slab Windows

A second prediction of Dickinson and Snyder (1979) is that a growing triangular slab-free region, or slab window, controlled the late Cenozoic magmatic and tectonic evolution of southwestern North America. In this hypothesis, asthenosphere welled up into this region, causing partial melting, basaltic and bimodal magmatism, and extension. Several other papers have enlarged upon this concept (Thorkelson and Taylor, 1989; Severinghaus and Atwater, 1990; Dickinson, 1997; Atwater and Stock, 1998), adding detail to the predicted geometry of slab windows or gaps.

As with the ancestral Cascades, the geologic record of the southwestern United States east of the San Andreas fault lends little support to the slab-window concept. The proportion of basalt among erupted products increased throughout the Cenozoic, a trend known for over a century (Lindgren, 1915), but this happened across western North America, not in an enlarging

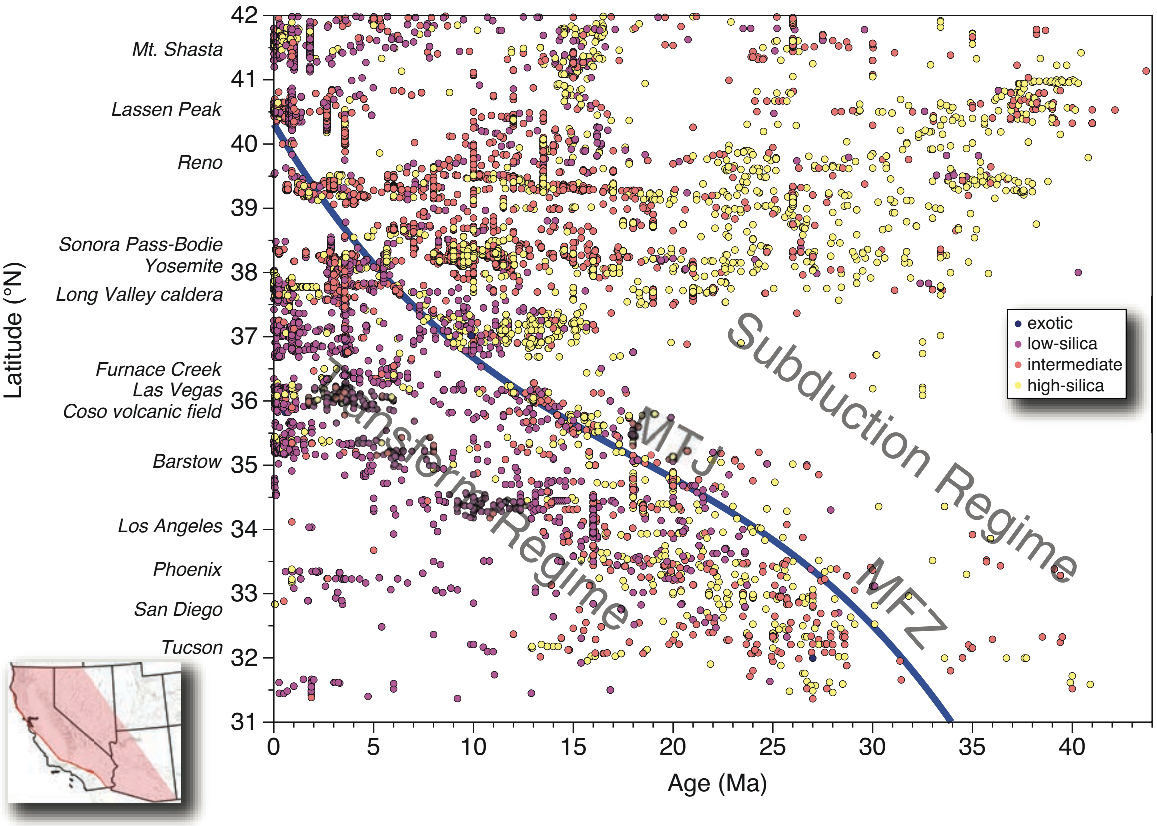

Figure 2. Latitude vs. age for rocks in the potential ancestral Cascade arc corridor (inset, lower left) between the western boundary of the North American plate (largely the San Andreas fault) and a line from north-central Nevada to southeastern Arizona. The Mendocino fracture zone (MFZ) trended roughly east-west, and so the latitude of the Mendocino triple junction (MTJ) at any time divides the points into a pre–Mendocino triple junction subduction regime and post–Mendocino triple junction transform regime. The ancestral Cascade arc hypothesis predicts that subduction magmatism shut off with passage of the Mendocino triple junction, but south of 37°N, the pattern is opposite that expected. High-silica points north of 37°N are the southward-sweeping belt that came out of Idaho (Nevada trend).

triangular region as predicted by the slab-window hypothesis. The belt of major extension in California and Arizona migrated northward with the subducted Mendocino fracture zone, which at later times marked the northern edge of the slab window (Glazner and Bartley, 1984), but these short-lived events did not persist. As with volcanism, extension began before the slab window formed and was widespread outside the window once it did form. Alkali basaltic magmatism became widespread in the area of the slab window starting in late Miocene time, but it was also widespread across most of western North America.

DISCUSSION

Slab Foundering Doctrine

The hypothesis of Coney and Reynolds (1977) was based on the limited data available at that time, and they omitted ages younger than 15 Ma (the westward trend in their data is weak, and it disappears if younger ages, which they assumed were produced in a different tectonic environment, are included). They assumed that arc magmatism happens when slabs reach 150 km depth, and they tied their speculative inboard and outboard sweeps to the area where the slab reached this depth.

Since publication of that paper, the concept of slab rollback has become firmly entrenched. Although rarely discussed in detail, Best et al. (2016, p. 1098) stated, “As used here, ‘rollback’ refers to slab steepening, as opposed to hinge migration,” akin to bending at the wrist when illustrating subduction with one’s hands. Hamilton (2007) argued convincingly against the fixed-hinge concept and that hinge retreat must be a dominant process to account for shrinking of the Pacific Ocean, migration of arcs such as the Lesser Antilles across oceanic plates, and other phenomena. Slab rollback is commonly used synonymously with hinge retreat (e.g., Schellart et al., 2006; Brun and Faccenna, 2008), but these are separate processes. Here, I use slab steepening to refer to an increase in the dip of the subducted slab, whether or not hinge retreat is involved. This concept is a form of slab removal in which a shallowly dipping slab (as inferred for the Laramide orogeny and observed along several stretches of the Andean arc) is removed via delamination or piecemeal sinking.

Slab foundering is used below to refer to either slab steepening or slab removal.

Slabs Are Not Slabs

It is important to remember that "slabs" in plate tectonics are not slabs in the normal use of the word (e.g., "a flat, broad, and comparatively thick piece or mass of anything solid" or "the stone on which a corpse is laid in a mortuary" [Oxford English Dictionary, 2021]), and their common depiction as such, with a well-defined defined top and bottom, is highly misleading. The downgoing plate has a thin crust of hydrated basalt on its well-defined upper surface, but the lower boundary is a gradational rheologic transition, typically treated as an isotherm. The physical distinction between the subducted slab and the mantle around it fades away as the slab warms up (Severinghaus and Atwater, 1990). This mechanical merging of the plate with its surroundings is obscured when plates are drawn the traditional way with sharp upper and lower boundaries, and if these are used as boundary conditions in modeling, as is common, they control the results.

The rheology of lithospheric slabs is typically compared to that of a strong material such as steel, and slabs are assumed to be capable of processes such as brittle failure under tension, boudinage, and shear failure (Lister et al., 2008; Duretz et al., 2012). However, temperature varies dramatically across a slab, with consequent extreme changes in rheology. After subduction to 150 km, the top of a slab might be ~800 °C (Syracuse et al., 2010). If the base of a slab is defined by the 1300 °C isotherm (e.g., Duretz et al., 2012), then this difference of 500 °C corresponds to a variation in effective viscosity of 4–10 orders of magnitude using typical olivine flow laws (Turcotte and Schubert, 2002, p. 322). Thick peanut butter and water have a viscosity ratio of 10^4–10^6. It is difficult to see how one could treat something with such an extreme variation in rheology as a coherent, breakable entity.

Slab Foundering as an All-Purpose Explanation

Slab foundering is commonly invoked to explain magmatism that does not fit the usual linear, trench-parallel volcanic chains of arcs, including the Nevada trend and voluminous Cenozoic magmatism in the southern Rocky Mountain volcanic field and southwestern New Mexico (Fig. 1; Humphreys, 1995; Dickinson, 2006; Chapin, 2012; Best et al., 2016). The supposition is that a dense slab falls away, melting once it reaches ~150 km, or else exposes the hydrated base of the continental lithosphere to hot, upwelling asthenosphere, leading to widespread melting (Farmer et al., 2008).

There are several reasons to move this line of reasoning from the realm of dogma to that of conjecture requiring continued testing.

1. Root cause of arc magmatism: Coney and Reynolds (1977) assumed that when a subducted slab reaches 150 km depth, magma is generated, and they assumed the corollary that a shallow slab that founders to this depth will also generate magma. This is far from certain, given how little is known about the way(s) in which magma is generated in subduction zones, the thermal structure of subducted plates, and where water in the subducted plate is given off (e.g., English et al., 2003; van Keken et al., 2011; Schmidt and Poli, 2014). Furthermore, in areas of the Andes with shallow Wadati-Benioff zones, there are no arcs farther inland where the seismic zones apparently descend to greater depth (Muñoz, 2005; Alvarado et al., 2009).
2. Variations in the depth to Wadati-Benioff zone and arc width: Movement of the locus of magmatism in an arc is commonly attributed to changes in slab dip, but the distributions of volcanoes in continental arcs show wide variability in the depth to the Wadati-Benioff zone, the arc width, and the volcano-trench distance (Syracuse and Abers, 2006; Schmidt and Poli, 2014). For example, active volcanoes in the Central American and Andean arcs are distributed between 80 and 150 km above the Wadati-Benioff zone, and in the Andes, active volcanoes range from ~200 to 500 km distance from the trench, with the majority between 250 and 400 km (see below). Trying to predict slab dip from the locations of volcanoes is thus fraught with uncertainty.
3. Dearth of current or recent examples: Although evidence of active hinge retreat is common (e.g., Schellart et al., 2006), there are few modern examples of slab foundering. Kay and Coira (2009) noted that ignimbrites of the Altiplano-Puna volcanic complex were erupted after an early Miocene lull in magmatism and inferred that they owed their origin to slab foundering. Ferrari et al. (2001) presented evidence that the Cocos plate is currently steepening beneath Mexico, producing a trenchward migration of volcanism, but this is distinct from the proposed situation of dropping a nonmagmatic flat slab to produce a magmatic flareup.
4. Patchy application of the concept: Slab foundering is the widely accepted explanation for huge ignimbrite eruptions that occurred in western North America in the Oligocene and Miocene (Best et al., 2016). However, in the United States, these ignimbrite flareups occurred in three regions that are relatively compact compared to western North America (southern Rocky Mountain volcanic field in Colorado, Mogollon-Datil volcanic field in southwestern New Mexico, and Trans-Pecos area of west Texas), and in the southward-propagating Nevada sweep. Large areas in between were bypassed, for reasons that slab foundering does not explain.
5. Ad hoc patterns of rollback: The Nevada trend was comparable in pre-extension diameter to the southern Rocky Mountain volcanic field. It moved from north to south in a relatively linear zone that was oriented subperpendicular to the trench but moved subparallel to the trench.

Explaining this by slab foundering (Henry and John, 2013; Best et al., 2016) requires that a strip peeled down in a direction subparallel to the trench, like a narrow bandage being pulled off the undersides of Montana, Idaho, and Nevada. Weak southwestward progressions of caldera development in the southern Rocky Mountain and Mogollon-Datil fields attributed to foundering by Chapin (2012) occurred simultaneously. Explaining these by slab foundering requires pulling off more bandages, in synchrony, on opposite sides of a postulated slab tear. These scenarios are not impossible, but the explanations are ad hoc and model-driven.

Ancestral Cascades?

Figures 1 and 2 clearly demonstrate that there was no ancestral Cascade arc in California or Nevada in the late Oligocene and early Miocene. North of 37°N, there are voluminous middle to late Miocene volcanic rocks north and east of Yosemite National Park (Sonora Pass and Bodie) that have been designated as the ancestral Cascades (John et al., 2012; Busby, 2013; du Bray et al., 2014). Most of these rocks are unusually potassic, as are Pliocene lavas farther south in the Sierra Nevada. The Pliocene event of highly potassic magmatism has been attributed to lithospheric delamination by a number of authors (Feldstein and Lange, 1999; Manley et al., 2000; Farmer et al., 2002).

Putirka and Busby (2007) attributed the high-K_2O contents of all these lavas, including shoshonites with >6 wt% K_2O, to small-degree partial melting, unrelated to delamination and controlled in some way by increased crustal thickness. This is questionable because these rocks are significantly more potassic than arc rocks anywhere around the Pacific Rim (Fig. 3), including those of the high Andes, where crustal thickness is far greater.

Figure 3 compares rocks from the Sonora Pass–Bodie region with analyses from circum-Pacific arcs. The proposed ancestral Cascade suite departs from the arc trend at a high angle. The regression line gives the trend of rocks from parts of the high Andes between latitudes 15°S and 37°S, where crustal thickness averages 55 km and reaches 80 km (McGlashan et al., 2008), fully twice the Sierran thickness assumed by Putirka and Busby

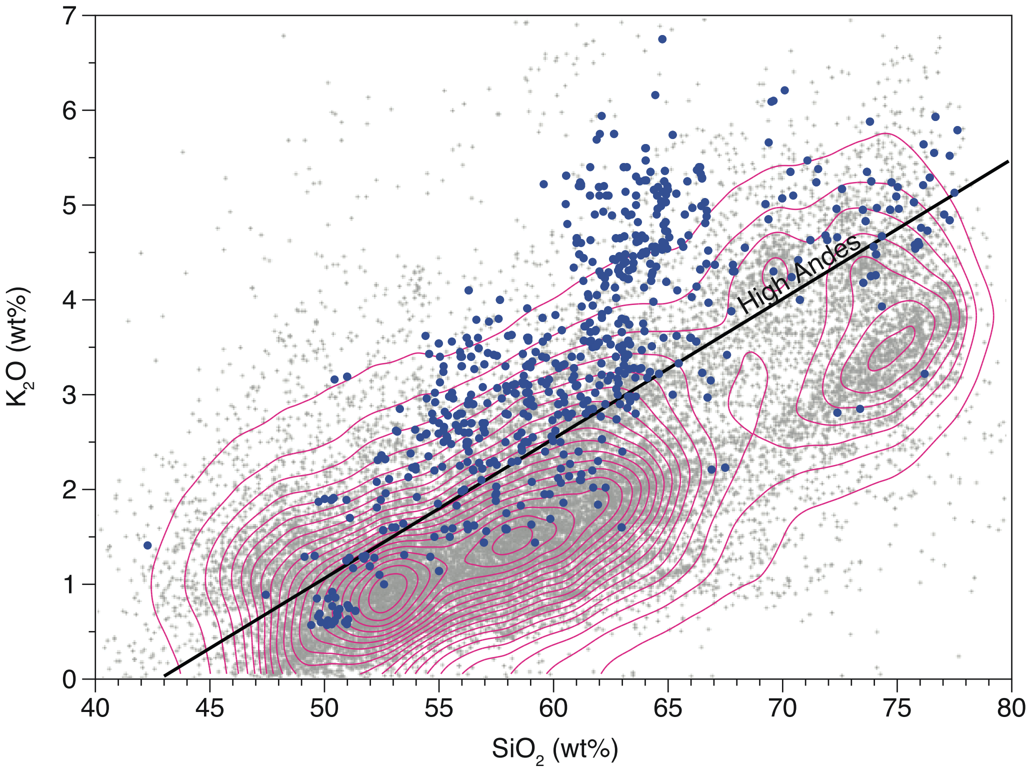

Figure 3. Sierra Nevada (Sonora Pass–Bodie) middle and late Miocene volcanic rocks inferred to be the ancestral Cascade arc (e.g., John et al., 2012) compared to Pacific Rim arc rocks. Although some of the rocks in this region fall on the arc trend, most follow a divergent trend to very high K_2O that is unlike the pattern seen in arcs. Background points are >23,000 analyses from the circum-Pacific arc data set of Glazner et al. (2015), contoured using the method from that paper. Outermost contour encloses 95% of the points. Line gives trend of high Andes built on crust >50 km thick; intermediate rocks from the Sonora Pass area have K_2O contents nearly double those of the high Andes, where the crust is locally twice as thick as Sierran crust. This calls into question the proposal that the Sierran rocks owe their high K_2O contents to excessive crustal thickness.

(2007). The Sonora Pass–Bodie rocks may owe their high K_2O contents in part to small degrees of partial melting, but this is unrelated to crustal thickness. Their compositions are quite distinct from modern arc rocks, and assigning them to an ancestral Cascade arc is problematic. Their high K_2O contents make them more similar to the Pliocene magmatism farther south that has been attributed to lithospheric delamination (Farmer et al., 2002).

Slab-Window Misconceptions

The concept of an enlarging hole in the slab, with hot asthenosphere welling up into it, is well established yet misleading. A slab window formed by ridge-trench interaction is not bounded by a thick descending slab with a steep rear boundary that leaves a deep gap in its wake into which hot mantle wells up, like water swirling around the stern of a rowboat (e.g., Hole et al., 1991; McCrory and Wilson, 2009). Rather, slabs are mechanical boundary layers with gradational lower boundaries. They thin to near-zero at ridges, where hot mantle rises into a relatively narrow zone, leading to decompression melting (Fig. 4). Maximum rates of mantle ascent under ridge axes are predicted to be near the half-spreading rate (Ligi et al., 2008), with melt scavenged from a region ~50 km wide (Spiegelman and McKenzie, 1987).

There is little evidence of slab-window magmatism east of the San Andreas fault in the data presented above, and there are several reasons why none should be expected:

1. Widening of zone of upwelling: In the box around the ridge in Figure 4B, mass balance requires that the lateral mass flux out the sides of the box must be balanced by a vertical mass flux into the bottom. The lateral flux is controlled by plate divergence and is the same in all three cross sections. Therefore, upwelling diminishes as the window widens. Pacific-Farallon spreading in the Miocene was rapid, >100 mm/yr full-spreading rate (Rowan and Rowley, 2014). Thus, by 1 m.y. after ridge-trench encounter, at a given point, the width of the zone of upwelling has roughly tripled or quadrupled (Fig. 4D), requiring that average vertical lift must have been reduced by the same factor, thus greatly attenuating any melting.
2. Increasing melting temperature: The solidus temperature of anhydrous peridotite increases ~3.5 °C/km (e.g., Takahashi et al., 1993). Thus, as the widening window sinks with the subducted plate, the pro-melting effect of lift owing to plate divergence (which is increasingly weak-

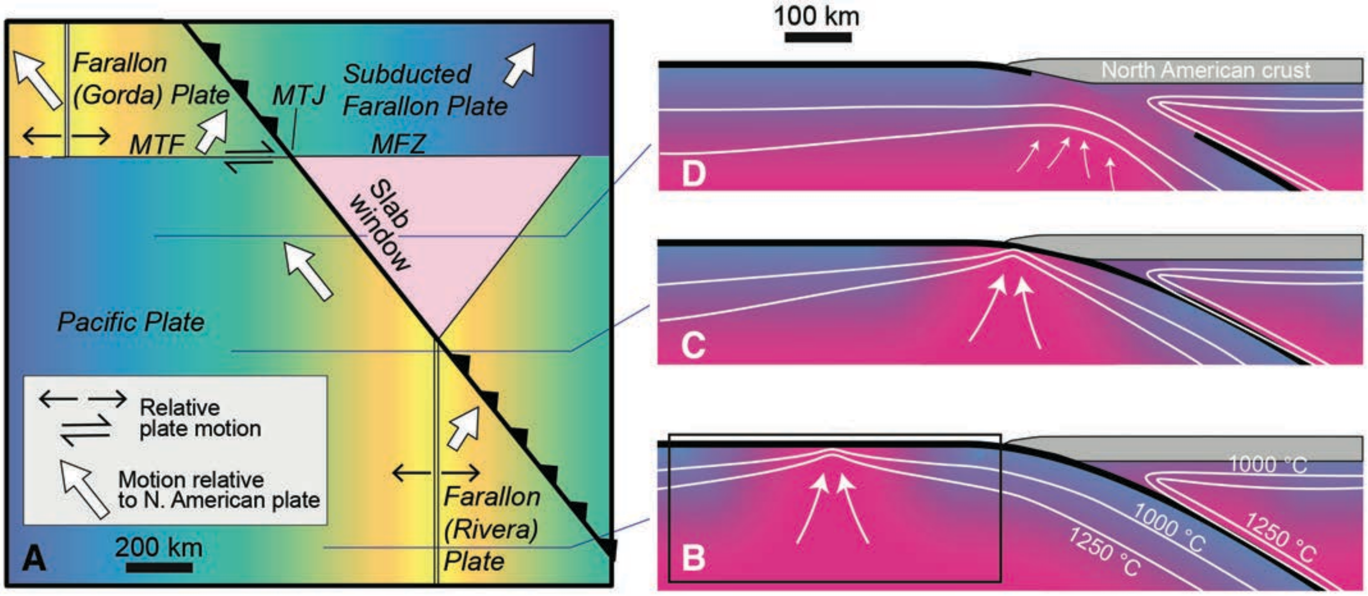

Figure 4. Hypothetical plate interactions around the developing slab window. Oceanic crust and continental crust in B–D are shown as black and gray, respectively; the bases of the various lithospheric slabs are ill-defined gradational boundaries, not sharp rheologic breaks. (A) Schematic view of Pacific-Farallon interactions at ca. 18 Ma, ~10 m.y. after formation of the Mendocino triple junction. North American plate (above subducted Farallon plate and slab window) is not shown, and dip of the subducted slab in A is ignored. At this time, a slab window should have formed and underlain much of southern California and the Mojave Desert. South-to-north evolution shown in three cross sections on the right is also an older-to-younger time progression. (B) Prior to ridge-trench meeting. At a spreading ridge, the material flux coming into the bottom of the box must balance that going out the sides. Relatively narrow zone of upwelling under the ridge lifts isotherms, causing decompression melting. Note that lithospheric plates have no sharp borders but are instead gradational mechanical and thermal boundary layers. (C) At the time of ridge-trench meeting. Material fluxes are the same, disregarding bending of slab. (D) Roughly 5 m.y. after ridge-trench meeting. Slab window is ~4 times wider than zone of upwelling at ridge in B; material fluxes are the same, and so vertical flux is spread out, and mantle lift is attenuated by the same factor. Combined with increasing pressure owing to sinking, this should rapidly shut off any tendency to melt. MTF, MTJ, MFZ—Mendocino transform fault, triple junction, and fracture zone.

ening) is counterbalanced by the increasing solidus temperature (Fig. 5). In Figure 4D, even with a shallow plate dip, the site of the former ridge is ~50–100 km deep, with a solidus rise of ~150–200 °C.

3. Removal of cold material: Subduction zones are anomalously cold regions in the mantle where surficial material at 0 °C sinks into much hotter rock. They refrigerate the hanging wall significantly, allowing blueschist-facies metamorphism to develop (Ernst, 1973). In slab windows, this cold material is absent. Removing a flat slab would be less akin to applying a blowtorch to the overlying plate (DeLong et al., 1979) than to removing an ice block from it.
4. Fallacy of through-the-slab upwelling: Slab windows are commonly depicted as gaps in a thick, solid slab through which hot asthenosphere pours like soldiers breaking through a defensive line (McCrory and Wilson, 2009; Ghiglione et al., 2016; Zheng et al., 2018). However, mantle rising into a gap in the slab cannot invade the overlying mantle simply because that space is already occupied.

Most of these arguments also apply to postulated slab-break-off magmatism (e.g., von Blanckenburg and Davies, 1995), but even more strongly because the lithosphere being subducted is not ridge or near-ridge lithosphere, and hence is significantly cooler. Given these effects, it is not surprising that there is little evidence for slab-window volcanism in the geologic record of southwestern North America. Volcanism near the plate boundary, however, where the effects listed above are minimal, is probably linked to ridge-trench interaction there and around the Pacific Rim (e.g., Weigand et al., 2002; Dickinson, 2006; Cole et al., 2006; Breitsprecher and Thorkelson, 2009).

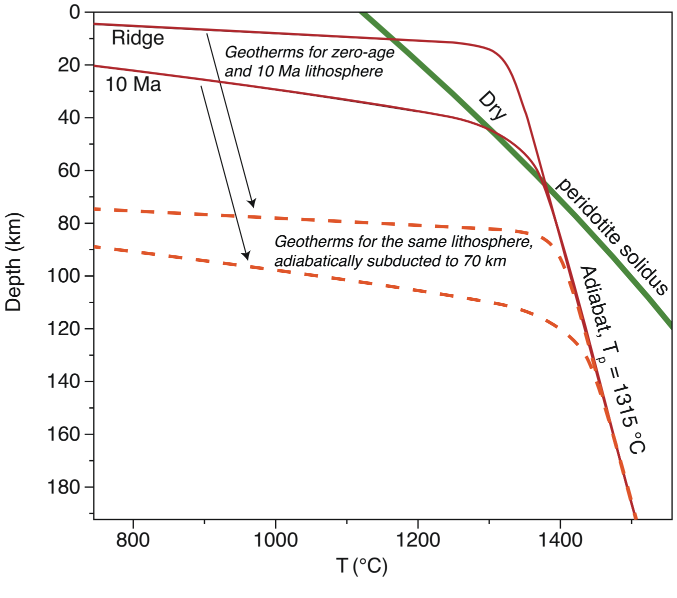

Figure 5. Illustration of the effect of subduction on geotherms and melting. Lithospheric geotherms for a ridge axis (Ligi et al., 2008) and 10 Ma oceanic crust (McKenzie et al., 2005) are connected schematically (melting ignored) to a mantle adiabat with potential temperature of 1315 °C (McKenzie et al., 2005). Subduction of either of these columns, here to 70 km (Fig. 4; Benoit et al., 2002), pushes them back down the adiabat to the positions marked by dashed lines, which are a significant distance below the solidus of peridotite (Hirschmann, 2000). Coupled with diminishing lift in a widening slab window, little or no melting is expected.

Problems with the Andes Analogy

The Andes are commonly taken as a modern analogue for Cretaceous–Holocene magmatism and tectonics in western North America. However, there are several important ways in which these two provinces differ (Fig. 6):

1. After restoration of Cenozoic extension, the southern Rocky Mountain and Mogollon-Datil fields reached as far inland as ~1200 km from the continental margin, whereas the most inboard Cenozoic magmatism in the Andes is about half this distance.
2. Sections of the Andean arc with flat Wadati-Benioff zones lack active arcs, rather than having them in far-inboard positions.
3. Although there are weak inland migrations of magmatism that have been ascribed to flattening of the slab, the active arc segments north and south of the Pampean flat-slab region reach significantly farther inland, as do belts of Cenozoic igneous rocks (Fig. 6). Thus, development of the flat slab did not push arc magmatism inland.
4. There are no analogues in the Andes for copious magmatism produced during far-inboard, followed by outboard, sweeps of magmatism.
5. There are no belts of calc-alkaline magmatism that extend inland for hundreds of kilometers at a high angle to the plate boundary.

What Are the Links between Magmatism and Plate Tectonics in Western North America?

Some of the classic ideas about the links between magmatism and plate tectonics in western North America can be ruled out on solid geologic evidence (e.g., ancestral Cascades south of Yosemite National Park). Others (e.g., copious slab-window magmatism) seem to violate what is known about the physics of melt generation at oceanic spreading centers. Space-time patterns of magmatism contradict many of the classic ideas, such as a return sweep of magmatism or progressive northward extinction of an ancestral Cascade arc. The patterns attributed to slab foundering (e.g., ignimbrite flareup and various local migrations) are not impossible, but they are ad hoc and untestable, and it is difficult to find modern examples.

So what controlled the space-time patterns of magmatism in western North America? Can we come up with new, testable

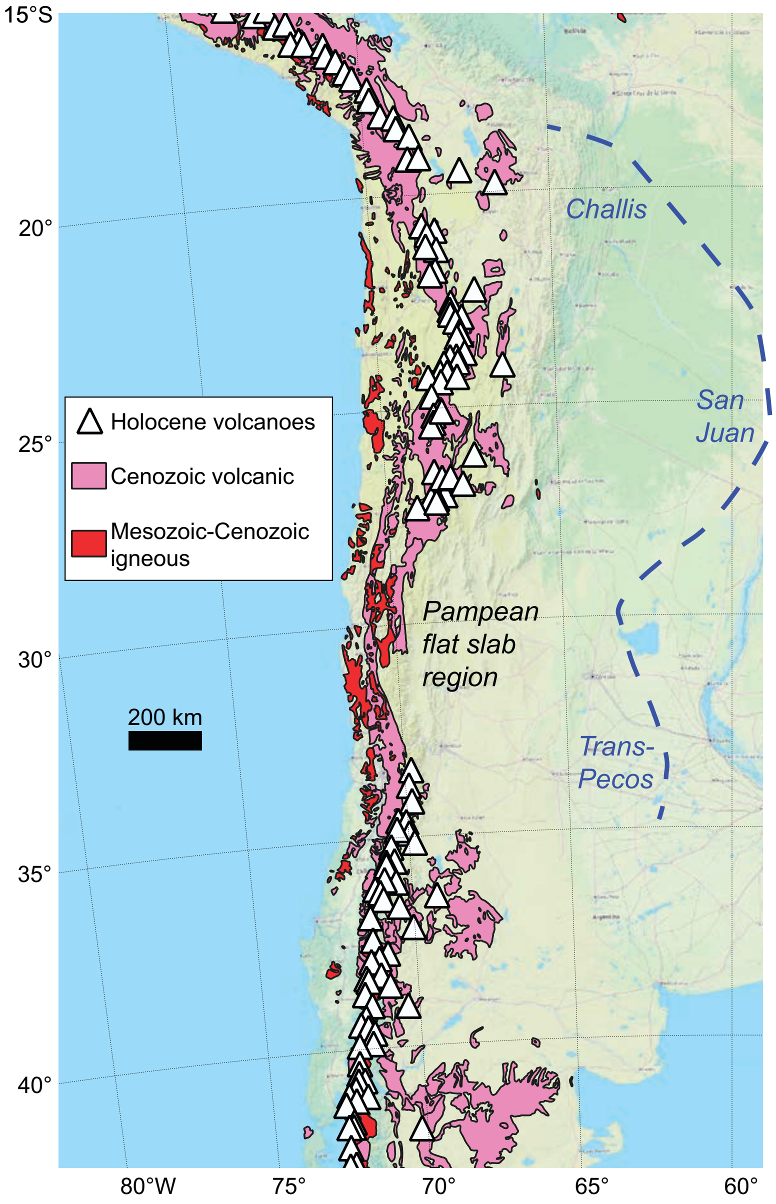

Figure 6. Distribution of Cenozoic volcanic rocks and Mesozoic–Cenozoic igneous (chiefly plutonic) rocks in the central Andes. Both Holocene volcanoes and Cenozoic volcanic rocks extend 200–300 km farther inland in the active arc segments north and south of the flat-slab region than in the region itself; thus, establishment of the flat slab was not accompanied by an inland sweep of magmatism. Dashed line gives the approximate corresponding inland extent of Cenozoic magmatism in the western United States after restoration of extension, from 36 Ma reconstruction of McQuarrie and Oskin (2010), scaled and aligned with plate boundary. Challis, San Juan, and Trans-Pecos refer to the relative positions of those volcanic fields. The Andean magmatic arc is a poor analogy for explaining the spatial patterns of Cenozoic magmatism in western North America.

hypotheses? Alas, none is on offer here, but the following items may play roles.

A key point, made many times (e.g., Smith, 1995; Humphreys et al., 2003) is that if shallow subduction persisted for tens of millions of years under western North America in the latest Cretaceous and early Cenozoic, then it is likely that the subcontinental lithosphere was metasomatized by fluids released by the subducted slab, but it was too cool to generate significant magma. Such fluids would have imparted a subduction-like geochemical flavor to the mantle, leaving it relatively enriched in fluid-mobile elements (e.g., Rb, Ba, Pb), depleted in high field strength elements (e.g., Ta, Ti), hydrated, and primed to produce magmas with the geochemical characteristics of arc magmas, even though they might have been erupted well after subduction ceased in a given area. This arc-like character was widespread across western North America until basalts with the geochemical characteristics of ocean-island basalts were erupted across the area in the last 5–10 m.y.

Consistent patterns that could be related to slab rollback as discussed above are not apparent in the data of Figure 1. However, slab foundering by separation of abnormally cool, dense lithosphere would expose the hydrated subcontinental lithosphere to hotter mantle, driving magmatism (Farmer et al., 2008). Perhaps the spacing of the giant ignimbrite fields is related to the geodynamics of such a process.

The huge scale of the Mendocino fracture could have played a role in triggering and localizing magmatism. Before 28 Ma, the Mendocino transform fault separated the Pacific-Farallon ridge by ~1000 km, with Pacific lithosphere on the south side being ~30 m.y. younger than Farallon lithosphere on the south side. This age difference means that lithosphere on the south side was significantly hotter and topographically higher than that on the north, a difference that may have produced noticeable topographic and sedimentologic effects in southern California (Glazner and Loomis, 1984; Glazner and Schubert, 1985)—and also correlated in time with the anti-ancestral Cascade burst of magmatism (Glazner and Supplee, 1982; Fig. 2). No fracture zone currently being subducted has remotely comparable offset.

The closest modern analogue to the Mendocino fracture zone today is the Romanche fracture zone in the Atlantic Ocean, with ~900 km separation. Abutment of the spreading ridge on one side of the Romanche fracture zone with much cooler lithosphere on the other suppresses basalt production, and it is likely that this cold ridge-transform intersection produces a section of heavily serpentinized peridotite several kilometers thick (Bonatti et al., 1996), representing a huge reservoir of water, given that serpentine contains 13 wt% H_2O. The Pacific-Farallon ridge spread much faster than the Mid-Atlantic Ridge, so this analogy may not be directly applicable, but if the Mendocino system produced a great deal of serpentinized peridotite, its subduction would have introduced a huge amount of water into the mantle.

The coincidence in time and space between the inferred position of the subducted Mendocino fracture zone (Fig. 1) and propagating magmatism of the Arizona trend suggests that the two were related, and perhaps intense serpentinization along the fracture zone was the link. Serpentine-rich rocks are highly enriched in several fluid-soluble elements (e.g., Sb, As, Pb; Hattori and Guillot, 2003), and it is possible that an abnormally serpentine-rich source region could be detected geochemically. Currently, the number of high-quality analyses of these elements in Cenozoic rocks from western North America is small. Small-scale convection induced by the significant difference in lithospheric thickness across the subducted Mendocino fracture zone (King and Anderson, 1998) could have aided magma generation.

SUMMARY

Some of the first attempts to explain continental magmatism with plate tectonics were made in western North America in the 1970s. This is perhaps unfortunate, because Cenozoic magmatism in western North America was confoundingly unlike anything seen on Earth today. The largely deductive analyses of the 1970s were cemented into place long ago and have rarely been questioned. When tested against observed space-time patterns, the hypotheses of an inboard-outboard sweep of magmatism, an ancestral Cascade arc, and slab-window magmatism fail. Slab rollback is unfalsifiable because it can be applied to any Cenozoic magmatic outbreak in western North America.

Warren Hamilton, in his acceptance speech for the Geological Society of America Structural Geology and Tectonics Division Career Contribution Award in 2007, stated, "A red flag for failed conjecture is special pleading to excuse each misfit of data to predictions…." In western North America, the failure of the dominant paradigm to account for space-time patterns of magmatism is explained by devices such as slab tears, tortuous patterns of slab rollback, bandage-ripping, and the like, or by invoking normal crustal thickness to explain abnormal rock compositions, or by assuming the existence of things that are required by the hypothesis, such as a continuous Oligocene–Miocene arc down the length of California, in spite of evidence to the contrary.

It is difficult to see how the plate-circuit reconstructions of Atwater and Stock (1998) can be in serious error, especially for the last few tens of millions of years, and yet the magmatic patterns that have been predicted from those reconstructions are not apparent. It is time to cast aside the current framework, entertain alternative ideas (e.g., Maxson and Tikoff, 1996; Hildebrand, 2009; Roy et al., 2009; Jones et al., 2011; Sigloch and Mihalynuk, 2013), come up with new ones, and reexamine how magmatism and plate tectonics in western North America interacted. Indeed, it is time to renew investigations into just how magmas are generated in arc settings and how arc-like magmas are generated in non-arc settings, such as the magmatism that followed in the wake of the Mendocino triple junction.

The Andes make a less-than-perfect analogy for western North America in the Cenozoic. The Trans-Mexican volcanic belt (Ferrari et al., 2012) is likely a better analogy.

As is commonly said, whatever did happen, can happen. Cenozoic magmatism in western North America definitely happened, but probably not in the way that has come to dominate thinking. Fresh, testable ideas are needed.

ACKNOWLEDGMENTS

This paper summarizes things that have bothered me since my undergraduate days at Pomona College when I was a novice plate tectonician. I will single out, in no particular order, just a handful of the many people who have made my brain hurt discussing these topics: Warren Hamilton, Steve Reynolds, Peter Lipman, Tanya Atwater, John Bartley, Doug Walker, Craig Jones, Ray Ingersoll, Derek Thorkelson, Myron Best, Lang Farmer, Basil Tikoff, Allen Stork, Luca Ferrari, and Bob Hildebrand. Many would disagree with the content of this paper, but their scientific work and willingness to think have been invaluable. The paper benefited greatly from thoughtful and thorough reviews by Edgardo Cañón-Tapia, Craig Jones, and an anonymous reviewer. Most of all, I credit my undergraduate mentor Donald McIntyre and my fellow Bruin Warren Hamilton for inculcating a healthy skepticism of whatever follows the phrase "But we know that…"

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Manuscript Accepted by the Society 15 April 2021
Manuscript Published Online 20 January 2022