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Birth of a plate boundary at ca. 12 Ma in the Ancestral Cascades arc, Walker Lane belt of California and Nevada

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ABSTRACT

The Walker Lane belt of eastern California and western Nevada is the northernmost extension of the Gulf of California transtensional rift, where the process of continental rupture has not yet been completed, and rift initiation can be studied on land. GPS and earthquake focal mechanism studies demonstrate that the Walker Lane belt currently accommodates NW–SE–directed movement between the Sierra Nevada microplate and the North American plate, but the timing and nature of rift initiation remains unclear. I present a model for plate-margin-scale initiation of the Gulf of California and Walker Lane transtensional rifts at ca. 12 Ma; localization of rifting in both was initiated by thermal weakening in the axis of a subduction-related arc undergoing extension due to slab rollback, and thermal weakening in the arc was enhanced by stalling of the trenchward-migrating precursor arc against a thick Cretaceous batholithic lithospheric profile on its western margin. Rifting succeeded very quickly in the Gulf of California, due to stalling of Farallon slabs, but the Walker Lane transtensional rift has been unzipping northward along the axis of the Cascades arc, following the Mendocino triple junction. I infer that plate-margin-scale Walker Lane transtension was signaled by the development of an unusually large and voluminous transtensional arc volcanic center, the ca. 11.5–9 Ma Sierra Crest–Little Walker arc volcanic center. I show that the style of faulting in this large Miocene arc volcanic center closely matches that of Quaternary transtensional structures in the central Walker Lane, where it lies, and that it differs from southern and northern Walker Lane structures. This indicates that the temporal transition from E–W Basin and Range extension to NW–SE Walker Lane transtension occurred earlier than most workers have inferred. I also summarize new data which show that the central

Sierra Nevada range front (from Long Valley to the Tahoe Basin) lies squarely within the Walker Lane belt, not to the west of it as previous workers have inferred.

The leading tip of Walker Lane transtension is marked by large arc volcanic centers sited in transtensional stepovers; these include the ca. 11.5–9 Ma Sierra Crest–Little Walker volcanic center; north of that, the ca. 6.3–4.8 Ma Ebbetts Pass volcanic center; and north of that, the active Lassen volcanic center. In its wake, large rift volcanic centers are sited on transtensional stepovers or bends; these include the Long Valley and Coso volcanic fields. I predict that any <12 Ma large volcanic centers identified by future workers in the Sierra Nevada–Walker Lane region, or in the Gulf of California, will prove to be sited at major releasing bends or stepovers.

INTRODUCTION

The Sierra Nevada–Walker Lane region (Fig. 1) is an archetype for early rupturing of continental lithosphere (Busby and Putirka, 2009; Putirka and Busby, 2007, 2011; Busby, 2011, 2012; Busby et al., 2010, 2013a, 2013b). This region has been described as the northernmost extension of the Gulf of California rift, where the process of continental rupture has not yet been completed, and rift initiation can be studied on land (Faulds and Henry, 2008; Jayko and Bursik, 2012; Busby, 2012). Extensive Cenozoic volcanic and sedimentary rocks, excellent exposure, and abundant previous geological mapping in the Walker Lane make it an excellent region in which to study rifting processes (e.g., Fig. 2; Henry and Perkins, 2001; Trexler et al., 2012; Putirka and Busby, 2007; Busby et al., 2008a, 2008b; Faulds and Henry, 2008; Busby and Putirka, 2009; Cashman et al., 2009, 2012; Jayko, 2009a, 2009b; Norton, 2011; Cousens et al., 2012; Jayko and Bursik, 2012; Putirka and Platt, 2012; Putirka et al., 2012; Riley et al., 2012; Trexler et al., 2012; Wakabayashi, 2013).

The Sierra Nevada frontal fault system was previously interpreted to accommodate Basin and Range extension (Bateman and Wahrhaftig, 1966; Surpless et al., 2002), but recent GPS and earthquake focal mechanism studies have shown that the faults currently accommodate NW–SE–directed movement between the Sierra Nevada microplate and the North American plate (shown on Fig. 3; Sonder and Jones, 1999; Unruh et al., 2003). The question is, when did NW–SE Walker Lane transtension replace E–W Basin and Range extension, i.e., when were the Sierra Nevada microplate and the future Pacific–North American plate boundary born? What are the geologic signals of the onset of transtensional rifting?

In two companion papers (Busby et al., 2013a, 2013b), I and others presented and interpreted detailed geologic maps of a large ca. 11.5–9 Ma arc volcanic center, which we named the Sierra Crest–Little Walker volcanic center (location on Fig. 1). In those papers, we showed in detail for the first time that transtensional rift faults occur along the central Sierra Nevada range front and range crest in the Sonora Pass region, and that these were active during Ancestral Cascades arc volcanism. This faulting triggered unusually voluminous high-K intermediate volcanism (Putirka and Busby, 2007), deposits of which are referred to as the Stanislaus Group. “Flood andesite” lavas erupted from fault-controlled fissures within a series of grabens that we called the Sierra Crest graben-vent system (Fig. 2; Busby et al., 2013a). The Sierra Crest graben-vent system consists of a single ~27-km-long, ~8–10-km-wide ~N–S full graben that lies along the modern Sierran crest between Sonora Pass and Ebbetts Pass, with a series of ~N–S half-grabens on its western margin, and a ~25-km-wide NE transfer zone emanating from the northeastern boundary of the full graben on the modern range front (Fig. 2). We showed for the first time that at least some N–S normal faults are dextral oblique, and that there are abundant NE-striking oblique sinistral-normal faults (Busby et al., 2013a). In a second paper (Busby et al., 2013b), we showed

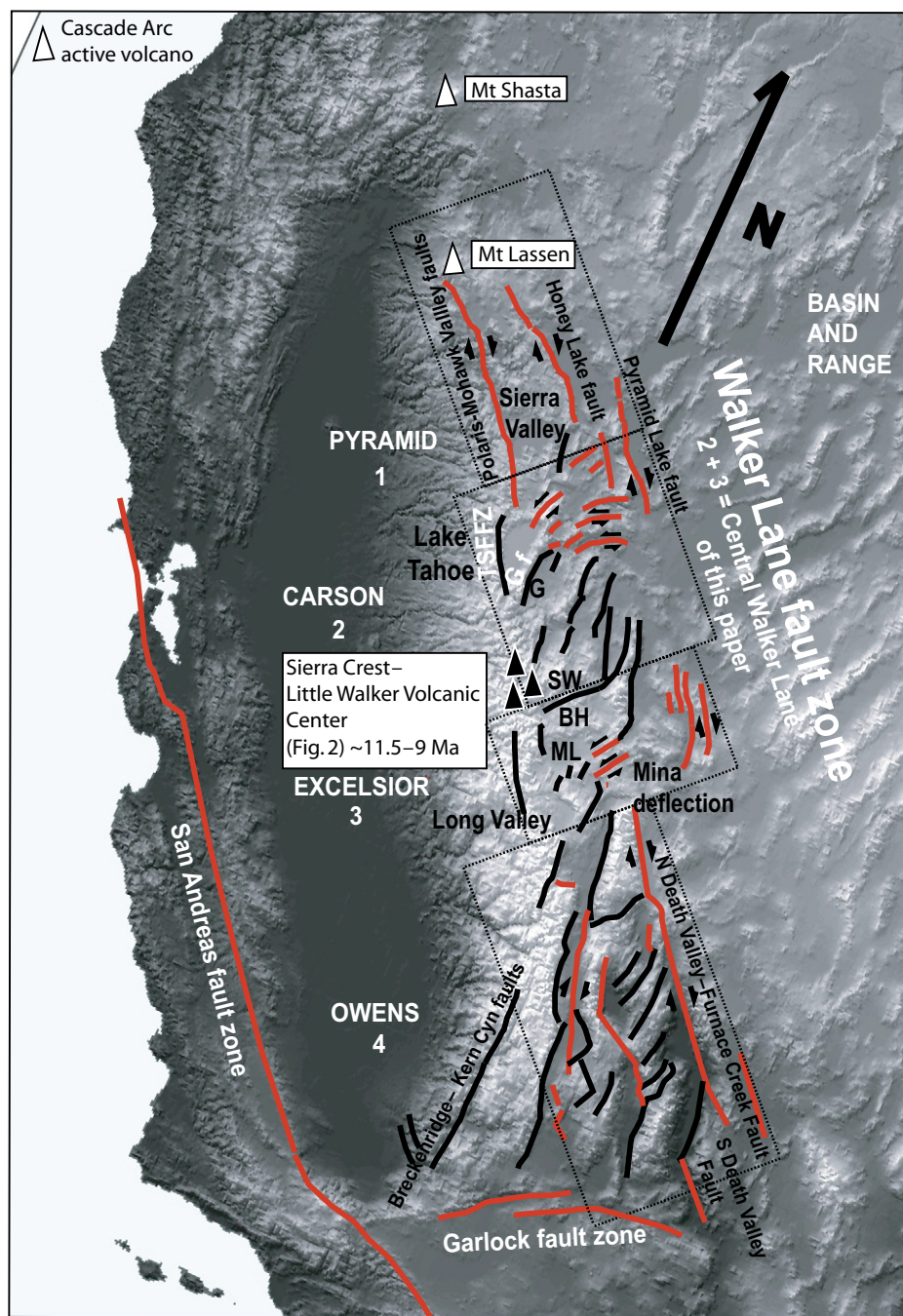
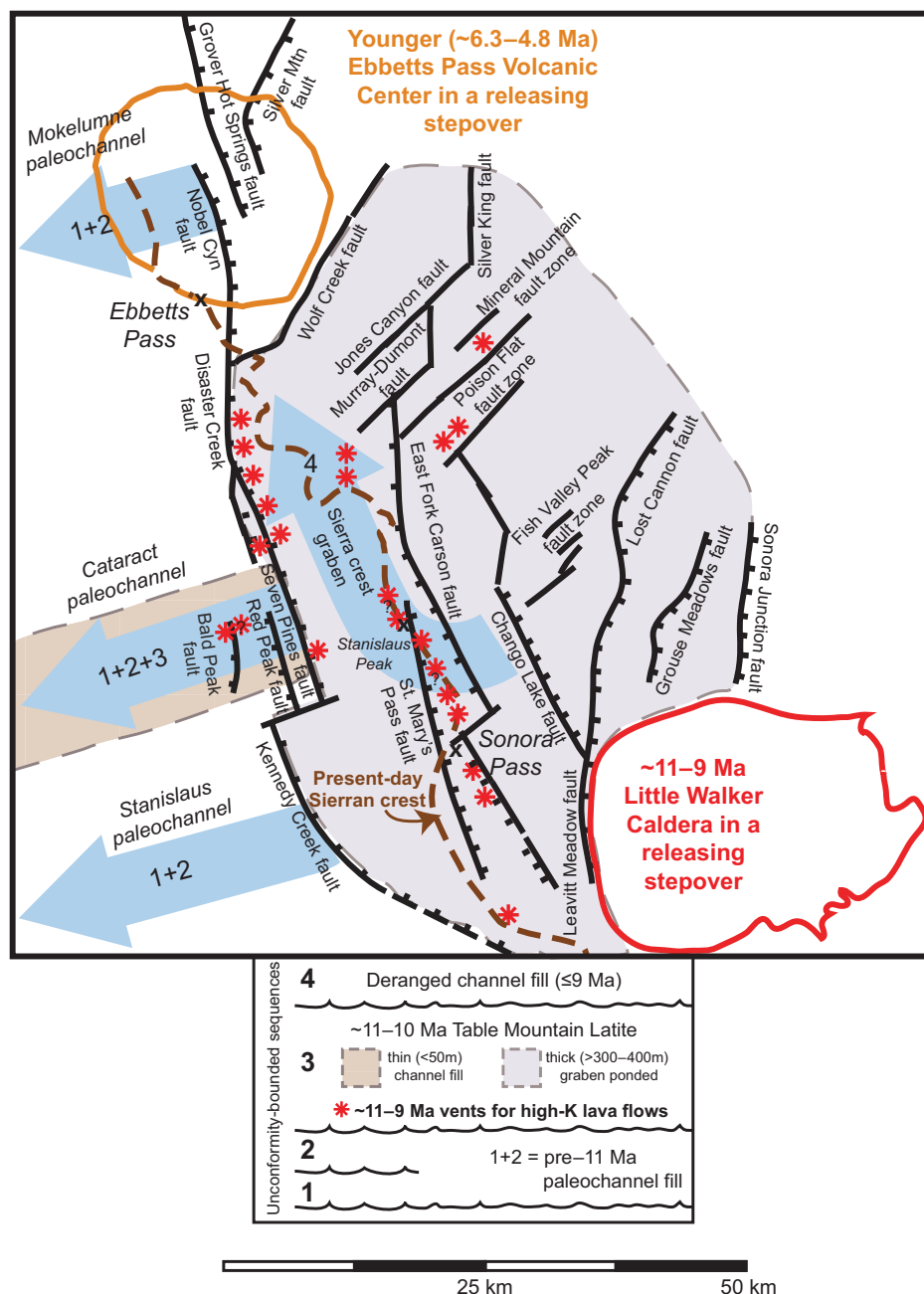


Figure 1. Simplified map showing major faults of the Walker Lane (western U.S.), with San Andreas fault also shown (modified from Jayko and Bursik, 2012). Dominantly strike-slip faults are shown in red, and dominantly oblique-slip (normal) faults are shown in black. Domains 1–4 are outlined in boxes (see text), as summarized by Jayko and Bursik (2012). The Pyramid and Owens domains (at the north and south ends, respectively) are dominated by long dextral strike-slip faults (red) that parallel the microplate transport direction. In contrast, the Carson and Excelsior domains have shorter strike-slip faults and more abundant NE-striking oblique faults (e.g., Mina deflection; see Nagorsen-Rinke et al., 2013), as well as more abundant Neogene to recent volcanic rocks, including the Long Valley volcanic field. In this paper, I refer to the Carson and Excelsior domains collectively as the central Walker Lane belt; the Sierra Crest–Little Walker volcanic center (Fig. 2) lies here (shown in black filled triangles). BH—Bodie Hills; G—Gardnerville Basin; Gf—Genoa fault; ML—Mono Lake; SW—Sweetwater Mountains; TSFFZ—Tahoe-Sierra frontal fault zone.

that at least half of the slip on down-to-the-west normal faults on the Sierra Nevada range front at Sonora Pass (in the lavender-shaded area lacking vents in Fig. 2) occurred during the ca. 11.5–9 Ma volcanism, and that synvolcanic throw on those faults increased southward toward the Little Walker caldera. This supports the interpretation of Putirka and Busby (2007) that the range-front faults formed a releasing right step that controlled the siting of the Little Walker caldera; however, Putirka and Busby (2007) did not realize that the right-stepping fault system on the range front at Sonora Pass forms only a small part (about a fourth) of a much larger structural stepover (the NE transfer zone shown on Fig. 2, and described in detail by Busby et al. [2013a, 2013b]). We concluded that the Sierra Crest graben-vent system and the Little Walker caldera together formed an unusually large transtensional volcanic field in the heart of the Ancestral Cascades arc, at ca. 11.5–9 Ma (Busby et al., 2013a, 2013b).

In this paper, I provide a summary of the transition from extensional arc (ca. 50–12 Ma; Fig. 3A) to transtensional arc and rift (ca. 12 Ma to present; Fig. 3B) in the southwest U.S. I also show that the style and timing of ca. 11.5–9 Ma synvolcanic faulting in the central Sierra Nevada is consistent with the interpretation that the arc volcanic field formed under a Walker Lane transtensional rift regime. I do these by first providing a general description of the Walker Lane belt, discussing its variation from domain to domain, in order to demonstrate that the central Sierran structures we have mapped (Fig. 2) closely match those of the domain in which it lies (Fig. 1). I then explore the plate-margin-scale setting of the Sierra Crest–Little Walker transtensional arc volcanic center, and present a new model, wherein: (1) transtensional rifting was initially focused in thermally weakened, partially extended crust of the Ancestral Cascades arc (Fig. 3A), producing an unusually large volcanic center at a releasing stepover (the Sierra Crest–Little Walker center; Fig. 2); (2) the rift tip then migrated northward, in concert with the Mendocino triple junction, to form the previously unrecognized Ebbetts Pass transtensional arc volcanic center at ca. 6.3–4.8 Ma (Fig. 2); and (3) the contemporary tectonic setting of the rift tip is the same, at the south end of the contemporary Cascades arc at the Lassen arc volcanic center. Meanwhile, rift volcanic centers have formed at releasing bends or stepovers in its wake (e.g., Long Valley and Coso volcanic centers; Fig. 3B). This model predicts that any large, <12 Ma arc or rift volcanic centers identified by future workers in the Sierra Nevada–Walker Lane region will be sited at major releasing bends or stepovers.

Figure 2. Generalized geology of the ca. 11.5–9 Ma Sierra Crest–Little Walker volcanic center (for location, see Fig. 1). Effusive rocks were vented from an area covering at least 250 km², and explosive rocks were mainly vented from the Little Walker caldera (Busby et al., 2013a, 2013b). In the area shaded in lavender on this diagram, synvolcanic transtensional faulting ponded high-K effusive volcanic rocks to thicknesses of 400 m. Vents (red stars) occur mainly as fault-controlled fissures, with minor fault-controlled point sources. These vents lie in the NNW-SSE Sierra Crest full graben, in smaller NNW-SSE half-grabens on the west side of the Sierra Crest graben, and in NE-SW transfer zone faults and basins along the northeast side of the Sierra Crest graben. The NNW-striking faults are normal faults with a dextral component of slip, while the NE-striking faults are sinistral-oblique normal faults (Busby et al., 2013a, 2013b). Note the position of the modern Sierra Nevada range crest (brown dashes); most fault reactivation since 9 Ma has occurred to the east of the crest, on the modern range front, but at least half of the range-front faulting occurred during development of the Sierra Crest–Little Walker volcanic center, and displacement increases southward toward the Little Walker caldera (Busby et al., 2013b). The scale and structural style of the Sierra Crest–Little Walker volcanic center is very similar to that of the Quaternary Long Valley center, and in both cases, the calderas formed at releasing stepovers (see Busby et al., 2013b, their figure 10); however, the Sierra Crest–Little Walker transtensional volcanic center formed within the Ancestral Cascades arc (north of the Mendocino triple junction), while the Long Valley transtensional volcanic center is a rift volcanic field (i.e., it formed south of the Mendocino triple junction; Fig. 3B). After formation of the Sierra Crest–Little Walker arc transtensional rift center, the rift tip propagated northward, following the Mendocino triple junction, to form a younger, newly recognized intra-arc Walker Lane pull-apart basin we call the Ebbetts Pass volcanic center (Busby et al., 2013c), shown here. This formed at a series of right-stepping N-S dextral-oblique down-to-the-east normal faults on the modern Sierra crest and range front (Nobel Canyon, Grover Hot Springs, and Silver Mountain faults shown here). For a description of the stratigraphic sequences and the Nevadaplano paleochannels shown on this diagram (Mokelumne, Cataract, and Stanislaus), and their derangement by the intra-arc Walker Lane faults shown here, see Busby et al. (2013a, 2013b).



WALKER LANE STRUCTURES

In this section, I briefly describe structures of the Walker Lane belt (Fig. 1), in order to show how the synvolcanic faults we have mapped on the central Sierra Nevada range crest and range front (Busby et al., 2013a, 2013b) are similar to

those in other parts of the central Walker Lane belt, and different from those of the Basin and Range province, in order to demonstrate that the Walker Lane belt extends to the central Sierran crest. I also discuss the evidence for timing of onset of transtension in the Walker Lane belt, in order to show that onset of transtension by ca.

12 Ma in the central Sierra is not inconsistent with regional data, although it is earlier than previously inferred by most workers. The onset of transtensional rifting at ca. 12 Ma is consistent with the reconstructions of Snow and Wernicke (2000) and McQuarrie and Wernicke (2005); they show ~E-W Basin and Range extension at

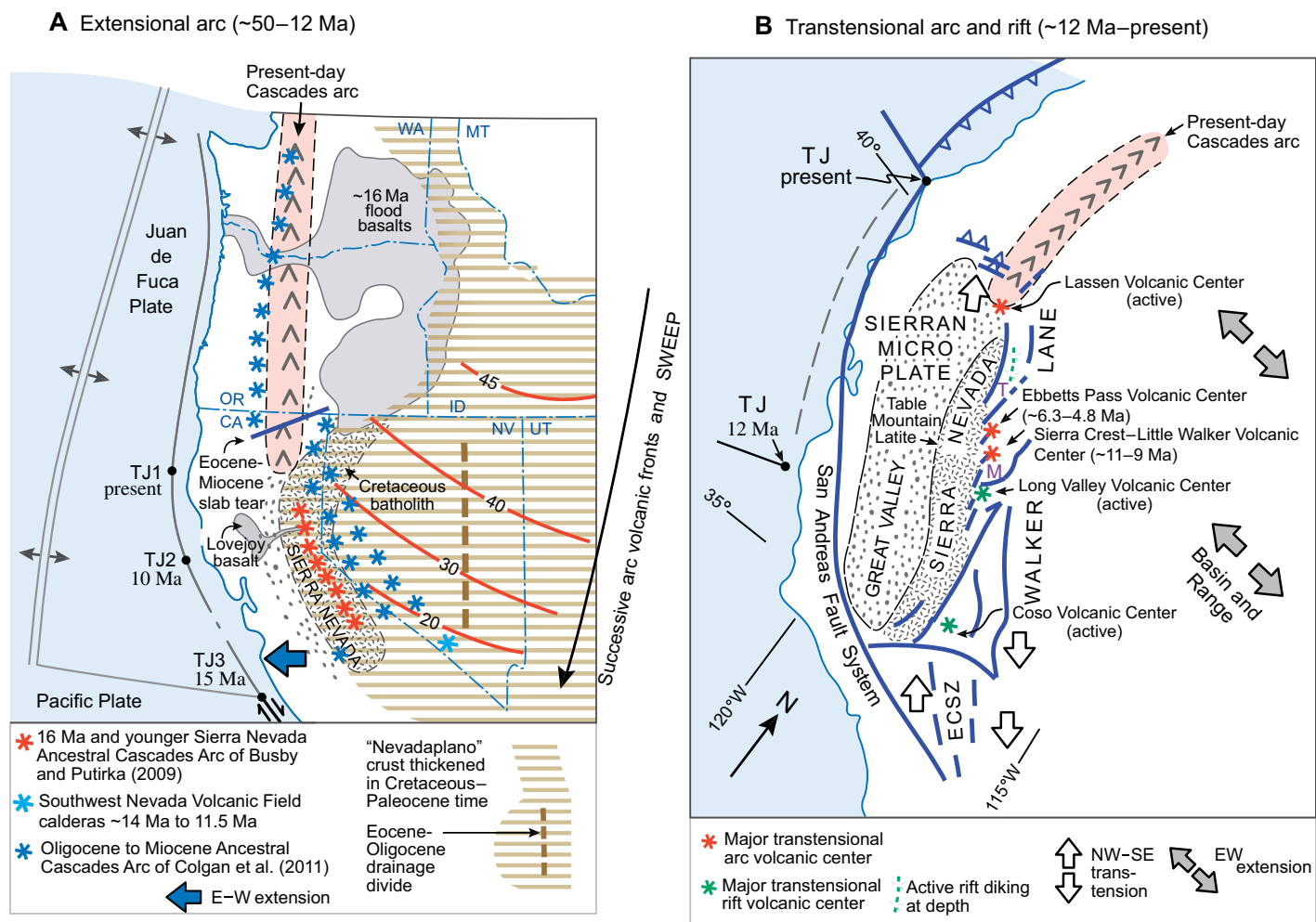


Figure 3. (A) Regional tectonic setting of the Eocene to Miocene extensional arc, which became exploited by the Walker Lane transtensional rift at ca. 12 Ma (SWEEP—southward encroachment of an Eocene plateau [correlated volcanic fronts, in red, labeled in Ma (Dickinson, 2006)]; CA—California; ID—Idaho; MT—Montana; NV—Nevada; OR—Oregon; UT—Utah; WA—Washington). (B) 12 Ma to recent transtensional arc and rift volcanism along the trailing edge of the Sierra Nevada microplate, shown in oblique projection of the western Cordillera about the preferred Sierra Nevada–North American Euler pole (following the perspective of Unruh et al., 2003) (ECSZ—Eastern California shear zone; T—position of Lake Tahoe; M—position of the Mina deflection [see Fig. 1]). Stipple pattern on A shows the Cretaceous batholith, which forms a relatively rigid crustal block; stipple pattern on B represents the present-day region of largely unfaulted Sierra Nevada block; note that from Lake Tahoe northward, the “stable” Sierra Nevada block is collapsing eastward into the Walker Lane belt (see text for references). Active dike swarms at depth north of Lake Tahoe (shown on B) are associated with an interpreted rift system (Smith et al., 2004, 2012; see text). The seafloor reconstruction in A is shown at 15 Ma, in order to represent the position of the Mendocino triple junction (TJ3, between the San Andreas fault, the Cascadia subduction zone, and the Mendocino fracture zone) around the time of arrival of the Ancestral Cascades arc in the Sierra Nevada at 16 Ma; the positions of the triple junction at 10 Ma (TJ2) and present (TJ1) are also shown (Dickinson, 1997; Atwater and Stock, 1998).

ca. 25–15 Ma, followed by the inland jump at 10–12 Ma of a significant portion of the right-lateral shear associated with the growing Pacific and North American transform. However, as summarized by Faulds and Henry (2008), some workers have estimated that strike-slip faulting began in the central Walker Lane as early as ca. 25 Ma (e.g., Dilles and Gans, 1995), while in most areas, the timing of onset of strike-slip faulting is constrained at somewhere between

ca. 13 and 3 Ma. For example, the onset of strike slip on the Stateline fault on the California–Nevada border is post–13 Ma (Guest et al., 2007); the Death Valley fault is post–8 Ma (Greene, 1997) or post–3 Ma (Norton, 2011); and the Panamint fault is post–4 Ma (Burchfiel et al., 1987). In this section, I summarize evidence to support the interpretation that Walker Lane transtensional rifting became a plate-margin-scale phenomenon at ca. 12 Ma, at the same

time as the onset of transtensional rifting in the Gulf of California.

Use of the term “Walker Lane belt” has varied (e.g., see Bennett et al., 2003, their figure 1B). Some workers included all faults north of the Garlock fault (Fig. 1) in the Walker Lane belt, and faults south of that (in the Mojave Desert region) in the Eastern California shear zone (e.g., Stewart, 1988; Faulds and Henry, 2008; Jayko and Bursik, 2012). Other workers (e.g., Oldow

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et al., 2008; Riley et al., 2012) extended the Eastern California shear zone northward from the Mojave Desert region to the Mina deflection (shown on Fig. 1), and began the Walker Lane belt north of that. Still other workers have included the Death Valley, Furnace Creek, and Owens Valley faults (Owens domain, Fig. 1) in the Eastern California shear zone, and began the Walker Lane north of that (see Faults and Henry, 2008, for references). In the introduction to the “Origin and Evolution of the Sierra Nevada and Walker Lane” *Geosphere* themed issue, we grouped the Walker Lane–Eastern California shear zone together as one continuous belt, with no distinct boundary; it connects southward to the San Andreas fault and the Gulf of California (see Putirka and Busby, 2011, their figure 1). We also extended the western boundary of the Walker Lane belt westward, relative to that mapped by Faults et al. (2005), Faults and Henry (2008), and Cashman et al. (2009), to coincide with the Sierra Nevada range front, including the range-front fault zone between Long Valley and Ebbetts Pass, and the Tahoe Basin (as shown on Figs. 1 and 3B; Putirka and Busby, 2011).

In addition to varying in their usage of the term “Walker Lane belt,” different workers have subdivided the belt of faults into different domains (e.g., Stewart, 1988; Faults and Henry, 2008); in this paper, I follow the domain divisions described by Jayko and Bursik (2012), shown with slight modifications on Figure 1. Not shown on Figure 1 is the “eastern Walker Lane” of Faults and Henry (2008), which lies to the east of the southern Owens domain, because the timing and style of deformation in this region is different from the system shown here (Faults and Henry, 2008; Umhoefer et al., 2010). Also not shown on Figure 1 are the faults south of the Garlock fault.

Walker Lane basins differ from Basin and Range basins in several fundamental ways. Walker Lane basins are in general bounded by dextral strike-slip and dextral-oblique normal faults that trend NW, subparallel to the kinematic direction (Faults et al., 2005; Kreemer et al., 2009; Jayko and Bursik, 2012); these lie at a high angle to the N-S to NNE-SSW basins of the Basin and Range (Fig. 1). Dextral NW-striking strike-slip faults may also occur in some of the basin axes in the Walker Lane (e.g., see Owens domain, Fig. 1; Jayko and Bursik, 2012). The Walker Lane belt also contrasts markedly with the Basin and Range by having NE- to ENE-striking basins formed by sinistral-oblique faults (e.g., Mina deflection, Fig. 1). Sinistral faults are prominent within domains that have undergone clockwise vertical-axis rotation, although the greater regional strain field is dex-

tral relative to stable North America (Jayko and Bursik, 2012). At the Coso rift volcanic center (Fig. 3B), boundaries between rotating blocks strike NE and are sinistral-oblique normal faults (Pluhar et al., 2006).

The position of the Sierra Crest–Little Walker volcanic center (Fig. 2) is shown on Figures 1 and 3B, in the context of Walker Lane structures. The Sierra Crest–Little Walker center lies on the boundary between the Carson and Excelsior domains of Figure 1; these two domains contrast markedly with domains to the north and south, and have important elements in common, so I refer to them here collectively as “central Walker Lane,” even though Faults and Henry (2008) placed the Carson domain in “northern Walker Lane.” The contrasts between central Walker Lane and the segments to the north and south will be discussed first, and then I will show how the structures at the Sierra Crest–Little Walker arc volcanic center match those of the central Walker Lane, supporting the interpretation that it formed as a Walker Lane arc volcanic field (and not a Basin and Range volcanic field).

The domains north and south of the central Walker Lane differ from the central Walker Lane in that they are dominated by long dextral strike-slip faults and subparallel basins (Fig. 1), parallel to the kinematic transport direction. The domain north of the central Walker Lane, the Pyramid domain, has a series of left-stepping en echelon right-lateral faults ranging from ~50 to 100 km in length; they have probably only been active since ca. 3.5 Ma (Faults and Henry, 2008). The domain south of the central Walker Lane, the Owens domain (Fig. 1; “southern Walker Lane” of Faults and Henry, 2008), is characterized by long, narrow graben complexes (e.g., Owens, Panamint, and Death Valleys), formed of laterally integrated oblique normal range-front faults and adjacent strike-slip faults (Jayko and Bursik, 2012). Dextral faulting began in this domain by ca. 10 Ma (cf. Faults and Henry, 2008). The west margin of the Owens domain has cut into the southern Sierra, with down-to-the-east normal faulting on the N-S Kern Canyon–Breckenridge fault zone (shown schematically in Fig. 1; Nadin and Saleeby, 2008; Saleeby et al., 2009; Brossy et al., 2012); two small down-to-the-west faults west of that (Fig. 1) include the West Breckenridge fault and the Kern Gorge fault, which were both probably active in the Miocene (Maheo et al., 2009; Saleeby and Saleeby, 2013; Saleeby et al., 2013).

The central Walker Lane of this study (Carson and Excelsior domains, Fig. 1) is quite different from the segments to the north and south of it, because normal faults are more abundant (shown in black in Fig. 1), and dextral faults are shorter (shown in red). The central Walker

Lane also has more abundant Cenozoic volcanic rocks than the segments to the south or north (see Busby et al., 2013b, their figure 1), which I suggest may reflect greater extension than in the other parts, perhaps due to a larger rift angle. For this reason, the central Walker Lane may form a more appropriate analog to the Gulf of California than the southern or northern Walker Lane, because it will probably succeed at rifting first. The abundance of dateable volcanic rocks in the central Walker Lane make it ideal for determining long-term (i.e., late Cenozoic) slip histories and vertical-axis rotations (e.g., see King et al., 2007; Farner et al., 2011; Carlson, 2012). The Sierra Crest–Little Walker arc volcanic center (Busby et al., 2013a, 2013b) lies on the western margin of the central Walker Lane, on the central Sierra Nevada range crest and range front, near the boundary between the Carson and Excelsior domains (Fig. 1). The central Sierra Nevada range front takes a series of steps westward, from Long Valley (Excelsior domain) northward up the west side of Lake Tahoe (Carson domain; Figs. 1 and 3B).

The Carson domain of the central Walker Lane is very complex (Fig. 1). The northeast part of the Carson domain has numerous ENE-striking faults with oblique sinistral-normal slip, and clockwise block rotation of up to 44°–90°, at least some of it as early as between ca. 9 and 5 Ma (Cashman and Fontaine, 2000; Faults and Henry, 2008; Kreemer et al., 2009). In contrast, the western part of the Carson domain has more abundant N-S faults and basins, including the Tahoe Basin (see Lake Tahoe, Fig. 1) as well as the smaller N-S Reno and Carson Basins to the east of it. This led Surpless (2008) to infer that strain is partitioned between dip-slip faults in the west and dextral wrench faulting in the east. Indeed, many areas within the northwest part of the Carson domain show only E-W extension (and no dextral motion); these include the following:

(1) The Pleistocene Reno–Verdi Basin northeast of Lake Tahoe, which shows evidence for E-W extension only (Cashman et al., 2012), although the style of an inferred earlier (11–10 Ma) stage of faulting is not known (Trexler et al., 2012); however, Henry and Perkins (2001) infer that both stages of deformation in that area (at ca. 12 and ca. 3 Ma) were extensional only.

(2) The Carson Range on the east side of Lake Tahoe, which lies in the footwall of an active normal fault, the Genoa fault (Fig. 1; Ramelli et al., 1999); the Gardnerville Basin (Fig. 1) on the hanging wall has been active for >7 m.y., with no evidence for dextral faulting (Cashman et al., 2009). However, since the analysis of Surpless (2008), the dextral Polaris fault of Hunter et al. (2011) has been discovered in the westernmost

part of the Carson domain (extending northward through the Pyramid domain; Fig. 1).

Although Faulds and Henry (2008) did not include the Lake Tahoe region in the Walker Lane, most authors have now modified their maps to include the Lake Tahoe region in the Walker Lane belt (e.g., compare Cashman et al. [2009, their figure 1] with Cashman et al. [2012, their figure 1]). However, the details of the structure of the Tahoe Basin remain controversial. Schweickert et al. (2004) inferred that transtension in the Tahoe Basin is partitioned between N-S normal faults and NE-striking strike-slip faults; however, they reported that the Tahoe-Sierra frontal fault zone (TSFFZ, Fig. 1) shows sinistral-normal displacement, even though it strikes NNW and steps right (as would be expected for a dextral-oblique normal fault in Walker Lane). More recently, Howle et al. (2012) used LiDAR imagery and surface dating on moraines to infer normal slip on the TSFFZ, and did not report an oblique component. However, the existence of an active Tahoe-Sierra frontal fault zone was called into question by Dingler et al. (2009) because it lacks offshore expression. Instead, they inferred that the active normal faults lie beneath the lake (West Tahoe, Stateline, and Incline Village faults), with averaged slip rates similar to those measured for the Genoa fault to the east (Gf, Fig. 1). Kent et al. (2005) inferred that the Tahoe Basin is a purely extensional basin, but formed at a releasing step between the Pyramid Lake and Mohawk Valley strike-slip faults (marked on Fig. 1). However, faults continue to be discovered using LiDAR imagery, including the Polaris fault, a strike-slip fault on the northwest side of Lake Tahoe that probably extends northward through the Mohawk Valley fault zone all the way to Mount Lassen (shown in generalized form on Fig. 1; Hunter et al., 2011). Whether or not transtensional faults are present in the Tahoe Basin, a general observation, which I will apply to the Sierra Crest–Little Walker volcanic center, is that “dextral transtension may be accommodated in large domains of the upper crust without large, through-going dextral strike slip faults, but rather by slip on complex arrays of normal and conjugate oblique-slip faults” (Schweickert et al., 2004, p. 320), in a manner envisioned by Dewey (2002).

The southwest Carson domain and northwest Excelsior domain of the central Walker Lane show clear evidence for dextral deformation, without the presence of major strike-slip faults. In the Bodie Hills (BH, Fig. 1), immediately east of the Sierra Crest–Little Walker volcanic center, the ca. 11.5–9 Ma Stanislaus Group has been rotated clockwise $\sim 10^{\circ}$ – 25° (King et al., 2007). In this same region, a rotation rate of

$1.70 \pm 0.24^{\circ}/\text{m.y.}$ determined by GPS is consistent with paleomagnetically determined rotation rates for 9.4 Ma ignimbrites that erupted out of the Sierra Crest–Little Walker volcanic center (Farner et al., 2011), suggesting that long-term (Miocene to recent) rotational rates may be the same as contemporary rates. New paleomagnetic results from the Sierra Nevada range front in the area mapped by Busby et al. (2013b) show that fault blocks of the Sierra Crest–Little Walker arc volcanic center are rotated $13.3^{\circ} \pm 7.9^{\circ}$ and $22.3^{\circ} \pm 6.2^{\circ}$ (hanging walls of the Lost Cannon and Grouse Meadows faults, respectively, shown on Fig. 2); indeed, clockwise vertical-axis rotations of 11° – 55° are reported for the entire region between the Sierra Crest–Little Walker volcanic center and Mono Lake (ML, Fig. 1), indicating that the region “should be included as an important part of the Walker Lane” (Carlson, 2012; Chad Carlson and Chris Pluhar, 2013, personal commun.).

The Excelsior domain (Fig. 1) of the central Walker Lane is a regional-scale releasing bend consisting of ENE-striking sinistral-oblique, sinistral, and normal faults (and minor NW-striking dextral faults) that include the Mina deflection (Ryall and Priestly, 1975; Oldow, 1992, 2003; Wesnousky, 2005; Faulds and Henry, 2008; Oldow et al., 2008; Jayko and Bursik, 2012). This ENE-striking zone ends eastward in a series of dextral faults (Fig. 1) referred to as the Walker Lane domain by Stewart (1988); these became active by ca. 10 Ma (Faulds and Henry, 2008). The Excelsior domain (and the Mina deflection within it) has ENE-striking basins and abundant volcanic rocks, including the Long Valley rift volcanic field (Figs. 1 and 3B; Riley et al., 2012). The Mina deflection is the largest ENE-striking structure in the Walker Lane belt (85–100 km wide), probably due to exploitation of a fundamental Paleozoic and Mesozoic crustal boundary (cf. Jayko and Bursik, 2012). I propose that the 25-km-wide NE transfer zone that lies between Sonora Pass and Ebbetts Pass (Fig. 2; described by Busby et al., 2013a) is structurally analogous to the Mina deflection; however, we have shown that it became active during eruption of the ca. 11.5–9 Ma Stanislaus Group (Busby et al., 2013a, 2013b), whereas the age of initiation of Walker Lane deformation on the Mina deflection is more controversial.

Riley et al. (2012) inferred the initiation of the Mina deflection to be temporally coincident with onset of voluminous magmatism at ca. 3 Ma in the Long Valley field. However, the age of initiation could be as old as ca. 12 Ma, according to Oldow et al. (2008); they stated that although the earlier history of faulting in the west-central Great Basin is locally well pre-

served (Proffett, 1977; Proffett and Dilles, 1984; Stewart, 1988; Dilles and Gans, 1995; Stockli et al., 2002, 2003), it is for the most part recognized on the basis of mid-Miocene cooling ages of exhumed footwall rocks (Stockli, 1999; Stockli et al., 2002, 2003). These structures are overprinted by late Miocene to early Pliocene structures formed in transcurrent displacement (Stockli et al., 2002, 2003), but the timing of kinematic reorganization and inception of the structural stepover is not firmly established (Oldow et al., 2008). Oldow et al. (2008) proposed that kinematic reorganization at 8 Ma would be more consistent with the Pacific–Farallon plate reorganization of Atwater and Stock (1998), but they considered the rapid fault slip and cooling of lower-plate rocks at ca. 12 Ma to be more consistent with transcurrent (rather than divergent) displacement. The age of the youngest volcanic rocks tilted $\sim 25^{\circ}$ east in the White Mountains block (12 Ma), and thermochronologic data from the block, are consistent with onset of extensional faulting at ca. 12 Ma (Stockli et al., 2002), but could possibly be explained by transtension, rather than extension.

The three most important conclusions of this section are that: (1) although not tightly constrained, transtension began by ca. 12 Ma in the central and southern Walker Lane, while in the northern Walker Lane it is probably younger than ca. 3.5 Ma and shows the least offset; (2) NE-striking structures are an important feature of the central Walker Lane, and have been since ca. 12 Ma; and (3) the western part of the central Walker Lane (Long Valley to Tahoe Basin) has previously been excluded from the Walker Lane, due to a lack of long strike-slip faults, but structural and paleomagnetic data show the region is squarely within Walker Lane. As discussed below, I suggest that our constraint on the timing of onset of plate-margin-scale transtension in the Walker Lane belt is the best existing one so far (i.e., it is the age of the ca. 11.5–9 Ma Sierra Crest–Little Walker volcanic center), and that since that time, the rift tip has propagated northward within the ancestral and modern Cascades arc.

BIRTH OF THE WALKER LANE TRANSTENSIONAL PLATE BOUNDARY WITHIN THE ANCESTRAL CASCADES EXTENSIONAL ARC

In this section, I develop a model whereby transtensional rifting was initially focused in thermally weakened, partially extended crust of the Ancestral Cascades arc. This model is developed in two time frames: extensional arc (ca. 50–12 Ma), and transtensional arc and rift (ca. 12 Ma to present).

Extensional Arc (50–13 Ma)

In Eocene to Miocene time, arc volcanism migrated southwestward across what is now the Great Basin (Fig. 3A), accompanied by extension resulting from slab steepening or fallback during ongoing subduction (Dickinson, 2006; Cousens et al., 2008; Busby and Putirka, 2009; McQuarrie and Oskin, 2010; Busby, 2012). This long-distance migratory volcanism is not recorded in the 45–4 Ma Washington-Oregon segment of the Ancestral Cascades arc, which forms the underpinnings to the present-day arc, because accretion of the oceanic Siletzia terrane along the Washington-Oregon coast at 50–45 Ma caused a westward jump in subduction there, so that segment of the Ancestral Cascades arc became established far west of the southern segment described in detail here (cf. DuBray and John, 2011). Colgan et al. (2011) inferred that this displacement was accommodated by a tear in the subducting Farallon slab (Fig. 3A).

Ancestral Cascades arc extension in what is now the Great Basin was superimposed across thickened crust of the “Nevadaplano” (Fig. 3A), inferred to have been a high, broad plain produced by low-angle subduction under a contractional strain regime during late Mesozoic to Paleocene time (DeCelles, 2004); however, the paleo-elevation of the “Nevadaplano” is not well constrained (Henry et al., 2012). Alternatively, based on oxygen isotope analyses, it is inferred that most of the uplift occurred due to southward encroachment of an Eocene plateau (SWEEP, Fig. 3A; Chamberlain et al., 2012). In the SWEEP model, uplift was diachronous, occurring ca. 49 Ma in British Columbia to Montana, and ca. 40 Ma in central Nevada (Mix et al., 2011). The timing of SWEEP is inferred to correlate with the timing of volcanism and extension, including generation of metamorphic core complexes (Kent-Corson et al., 2006; Horton and Chamberlain, 2006; Mulch et al., 2007; Chamberlain et al., 2012). The SWEEP hypothesis (Chamberlain et al., 2012) agrees with tectonic models that call for either removal or fallback of the Farallon slab; I follow Dickinson (2006) by using the fallback model (instead of removal) because the plate record shows that subduction continued under North America at this time, and because the positions of successive arc fronts track the fallback (Fig. 3A). However, Henry et al. (2012) argued that a lack of significant paleovalley incision during magmatism in Nevada indicates little surface uplift in the Eocene; they inferred that the highland shown in Figure 3A formed mainly in Cretaceous time. Furthermore, Druschke et al. (2009a) argued that the earliest surface-breaking extension was not driven by Eocene magmatism

(Armstrong and Ward, 1991) because it began in Late Cretaceous time, coeval with mid-crustal hinterland extension, and coeval with contraction in the Sevier foreland to the east (Druschke et al., 2009b); this hinterland extension produced internally drained Cretaceous to Eocene basins (Druschke et al., 2011).

The southern extent of the Nevadaplano is not well known. Ernst (2009) inferred that it extended along much of the length of the Cordillera. Henry et al. (2012) inferred that it persisted at least as far south as Sonora, Mexico, which, as they stated, is far beyond the proposed reach of SWEEP. In contrast, Lechler et al. (2013) inferred that the Nevadaplano extended no further south than the modern boundary of the northern Basin and Range (i.e., southern Nevada). A further complication on the Nevada-plano reconstruction shown in Figure 3A is the possibility that the ancestral Sierra Nevada formed a paleodivide in Cretaceous time, rather than lying lower on the west shoulder of a Nevadaplano paleodivide in Nevada. Van Buer et al. (2009) analyzed the regionally extensive unconformity that separates mesozonal plutonic rocks of the Cretaceous Sierra Nevada batholith from Eocene to Miocene strata above, in northern California and northwestern Nevada (see Fig. 3A, which shows the locus of the Cretaceous Sierra Nevada batholith and its extension into northwest Nevada). Van Buer et al. (2009) concluded that erosion along this unconformity is greatest over the axis of the batholith, decreasing rapidly eastward away from it; therefore a western paleodivide appears to have existed over the northern part of the batholith in Cretaceous to Paleocene time. Very high Cretaceous paleo-elevations are also required for the area of the southern Sierra Nevada batholith, where gravitational collapse caused south-southwestward transport of the upper ~5–10 km of crust at 77 ± 5 Ma (Saleeby et al., 2007; Chapman et al., 2012); this Late Cretaceous orogenic collapse led to formation of basins at or below sea level by Paleocene time in the southernmost Sierra (Lechler and Niemi, 2011). Regardless of the Cretaceous to Paleocene paleogeography, ignimbrite stratigraphy in paleochannels shows that by 46 Ma, the drainage divide lay in east-central Nevada, and paleochannels extended westward from it across what is now the northern and central Sierra Nevada, to the California Central Valley (shown by dot pattern west of the Sierra Nevada, Fig. 3A; Henry, 2008, 2012).

Regardless of the relative importance of Cretaceous versus Eocene surface uplift in the Great Basin, I agree with Henry et al. (2010) that the regular pattern of arc migration is consistent with rollback of a slab fragmented into a few major panels, and not the independent

collapse of many small pieces as proposed by Humphreys (1995, 2009). The panels defined by Henry et al. (2010) include the Great Basin (shown on Fig. 3A), as well as Southern Rocky Mountain, Mogollon-Datil, Trans-Pecos volcanic fields of the U.S. (not shown) and the Sierra Madre Occidental of Mexico (also not shown; see Murray et al., 2013; Ferrari et al., 2013). Eocene to Miocene slab fallback and arc extension associated with it in Mexico ultimately led to Miocene rifting in the Gulf of California (Ferrari et al., 2007, 2013).

Slab fallback across what is now the Great Basin was completed by 16 Ma, when the arc front reached the position of the eastern Sierra Nevada (see red stars on Fig. 3A). Extension (and uplift?) associated with arrival of the SWEEP thermal anomaly may have produced the unconformity between Oligocene and Miocene strata in the central Sierra (unconformity 2 of Busby et al., 2008a, 2008b, 2013a, 2013b; Busby and Putirka, 2009). Arc extension between 16 and 12 Ma was likely controlled by direct interaction between the North American and Pacific plates, because microplates between the Pacific plate and the North American plate were subducted by then (Dickinson, 2006). As shown on Figure 3A, the ca. 16 Ma flood basalts of Washington and Oregon were erupted in a backarc position, but the 16 Ma Lovejoy basalt of California was erupted within or immediately in front of the arc (Garrison et al., 2008; Busby and Putirka, 2009). The Lovejoy basalt is the largest known eruptive unit in California, and has geochemical affinities with coeval flood basalts of the Columbia River Basalt Group (Garrison et al., 2008). It erupted from a fissure sited along a 16 Ma NNW-SSE normal fault that became exploited by a major fault zone of the modern Walker Lane transtensional fault zone (Honey Lake fault, Fig. 1; Busby and Putirka, 2009).

From 16 to 12 Ma, Miocene intra-arc thermal softening and extension weakened the continent just inboard of a strong lithospheric block created by the Cretaceous batholith; this batholith remains largely unfaulted today, except where Walker Lane strike-slip faults have begun to disrupt it (e.g., Polaris–Mohawk Valley fault zone, discussed above). During the ca. 16–12 Ma time frame, only small arc volcanic centers formed in the Sierra Nevada, marked by hypabyssal intrusions, block-and-ash-flow tuffs, and rare lava flows (Busby et al., 2008a, 2008b, 2013a, 2013b; Hagan et al., 2009; Busby and Putirka, 2009); I infer that large arc volcanic centers did not begin to form along the eastern edge of the Sierra Nevada batholith until transtension began. However, a large (>700 km²) arc volcanic center began to form in this time frame (14.7 Ma) east

of the main batholithic belt, in the Bodie Hills (BH, Fig. 1), under an apparently neutral strain regime (John et al., 2012).

Also in the 16–12 Ma time frame, a super-volcano field formed in southwest Nevada, referred to as the southwest Nevada volcanic field (SWNVF; Fig. 3A). The SWNVF lies at the southeasternmost edge of the Walker Lane belt (Grauch et al., 1999). However, it is an area of widely spaced faults and low stratal dips, and it shows only local evidence for vertical-axis clockwise rotations, suggesting it is not underpinned by Walker Lane faults (Hudson et al., 1994; Fridrich et al., 1998). Although volcanism occurred from ca. 16 Ma to ca. 6.5 Ma (Vogel and Byers, 1989), most of the magmatism occurred at supervolcano calderas between 14 Ma and 11.5 Ma, during peak extension in adjoining parts of the Basin and Range (Sawyer et al., 1994), including detachment faulting immediately to the west of the caldera complex (Fridrich et al., 1999). Best et al. (2013) did not consider the SWNVF to be part of the 36–18 Ma southern Great Basin ignimbrite province, which they inferred formed in response to slab steepening/rollback (as described above; Henry et al., 2010). The origin of the SWNVF is not clear, and for that reason, the SWNVF is shown separately from the southwest-sweeping Eocene to Miocene arc front on Figure 3A; nonetheless, its earlier stages could represent the southwesternmost manifestation of slab rollback (O' Leary, 2007). Upper mantle velocities are high (rather than the low that would be expected from a still-warm mantle), to a depth of 300 km, in a near-vertical structure best attributed to melt extraction. The depth of this root suggests that the location of the SWNVF cannot be attributed to a location in a releasing right step of the Walker Lane belt (Biasi and Humphreys, 1992; Glenn Biasi, 2013, personal commun.). It may instead represent slab window magmatism related to the passage of the Mendocino triple junction (MTJ; Fig. 3), as suggested by Putirka and Platt (2012). The SWNVF lies between 36.5°N and 37.5°N, and the MTJ passed those latitudes at 17.6 and 13.0 Ma (Keith Putirka, 2013, personal commun.). Therefore, the SWNVF may record a transition from slab rollback to slab window magmatism; however, because it shows no strong evidence of Walker Lane tectonism, it is not shown as a Walker Lane volcanic center on Figure 3B.

The Bodie Hills arc volcanic field of the central Walker Lane covers the right time span to record a ca. 12 Ma changeover from extension to transtension, because its age ranges from 14.7 Ma to 8 Ma; however, the field lacks faults that are demonstrably coeval with magmatic activity, nor does it have dikes, fissure-

fed eruptive features, elongate grabens, or volcanotectonic depressions (John et al., 2012). This indicates minimal differential horizontal stress variation during formation of the Bodie Hills volcanic field (John et al., 2012). However, large-magnitude E-W (Basin and Range) extension is well-documented to the north of the Bodie Hills at Yerington at 15–14 Ma (Dilles and Gans, 1995). As described by John et al. (2012), the ~N-S normal fault zone of the Yerington area ends southward into a NE-striking normal fault zone that dips south along the north side of the Bodie Hills volcanic field (shown schematically as one fault in Fig. 1), and one of these faults bounds a basin with strata as old as 11.7 Ma (Gilbert and Reynolds, 1973). I suggest that the NE trend of this fault zone is more typical of Walker Lane faults than it is of Basin and Range faults, and that the 11.7 Ma basin was formed by early Walker Lane transtension. As described in the following section, Walker Lane transtension exploited the arc, and has propagated northward along it to the present-day Lassen volcanic center.

Transtensional Arc and Rift (ca. 12 Ma–Present)

I infer that, over the past 12 m.y., the largest volcanic centers have formed at major transtensional fault stepovers on the eastern edge of the Sierra Nevada, in the Walker Lane belt (Fig. 3B). These include two active rift centers (Long Valley and Coso volcanic fields) and an active arc center (Lassen), described further below. These also include two major arc volcanic centers not recognized before our work (Figs. 2, 3): the 11.5–9 Ma Sierra Crest–Little Walker volcanic center (Busby et al., 2013a, 2013b), and the ca. 6.3–4.8 Ma Ebbetts Pass volcanic center (Busby, 2011; Busby et al., 2013c), described briefly here. These arc volcanic centers formed in the Ancestral Cascades arc, when the position of the MTJ was further south than it is now (position at 12 Ma shown on Fig. 3B). I infer that the rift tip has exploited the arc, moving northward in concert with the MTJ, and that large rift volcanic centers are sited at releasing stepovers or bends south of the MTJ. It is not a new idea that Walker Lane faults have propagated northward in concert with MTJ migration (Faulds and Henry, 2008); nor is it a new idea that northward propagation of the MTJ, and the opening of the slab window, exerts important controls on tectonic events and volcanic compositions far inboard of the MTJ (Dickinson and Snyder, 1979; Zandt and Humphreys, 2008; Putirka et al., 2012). However, the northward unzipping along the arc, and the siting of the major centers on transtensional stepovers,

are new concepts. I suggest that this northward unzipping (i.e., northward rift-tip propagation at the south end of the Cascades arc) is superimposed on a broader pattern of transtensional faulting that became established on a plate-margin scale at ca. 12 Ma, from the Gulf of California (Umhoefer, 2011) to the Walker Lane belt.

Space-time-composition trends in magmatism show that the Walker Lane is a principal region of mantle upwelling and lithosphere removal, and that this process is linked to northward migration of the MTJ, which terminates arc magmatism diachronously northward (Putirka et al., 2012). Full degradation of the mantle lithosphere, and production of asthenosphere-like compositions, takes ~20 m.y. and is only now being approached at the Coso volcanic field (Putirka et al., 2012), shown at the south end of Figure 3B. $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios indicate that, upon arrival of the MTJ at any given latitude, continental mantle lithosphere is progressively heated, showing increasing continental mantle lithosphere influence for 10–12 m.y., and then degraded, showing increasing mantle asthenosphere influence until ca. 17–20 Ma post-MTJ (Putirka et al., 2012; Putirka and Platte, 2012). These authors inferred that the MTJ influenced magmatism and tectonics at 27 Ma in southeast California (33°N) and at 17–18 Ma near Lake Mead (36°N), southeast of the region shown on Figure 1, and at 15–16 Ma at Death Valley (36.5°N), at the south end of Figure 1 (Putirka and Platt, 2012). However, it is important to emphasize that the enriched arc signal (e.g., high La, Ba) can last for as long as 17 m.y. post-TMJ (see Putirka et al., 2012, their figure 4); this explains why 13.1 Ma rhyolites displaced by the Stateline fault (Guest et al., 2007), which show an enriched arc signal (Keith Putirka, 2013, personal commun.), as well as ca. 15–12 Ma andesites in the Death Valley region (Fridrich and Thompson, 2011), erupted after passage of the MTJ. However, despite evidence for MTJ-influenced tectonic and magmatic events beginning at 27 Ma at the latitude of initial interaction, I argue that Walker Lane transtension at the plate-margin scale did not begin until 12 Ma, when the MTJ was at the latitude of the central Sierra.

As described above, earlier (pre-12 Ma) strike-slip faulting has been demonstrated in the eastern Walker Lane of Faulds and Henry (2008), at the latitude where the San Andreas system was born. Early (pre-12 Ma) faults of the eastern Walker Lane include the sinistral NE-SW Lake Mead fault system in the east (“Lake Mead domain”), and dextral NW-striking faults in the west (Las Vegas Valley shear zone). The siting and orientation of these faults is controlled by an ancient crustal boundary

Birth of a plate boundary at ca. 12 Ma, Ancestral Cascades arc, Walker Lane belt

(see discussion in Faults and Henry, 2008). They lie at the north end of the Colorado River extensional corridor, where magmatism and detachment-style extension are related to the slab window that was created at the birth of the San Andreas fault (cf. Umhoefer et al., 2010); a change at 15–14 Ma from detachment faulting to “mixed mode transtensional faulting with waning detachment faulting” in the Lake Mead domain is related to this setting (Umhoefer et al., 2010, p. 391). Faults and Henry (2008) proposed that shear shifted westward from the eastern Walker Lane to a far more extensive NNW-striking belt of faults in the Mojave Desert block and the southern and central Walker Lane, sometime between ca. 11 and 6 Ma. These NNW-striking faults include the Stateline strike-slip fault, which is post-13 Ma, as mentioned above (Guest et al., 2007). The Las Vegas Valley shear zone is inactive, while the Stateline fault is active (Baran et al., 2010; Mahan et al., 2009; Scheirer et al., 2010). I suggest that the far more extensive belt of active NNW-striking faults signal the beginning of plate-margin-scale transtension. Plate-margin-scale transtension began when the MTJ reached the latitude shown on Figure 3B (at ca. 12 Ma), and the rift tip lay within the Ancestral Cascades arc at Sonora Pass (Fig. 2; Busby et al., 2013a, 2013b), described in the introduction section. The transtensional rift tip then propagated northward, following the Mendocino triple junction, to form a younger, newly recognized intra-arc pull-apart basin we call the Ebbetts Pass volcanic center (Fig. 2).

The Ebbetts Pass volcanic center formed at a series of right-stepping N-S dextral-oblique down-to-the-east normal faults on the modern Sierra crest and range front (Fig. 2; Hagan, 2010; Busby, 2012; Busby et al., 2013c). Older (Stanislaus Group) rocks were downropped ~500 m along the Wolf Creek fault (Fig. 2), and the pull-apart basin to the north of the fault filled with volcanic rocks at ca. 6.3–4.8 Ma. Like the Little Walker caldera, the pull-apart basin formed along a system of right-stepping faults (the Nobel Canyon, Grover Hot Springs, and Silver Mountain faults, Fig. 2). The eastern two faults became inactive during the growth of the Ebbetts Pass volcanic center, while the westernmost fault (Nobel Canyon) remained active throughout and after volcanism (Hagan, 2010; Busby et al., 2013c). The oldest volcanic rocks in the Ebbetts Pass pull-apart basin are late Miocene, 6.305 ± 0.017 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$ hornblende, on a two-pyroxene biotite quartz dacite lava flow at Elder Creek), but most of the pull-apart basin fill is Pliocene, and somewhat bimodal, perhaps indicating a transition from subduction to rift magmatism (Busby et al., 2013c). Earlier Pliocene rhyolites include a flow at Nobel Lake

(4.581 ± 0.018 Ma on hornblende) and a biotite sanidine hornblende quartz rhyolite ultrawelded ignimbrite near Silver Peak (4.636 ± 0.014 Ma on 14 sanidine crystals; Busby et al., 2013c). Later Pliocene basaltic andesites form a large cone (4.85 ± 0.02 Ma on plagioclase), but the youngest parts of the cone are silicic, with block-and-ash-flow tuffs and central intrusions, including a hornblende biotite sanidine quartz dacite intrusion dated at 4.434 ± 0.007 Ma (sanidine; Busby et al., 2013c). The edifice grew to a diameter of >18 km, and was comparable in dimensions and volume to the post-Rockland caldera stratocone-dome field of the Lassen volcanic center (600 ka to present, described by Hildreth, 2007; Clynne and Muffler, 2010).

No very large volcanic centers have been identified in time and space between the ca. 6.3–4.8 Ma Ebbetts Pass arc volcanic center and the ca. 3.5 Ma to recent Lassen arc volcanic center (Fig. 3B), suggesting that either (1) no important stepovers formed within the arc in this segment, or (2) they have not been recognized. The latter is certainly possible, because the Ebbetts Pass volcanic center was not recognized prior to our work (Busby et al., 2013c), and much of the Sierra Crest–Little Walker volcanic center had not been recognized (Busby et al., 2013a, 2013b). But it is clear that by ca. 4 Ma, dextral shear propagated northwestward into the Pyramid domain of the northern Walker Lane (Fig. 1) “in concert with the offshore northward migration of the Mendocino triple junction” (Faults and Henry, 2008, p. 1). The Quaternary fault geometry there (Henry et al., 2007) is very similar to the active structures beneath the active Lassen arc volcanic center, inferred from seismicity (Muffler et al., 2008; Janik and McLaren, 2010). Seismicity on three faults in the western part of the Lassen volcanic center are interpreted to record E-W extension on N-S faults, while the eastern of these three faults is interpreted to show evidence for oblique faulting and right-lateral shear (Janik and McLaren, 2010). A fourth, deeper (7–10 km) seismogenic zone southeast of that (Devil’s Kitchen) extends southeastward to NNW-striking faults of the Walker Lane belt (Janik and McLaren, 2010). A “pronounced unconformity” separates <3.5 Ma volcanic rocks from underlying pre-Tertiary rocks; this may indicate that “beginning at 3.5 Ma, the northern Walker Lane increasingly interacted with the Cascade subduction zone to produce transtensional environments favorable to the development of major volcanic centers” (Muffler et al., 2008). Thus, the transtensional rift tip continues to exploit thermally weakened crust of the Cascades arc.

The siting of the two largest rift volcanic centers at transtensional stepovers has only

recently been recognized: Long Valley, by Burdick (2009) and Riley et al. (2012), and Coso, by Pluhar et al. (2006). GPS and Interferometric System Aperture Radar (InSAR) measurements show that the Coso volcanic center is subsiding (Hammond et al., 2012), as it should be if it lies within an active releasing stepover. Fialko and Simons (2000) attributed subsidence over a ~50 km-long region at Coso to deflation of the geothermal reservoir, but Wicks et al. (2001) inferred a source of deformation deeper than the geothermal reservoir, lying at the brittle-ductile transition at 4 km depth. Instead of attributing the deep subsidence to tectonic deformation, however, Wicks et al. (2001) related the subsidence to leakage of magmatic fluids from a rhyolite magma body inferred to lie at that depth in the region of deflation. Work in progress by Bill Hammond and his group at the University of Nevada Reno (2012, personal commun.) may determine whether the cause of subsidence at Coso is tectonic or magmatic.

Active emplacement of rift dikes is currently taking place in the region between Lake Tahoe and Mount Lassen (Fig. 3B), in the wake of the northward-migrating MTJ, where the competent Sierra Nevada block is collapsing eastward (Smith et al., 2004, 2012). Geochemical studies show that the change from arc volcanism to rift volcanism occurred at the latitude of Lake Tahoe at ca. 3 Ma (Cousens et al., 2008), and the base of the seismogenic zone is shallow (15–18 km; Smith et al., 2004), consistent with rifting. Earthquake swarms in A.D. 2003 and 2011 between Lake Tahoe and Sierra Valley to the north (locations on Fig. 1) define two nearly identical dike injection events 50 km apart (shown schematically on Fig. 3B; Smith et al., 2004, 2012). Each of the two swarm outlines an ~7 × 7 km fault area, and initiates at the deepest extent, and they are aligned along a N45W-striking, 50°E-dipping Moho-depth structure (Smith et al., 2012). Dilational strain is shown from GPS data, and the temporal progressions of earthquakes defined the injection fronts of the propagating dikes, due to brittle failure of rock at the crack tip defined by high-frequency earthquakes. Midway between the two dikes along the east-dipping Moho-depth structure, a long-period earthquake was detected in 2011; this is the first long-period earthquake identified in the Walker Lane belt, outside of the Long Valley volcanic center (Smith et al., 2012). Extrapolating rift initiation from the Sierra Crest–Little Walker volcanic center, Smith et al. (2012) calculated a northwest rift propagation rate of ~18 mm/yr, within 30% of the current Sierran rate of motion as determined from GPS.

Although rifting has not yet succeeded in forming new seafloor along the Walker Lane belt,

it has many features in common with the Gulf of California rift, including: (1) timing of initiation, at ca. 12 Ma; (2) localization of rifting due to thermal weakening in the axis of a subduction-related arc undergoing extension due to slab rollback; and (3) enhanced thermal weakening in the arc, due to stalling of the trenchward-migrating precursor arc against a thick Cretaceous batholithic lithospheric profile on its western boundary (McCrory et al., 2009; Busby et al., 2010; Umhoefer, 2011). The Walker Lane transtensional rift bears many similarities to the Gulf of California transtensional rift. The Gulf of California is an oblique rift system with short spreading segments connected by long transform faults (Lizarralde et al., 2007); similarly, geologic and GPS velocity data in the Walker Lane indicate that NNW strike-slip motion and WNW extension are partitioned (Wesnousky, 2005; Surpless, 2008). Lonsdale (1989) suggested that the central Gulf of California formed as a series of pull-apart basins that were precursors to the current spreading centers and transform faults; as noted above, pull-apart basins are forming in the central Walker Lane, probably due to a higher rift angle there, relative to the northern and southern Walker Lane. There are still some workers who object to calling Walker Lane a transtensional rift; my response is that if Walker Lane is not a rift, the Gulf of California is not a rift.

Rifting at ca. 12 Ma led to seafloor spreading very quickly in the Gulf of California (by 6 Ma; Umhoefer, 2011), due to stalling of large Farallon microplates, which resulted in efficient coupling between the Pacific plate and the Baja California Peninsula (Stock and Lee, 1994; Atwater and Stock, 1998; Plattner et al., 2010; McCrory et al., 2009), so rifting did not progress from south to north (Lizarralde et al., 2007) like it has in the Walker Lane. In contrast, transtensional rifting is proceeding at a more typical rate in the Walker Lane belt (continental rifting commonly takes tens of millions of years to accomplish; cf. Busby and Ingersoll, 1995; Busby and Azor, 2012); furthermore, it is progressing from south to north, following the MTJ, as shown by the structural and magmatic history of the region, described herein.

A Note on Continental Extensional or Transtensional Arcs (or Arc Rifts)

There remains a common misconception that subduction causes contraction in upper plate continental rocks, but there are abundant examples of modern and ancient extensional and transtensional continental arcs, as summarized by Busby (2012). It has also long been recognized that strike-slip faults, transtensional faults, and block rotations play an important role

in modern volcanic arcs. Examples include the Central American arc (Burkart and Self, 1985; Jarrard, 1986; Weinberg, 1992); the Trans-Mexican volcanic belt (Israde-Alcantara and Garduno-Monroy, 1999); the Andean arc of southern Chile and Patagonia (Cembrano et al., 1996; Thomson, 2002); the Sumatra arc (Bellier and Sebrier, 1994); the Aeolian arc (Gioncada et al., 2003); the Calabrian arc (Van Dijk, 1994); the Aleutian arc (Geist et al., 1988); the Taupo volcanic zone (Cole and Lewis, 1981; Villamor et al., 2011); the central Philippine arc (Sarewitz and Lewis, 1991); and others. There are also examples of strain partitioning in transtensional arc settings (Acocella et al., 1999; Marra, 2001; Busby et al., 2005), where partitioning may be controlled by relative fault strengths, which in turn may depend on magmatism at depth (de Saint Blanquat et al., 1998). Styles of magmatism are strongly controlled by structural style. For example, along the modern Sumatra dextral strike-slip fault (Bellier and Sebrier, 1994; Bellier et al., 1999; Ventura, 1994), as well as the Late Jurassic sinistral Sawmill Canyon fault zone of southern Arizona (Busby et al., 2005; Busby and Bassett, 2007), small volcanic centers occur along releasing bends, whereas large volcanic centers, such as caldera complexes, occur along releasing stepovers, in pull-apart basins.

Strike-slip faults are common in continental arcs because (1) oblique convergence is far more common than orthogonal convergence, and at most continental arcs, an obliquity of only 10° off orthogonal results in the formation of strike-slip faults in the upper plate; and (2) faults are concentrated in the thermally weakened crust of arcs, particularly on continental crust, which is weaker and better coupled to the subducting slab than oceanic arc crust (Dewey, 1980; Jarrard, 1986; McCaffrey, 1992; Ryan and Coleman, 1992; Smith and Landis, 1995; Busby, 2012).

In the case of the Cascades arc, subduction is not oblique; however, for the past 12 m.y., a transtensional rift has been propagating northward within the south end of the arc, exploiting its thermally weakened lithosphere. This will ultimately result in complete transfer of the northward-lengthening Sierra Nevada microplate onto the immense Pacific, which is moving obliquely away from North America.

CONCLUSIONS

The Walker Lane belt (termed “the future plate boundary”) offers the opportunity to examine a Gulf of California-type transtensional rift in its earlier stages, before continental lithosphere is ruptured. The trailing edge of the Sierra Nevada microplate is divided into three

segments (Fig. 1). The southern and northern segments have long dextral strike-slip faults, while the central segment generally lacks long strike-slip faults (except locally along its eastern edge). The central segment is dominated by NNW-striking normal to dextral-oblique faults and NE-striking sinistral-oblique faults, and shows clockwise vertical-axis block rotations. Because of the lack of long dextral strike-slip faults in the western part of the central Walker Lane, previous workers have excluded it from the Walker Lane, inferring that it is purely extensional; however, this paper summarizes evidence that this area has been undergoing dextral deformation since ca. 12 Ma. The western part of the central Walker Lane lies along a segment of one of the most prominent topographic features in the U.S., the Sierra Nevada range front, and it has some of the deepest basins of the Walker Lane (Mono and Tahoe), with the most abundant Miocene to recent volcanic rocks, including the Long Valley volcanic field. I propose here that the central Walker Lane was the site of initiation of plate-margin-scale rifting, at ca. 12 Ma, and that the geologic signal of rift initiation lies at the large, geologically unusual Sierra Crest–Little Walker arc volcanic center.

The Walker Lane transtensional rift is similar to the Gulf of California transtensional rift in many ways, but differs in one important way: rifting led to seafloor spreading very quickly in the Gulf of California, because large Farallon microplates stalled west of the Baja California Peninsula, efficiently transferring the entire length of the Peninsula to the Pacific plate simultaneously, at 12 Ma. In contrast, the Sierra Nevada microplate is being rifted off progressively, from south to north, following the Mendocino triple junction (Fig. 3). This process began at ca. 27–12 Ma in southeast California and southwest Nevada, while to the north, slab rollback continued to produce an extensional arc that retreated westward across central Nevada, into the central and northern Sierra Nevada. Similar to the Gulf of California, this westward-migratory arc stalled against the strong Cretaceous batholithic lithosphere to the west, and the thermally weakened belt became exploited by the rift. Regional structural and volcanological data, summarized herein, suggest that the Walker Lane belt did not become organized as a plate-margin-scale transtensional rift until ca. 12 Ma, when the Gulf of California transtensional rift also formed.

The ca. 11.5–9 Ma Sierra Crest–Little Walker arc volcanic field is extremely unusual, compared to other intermediate-composition volcanic centers (Fig. 2; Busby et al., 2013a, 2013b). Volcanism there was immediately preceded by rapid subsidence of deep transtensional

Birth of a plate boundary at ca. 12 Ma, Ancestral Cascades arc, Walker Lane belt

grabens, which partially filled to depths of 400 m with avalanche deposits shed from the footwalls. Intermediate-composition lavas of unusually large volume were erupted from fissure vents up to 8 km long, in a style more typical of flood basalts. This high-K melt pulse was produced by the tapping of low-degree partial melts trapped beneath a thick lithospheric column at the inception of transtensional stresses, recording the birth of the Walker Lane plate boundary.

The leading tip of the Walker Lane rift exploits large volcanic centers at major transtensional stepovers at the southern end of the Cascades arc, as is presently occurring at Mount Lassen; rift magmatism just south of Lassen is recorded by contemporary diking events (Fig. 3B). The transtensional arc rift tip has been migrating northward at a rate consistent with the current Sierran rate of motion determined from GPS, from the 11.5–9 Ma Sierra Crest–Little Walker volcanic center, to the ~6.3–4.8 Ebbetts Pass volcanic center, to Mount Lassen. In its wake, the largest rift volcanic centers are sited on transtensional stepovers or bends; these include the Long Valley and Coso volcanic fields. I predict that any <12 Ma large volcanic centers identified by future workers in the Sierra Nevada–Walker Lane region, or in the Gulf of California, will prove to be sited at major releasing bends or stepovers. Furthermore, I suggest that unusually large volcanic centers form an important geologic signal of transtensional rifting.

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