

Chapter 19

Extensional and transtensional continental arc basins: case studies from the southwestern United States

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ABSTRACT

Extensional and transtensional continental arc basins preserve very thick, continuous sequences and are an important contributor to the growth of continents; therefore, it is important to understand how they evolve. In this chapter, I describe four continental arc basin types, using Mesozoic to Cenozoic case studies from the SW US: (1) early-stage, low-lying extensional; (2) early-stage, low-lying transtensional; (3) late-stage, high-standing extensional; and (4) late-stage high-standing transtensional.

During the breakup of Pangea in early Mesozoic time, the paleo-Pacific Ocean basin was likely composed of very large, old, cold plates; these rolled back during subduction to produce subsidence and extension in the upper plate, particularly along the thermally-weakened arc that formed along the western margin of North and South America. Late Triassic to Middle Jurassic early-stage low-lying extensional continental arc basins of the SW US were floored by supracrustal rocks, showing that uplift did not precede magmatism, and they subsided deeply at high rates, locally below sea level. These basins formed a sink, rather than a barrier, for craton-derived sediment. They were characterized by abundant, widespread, large-volume silicic calderas, whose explosive eruptions buried fault scarps and horst blocks, resulting in a paucity of epiclastic debris in the basins. In Late Jurassic time, early-stage low-lying transtensional continental arc basins formed along the axis of the early-stage low-lying extensional continental arc basins, due to the opening of the Gulf of Mexico, which resulted in oblique subduction. Basins were downropped at releasing bends or stepovers, in close proximity to uplifts along restraining bends or stepovers (referred to as “porpoising”), with coeval reverse and normal faults. Uplift events produced numerous large-scale unconformities, in the form of deep paleocanyons and huge landslide scars, while giant slide blocks of “cannibalized” basin fill accumulated in subsiding areas. Erosion of pop-up structures yielded abundant, coarse-grained epiclastic sediment. Silicic giant continental calderas continued to form in this setting, but they were restricted to symmetrical basins at releasing stepovers.

In Cretaceous to Paleocene time, the arc migrated eastward under a contractional strain regime, due to shallowing of the progressively younger subducting slab. This produced a broad, high plateau, referred to as the “Nevadaplano” because of its similarity to the modern Altiplano of the Andean arc. Then, in Eocene to Miocene time, volcanism migrated westward due to slab rollback or steepening, producing late-stage high-standing extensional continental arc basins. Late-stage extensional continental arc basins were similar to early-stage extensional arc basins in having “supervolcano” silicic caldera fields, but they were restricted to areas of thickest crust (along the crest of the Nevadaplano), rather than forming everywhere in the arc. Late-stage basins differed markedly from early-stage basins by forming atop a deeply eroded substrate, with eruptive products funneled through canyons carved during the preceding phase of crustal shortening. These basins lack marine strata, and stood too high above the rest of the continent to receive sediment from the craton. At ~ 12 Ma, E-W extension was replaced by NW-SE transtension, corresponding to a change from more westerly motion to more northerly motion of the Pacific plate relative to the Colorado

Plateau, resulting in microplate capture. The Sierra Nevada microplate was born, with its trailing edge in the axis of the Ancestral Cascades arc. The late-stage transtensional continental arc is characterized by siting of major volcanic centers at transtensional fault stepovers. Each transtensional pulse produced an unconformity, followed by a magmatic pulse. Lithosphere-scale pull-apart structures tapped deep melts, producing “flood andesite” eruptions. Close proximity of uplifts and basins resulted in preservation of huge landslide deposits, and ancient E-W drainage systems coming off the Nevadaplano were deranged into N-S drainage systems along the new plate boundary.

The stratigraphic and structural aspects of continental arcs have been neglected relative to geochemical and geophysical aspects; however, these features are important for providing constraints on the tectonic evolution of such regions.

Keywords: extension; arc; Cascades; Jurassic; Cordillera

INTRODUCTION

This chapter synthesizes the results of tectonic and stratigraphic work in extensional and transtensional continental arc basins, in order to identify their key distinguishing features. This is done by focusing on the SW US, where rocks of this type have been studied by many workers, using a wide variety of field and lab approaches. This chapter begins by summarizing the evolution of thought on continental arc tectonic processes, and how this evolution of thought affected the understanding of continental arc basins in the western US. The main body of the chapter describes the following extensional and transtensional basin types: (1) early-stage low-lying continental arc basins (Figure 19.1), and (2) late-stage high-standing continental arc basins (Figure 19.2). I present block diagrams of basin architectures and fills, published over the last 25 years, and refer the reader to detailed publications for primary data (geologic maps and cross-sections, measured sections, geochronology, geochemistry, paleontology, etc.). The diagnostic features of the early-stage basins are then summarized in lithostratigraphic columns, prior to presenting new advances in understanding of the late-stage basins, which are not yet as well studied. The last part of the chapter summarizes my new published and unpublished results from late-stage basins, along with generalized lithostratigraphic columns, with the goal of emphasizing the differences between extensional/transtensional continental arc basins in the early versus late stages of subduction (Table 19.1)

Many modern continental arcs clearly include examples of contractional structures and associated basins (e.g., Tibaldi et al., 2009), but these generally do not have the preservation potential of

extensional and transtensional basins in continental arcs, which are better represented in the geologic record. Extensional continental arc basins preserve very thick, continuous sequences (Smith and Landis, 1995), and have high magma production rates (e.g. Taupo volcanic zone; White et al., 2006). Therefore, they are an important contributor to the growth of continents. For this reason, it is important to understand how they evolve. The goal of this chapter is to give the reader an overview of the geodynamic setting, structure, basin architecture, sedimentology, and volcanology of extensional and transtensional continental arc basins. This is done in the context of an evolutionary tectonic model for long-lived, Mesozoic, and Cenozoic subduction under the western US.

TECTONIC SETTINGS AND EVOLUTION OF THOUGHT

Prior to the late 1980s, the term “Andean arc” was commonly applied to all volcanoplutonic arcs formed on continental crust, leading to the notion that continental arcs are characteristically high-standing regions of uplift, formed under contractional strain regimes (e.g., Hamilton, 1969; Burchfiel and Davis, 1972). At that time, only a few workers had proposed that continental arcs may instead occupy deep, fault-bounded depressions that owe their origin to extension or transtension. In this respect, modern examples of extensional or transtensional arcs were recognized only in the Central American arc (Burkart and Self, 1985), the Kamchatka arc (Erlich, 1979), and the Sumatra arc (Fitch, 1972). Although active extension was recognized across the Taupo volcanic zone, it was inferred to represent a backarc setting (Cole, 1984),

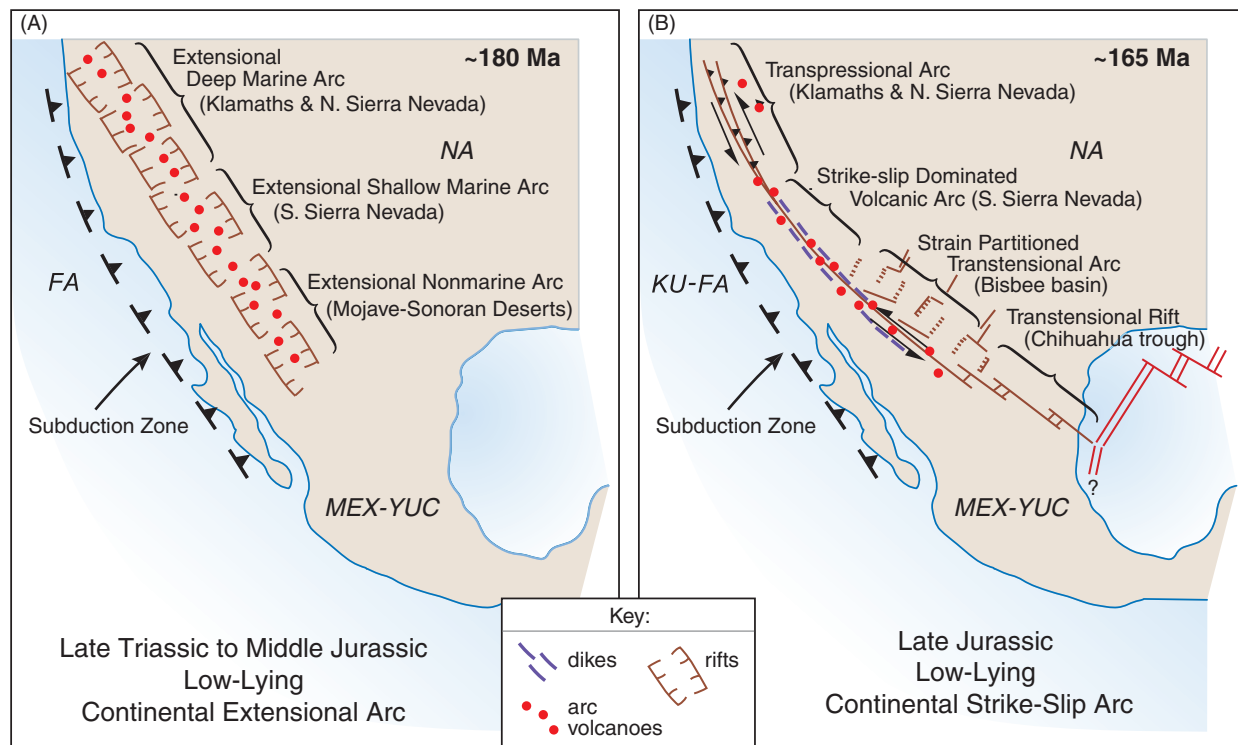


Fig. 19.1. The Late Triassic to Jurassic low-lying extensional to transtensional continental arc in the SW US. (A) The Late Triassic to Middle Jurassic arc was dominantly extensional, probably due to high rates of slab rollback during subduction of old, cold lithosphere (Busby-Spera, 1988; Busby et al., 2005). (B) The Late Jurassic arc records sinistral oblique convergence along sinistral strike-slip faults related to rifting along the Gulf of Mexico (Silver and Anderson, 1974). The curvature of the continental margin relative to these faults resulted in transpression in the north and transtension in the south (Saleeby and Busby-Spera, 1992).

until later geologic and geochronological studies demonstrated that it is an extensional continental arc basin (Houghton et al., 1991). Because modern examples of extensional or transtensional continental arcs are few, their origins were poorly understood, and tectonic models for extensional arcs in the geologic record were considered speculative (Busby-Spera, 1988). Nonetheless, an extensional setting seemed to be required to explain the continuous belts of very thick continental arc sequences that are common in the geologic record (Busby-Spera, 1988). This was a case where actualistic models did not satisfactorily explain a volumetrically significant contributor to the growth of continents.

By the early 1980s, it was understood that extensional oceanic arcs are produced by slab rollback during subduction of old, cold oceanic lithosphere, but that mechanism was not initially proposed for continental arcs (Molnar and Atwater, 1978; Dewey, 1980). At the same time, it was becoming increasingly clear that in its early stages,

the continental arc along the western edge of both North and South America was at least in part a rapidly subsiding feature (Busby-Spera, 1983; Maze, 1984; Burke, 1988). This suggested a process that was underrepresented in the modern world.

Jarrard's (1986) analysis of the dynamic controls on the tectonics of modern arc-trench systems showed a strong positive correlation between the longevity of a subduction zone and the amount of compressional strain in the overriding plate. Jarrard (1986) also showed that most subduction zones in the world have been running for a long time. This led me to speculate that, during the breakup of Pangea in early Mesozoic time, the paleo-Pacific Ocean basin was composed of very large, old lithospheric plates that subducted to produce extensional continental arcs along the western margin of the paleo-Pacific ocean basin (Busby et al., 1998; Figure 19.1A). Since the modern world is dominated by long-lived subduction zones, we must look to the geologic record to learn more about the growth of continents in extensional

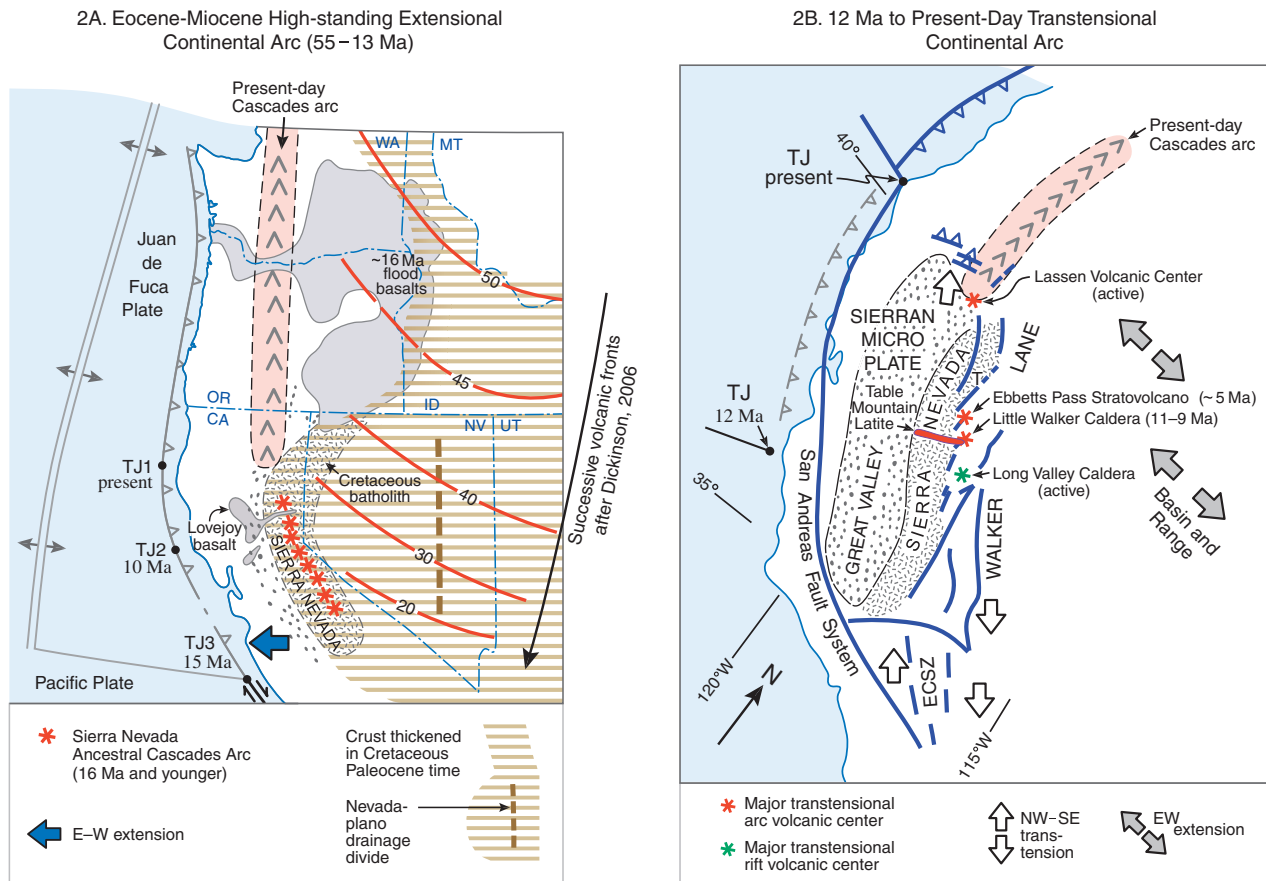


Fig. 19.2. The Cenozoic high-standing extensional to transensional continental arc of the western US. (A) Migratory Eocene to Miocene arc volcanism in the Great Basin: the arc migrated southwestward, accompanied by extension resulting from slab steepening/rollback during ongoing subduction (Dickinson, 2006; Cousens et al., 2008; Busby and Putirka, 2009). This extension was superimposed across a high, broad plain produced by low-angle subduction time under a contractional strain regime during Late Mesozoic to Paleocene time, termed the “Nevadapiano” (DeCelles, 2004). Also shown is the locus of the Cretaceous Sierra Nevada batholith and its extension into northwest Nevada, and relicts of basins active during unroofing of the batholith in Late Cretaceous to Tertiary time (dot pattern) during the low-angle subduction that preceded slab fallback. Slab fallback was completed by 16 Ma, when the arc front reached the position of the eastern Sierra Nevada, and arc extension between 16 and 11 Ma was likely controlled by development of the San Andreas Fault system (south of the triple junction), and direct interaction between the North America and Pacific plates (Dickinson, 2006). The ~16 Ma flood basalts were mainly erupted in a backarc position, except for the Lovejoy basalt of California, which erupted within or immediately in front of the arc front (Garrison et al., 2008; Busby and Putirka, 2009). The sea-floor reconstruction is shown at 15 Ma (Dickinson, 1997), showing positions of the triple junction at 15 Ma and 10 Ma (see also Atwater and Stock, 1998). TJ1 (the present position of triple junction between the San Andreas Fault, the Cascadia subduction zone, and the Mendocino fracture zone) is shown for reference. (B) Transensional 12 Ma to recent arc volcanism at the trailing edge of the Sierra Nevada microplate. Following the widely used Figure 19.1 of Unruh et al. (2003), the perspective shown is an oblique projection of the western Cordillera about the preferred Sierra Nevada–North American Euler pole. The Sierran microplate lies between the San Andreas fault and the Walker Lane belt, which currently accommodates 20–25% of the plate motion between the North American and Pacific plates, and may represent the future plate boundary (see references in Busby and Putirka, 2009). Plate-tectonic reconstructions show a change from more westerly motion to more northerly motion of both the Pacific plate and the Sierra Nevada microplate, relative to the Colorado Plateau, at 10–12 Ma (see references in McQuarrie and Wernicke, 2005). This indicates that the Sierra Nevada microplate was born at that time (see text). The biggest volcanic centers lie in transensional basins, including an active rift center (Long Valley caldera) and an active arc center (Lassen), as well as a Miocene arc caldera (Little Walker) and a Miocene arc stratovolcano (Ebbetts Pass). The structural setting of the biggest Miocene arc volcanoes is compared with that of the modern Long Valley caldera in Figure 19.8.

Table 19.1.

Geodynamic setting & age (SW U.S.A.)		Early-Stage Low-Lying Continental Arc Basins		Late-Stage High-Standing Continental Arc Basins	
		Subduction of old, cold oceanic lithosphere		Slab roll back	Microplate capture
Basin substrate	Late Triassic to Middle Jurassic Extensional Arc (Figures 1A, 3, 4, 6A, 6B)	Late Jurassic Transensional Arc (atop extensional arc) (Figures 1B, 5, 6C)	Eocene to Miocene Extensional Arc (migratory) (Figures 2A, 7)	12 Ma to Present Transensional Arc (trailing edge of microplate) (Figures 2B, 7)	
	Deeply-subsidised supracrustal rocks (no preceding uplift).	Down-dropped extensional arc strata and uplifted basement in close proximity.	Cretaceous mesozonal plutons unroofed and cut by long paleocanyon systems on the "Nevadaplano."	Down-dropped Eocene to Miocene extensional arc strata + uplifted basement blocks.	
Structure & Unconformities	Uniformly fast & continuous subsidence along syndepositional normal faults ⇒ UNCONFORMITIES RARE.	"Porpoising" on all scales along coeval normal and reverse faults ⇒ NUMEROUS DEEP UNCONFORMITIES.	Thermal uplift and E-W extension follows slab rollback and inrush of asthenosphere ⇒ UNCONFORMITIES.	NW-SE transension produces NNW-trending and NE-trending normal faults, with right-lateral & left-lateral component of motion (respectively). Transensional pulses ⇒ unconformity followed by magmatic pulse.	
	Arc graben-depression locally subsides below sea level and acts as a sink for craton-derived sediment (not a barrier).	Complex topography disrupts large depositional systems; localized sediment sources.	Paleocanyons cut onto western flank of Nevadaplano funnel material westward to California Great Valley.	Derangement of west-flowing paleocanyons along the Western Walker Lane Belt ⇒ ≈ N-S drainages form.	
Volcanism	Wide spread silicic large-volume caldera-forming eruptions.	Silicic calderas restricted to releasing step-overs; smaller centers along releasing bends.	Silicic calderas on Nevadaplano crest, followed by intermediate-composition volcanism as arc swept west across thinner crust. Lovejoy flood basalt vented at 16 Ma along fault-controlled fissure.	Large volcanic centers sited on fault step-overs (e.g. Little Walder Caldera at ≈ 10 Ma; Ebbetts Pass stratovolcano at ≈ 5 Ma; Lassen Volcanic Center today.) Tapping of deep melts beneath a thick crustal filter along lithospheric scale pull-apart structures ⇒ high-K volcanism including "flood andesite."	
	Fault scarps and horst blocks buried by pyroclastic debris ⇒ sparse epiclastic debris.	Abundant epiclastic debris and landslides shed off intrabasinal and extrabasinal highs.	Primary volcanic rocks, reworked down-paleocanyon into volcanic debris flow and stream flow deposits (westward).	Landslides shed off extrabasinal and intrabasinal highs. Streams flow N-S.	

LOW-ANGLE SUBDUCTION
Cretaceous crustal shortening and thickening due to

arcs during the early stages of subduction (Table 19.1; Busby, 2004). This topic is the focus of the first section of this chapter.

Throughout the 1990s and into the 2000s, there was also a growing appreciation for the importance of strike-slip fault systems in modern and ancient arc terranes. This is because (1) oblique convergence is far more common than orthogonal convergence, and at most continental arcs, an obliquity of only 10 degrees 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). Strike-slip faults were described from a number of modern continental arcs, including the Trans-Mexican Volcanic belt (van Bemmelen, 1949), the Andean arc (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), and the central Philippine arc (Sarewitz and Lewis, 1991). However, studies of intra-arc strike-slip basins remain sorely lacking, relative to studies of strike-slip basins along transform margins (Busby and Bassett, 2007). In the second section of this chapter, I describe the key features of Late Jurassic strike-slip intra-arc basins that formed along the axis of earlier Late Triassic to Middle Jurassic extensional continental arc basins, in what is now the Mojave-Sonoran Deserts of California and Arizona (Figure 19.1B). These intra-arc strike-slip basins can be distinguished from the underlying extensional arc basins on the basis of their fill and structure (Table 19.1).

In the third section of this chapter, I describe extensional continental arc basins that form during the later stages of subduction, under conditions of slab rollback/steepening beneath pre-thickened continental crust (Figure 19.2A; Table 19.1). The crust was pre-thickened during Cretaceous to Paleocene time, when the arc migrated eastward under a contractional strain regime, due to progressive shallowing of the subducting slab (Coney and Reynolds, 1977; Humphreys, 2008, 2009; Dickinson, 2006; DeCelles et al., 2009). This produced a high plateau, referred to as the “Nevadaplano” by DeCelles (2004) because of its similarity to the modern Altiplano of the Andean arc (Figure 19.2A). Then, in Eocene to Miocene

time, volcanism in the SW US and northern Mexico migrated westward (Figure 19.2A); this has been interpreted to record arc magmatism during slab steepening (Coney and Reynolds, 1977; Dickinson, 2006; Cousens et al., 2008). Other models have been proposed to explain this volcanism (e.g. Humphries, 2009) but I consider extensional basins that formed within these volcanic belts to be intra-arc basins (see summary in Busby and Putirka, 2009). Plate-tectonic reconstructions of McQuarrie and Wernicke (2005) show that this extension was E-W (Figure 19.2A).

In the fourth section of this chapter, I describe transtensional arc basins that formed, and are still forming, due to microplate capture by the Pacific plate, beginning at 12 Ma (Figure 19.2B; Table 19.1). By 16 Ma, the arc front (and associated extensional structures) had swept trenchward until it encountered the great Cretaceous batholith of the Sierra Nevada (Figure 19.2A). From 16 to 12 Ma, Miocene intra-arc thermal softening weakened the continent just inboard of a strong continental block (which still remains largely unfaulted today). Plate-tectonic reconstructions of McQuarrie and Wernicke (2005) show a change from more westerly motion to more northerly motion of both the Pacific plate and the Sierra Nevada microplate, relative to the Colorado Plateau, at 10–12 Ma (Figure 19.2B). Geodetic studies show that the transtensional eastern boundary of the Sierra Nevada microplate (Walker Lane Belt, Figure 19.2B) currently accommodates about 25% of the plate motion between North America and the Pacific plate (Unruh et al., 2003). This boundary is a reasonable approximation to a “classic” plate boundary, because it is discrete relative to its north and west boundaries, which are diffuse and complex due to structural interleaving by compressional and transpressional tectonics, respectively. The eastern microplate boundary is thus ideal for determining when the microplate formed, and for identifying the timing of features that signal the birth of a transtensional microplate boundary within the axis of an arc.

Although rifting has not yet succeeded in forming new sea floor along the Walker Lane Belt, I suggest that it has many features in common with the Gulf of California rift, including: (1) timing of initiation, at about 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 crustal profile on its western boundary. Rifting led to seafloor spreading very quickly in the Gulf of California (by 6 Ma), perhaps because the spreading center between the plate subducting under Mexico and the huge Pacific plate froze offshore of Mexico; the Pacific plate then pulled the dead slab northwestward, dragging the upper plate of the slab (Baja California) with it (Busby and Putirka, 2010a, 2010b). In contrast, continental breakup is still in progress in California, and the continent appears to be unzipping northward along the axis of the modern Cascades arc (Figure 19.2B).

EARLY-STAGE LOW-LYING CONTINENTAL ARC BASINS

Late Triassic to Middle Jurassic extensional arc

Paleogeographic elements of the early-stage low-lying extensional continental arc (Figure 19.1A) are shown in Figure 19.3A and Table 19.1. This feature was referred to as a “graben depression” by Busby-Spera (1988) to emphasize the fact that it was a low-lying feature (and not a graben at the apex of an uplifted region). Arc volcanoes lay within a >1,200 km-long graben that lay above sea level in the south (yellow), in a cratonal environment inherited from Paleozoic time, and below sea level in the north (blue), on Paleozoic miogeoclinal (thinned continental) to accretionary crust (see also Figure 19.1A). The Early to Middle Jurassic erg field of the present-day Colorado Plateau blew supermature quartz sands into, across, and along the full width and length of the arc graben depression, where tectonic subsidence preserved them to even greater thicknesses than they were in the backarc area of the present-day plateau (Figure 19.3B). Uniformly fast tectonic subsidence at rates of about 300–1,000 m/my resulted in preservation of nonmarine and shallow marine sections up to 10 km thick, with no erosional unconformities (Busby et al., 1990, 2005). In the southern Arizona segment of the continental arc, basement rocks outcrop nowhere at the surface, although they bound the graben-depression, and the isotopic characteristics of Mesozoic and Cenozoic igneous rocks indicate that they are present beneath it (Tosdal et al., 1989). This indicates that they are deeply buried beneath the arc graben depression. A recent paper by Haxel et al. (2005) emphasizes the importance of deep basins within

the Jurassic magmatic arc of southern Arizona. Silicic calderas and high-level silicic intrusions are abundant, as is typical of extensional arcs in both continental and oceanic settings (see references in Busby, 2004). Syndepositional normal faults are more difficult to identify, due to common reactivation as reverse faults during later (Cretaceous) stages of subduction, but in those cases, stratal patterns and fault talus wedges provide clear evidence for them. Additional evidence for arc rifting includes oxygen isotope data from Solomon and Taylor (1991), indicating that meteoric water penetrated deep into the crust, and Fe oxide-rich mineral deposits, indicating arc rifting in an arid environment (Barton and Johnson, 1996). The style of volcanism also records an arid environment: there are no deposits that would indicate eruption through caldera lakes or groundwater, such as phreatoplinian fall or nonwelded ignimbrite; instead, ignimbrites are strongly welded to ultra-welded (Busby et al., 2005). The arid environment is, of course, not an inherent feature of extensional arcs; it merely reflects the fact that the SW US lay in the horse latitudes in Early and Middle Jurassic time (Busby et al., 2005).

The structural and stratigraphic styles in a nonmarine sector of the early-stage low-lying extensional continental arc are shown in Figure 19.4A. Many small monogenetic volcanic centers were sited along numerous splays of the graben-bounding fault zone, frequently leaking magmas to the surface; this was referred to as a “multi-vent complex” by Riggs and Busby-Spera (1990). Vents were rapidly buried by eruptive products from other centers, or craton-derived eolian quartz sand, due to very high rates of tectonic subsidence. Like the rapidly extending continental arc of the Taupo Volcanic zone, fault scarps were buried too rapidly by pyroclastic debris to develop significant alluvial fans, and rapid subsidence prevented the development of erosional unconformities (Busby et al., 2005).

Silicic giant continental calderas (Figure 19.4B, 4D), or “supervolcanoes”, are common to the early-stage low-lying extensional continental arc setting (Table 19.1). For example, the Middle Jurassic Cobre Ridge caldera (Figure 19.4D) is 50 × 25 km in size, with at least 3.0 km of ignimbrite fill (Riggs and Busby-Spera, 1991). The unusually large size, the rectilinear shape, the NW-SE strike of bounding structures, the complex collapse history, and the great thickness of the fill of this caldera indicate regional structural controls on its development.

Late Triassic to Middle Jurassic Continental Arc Graben Depression

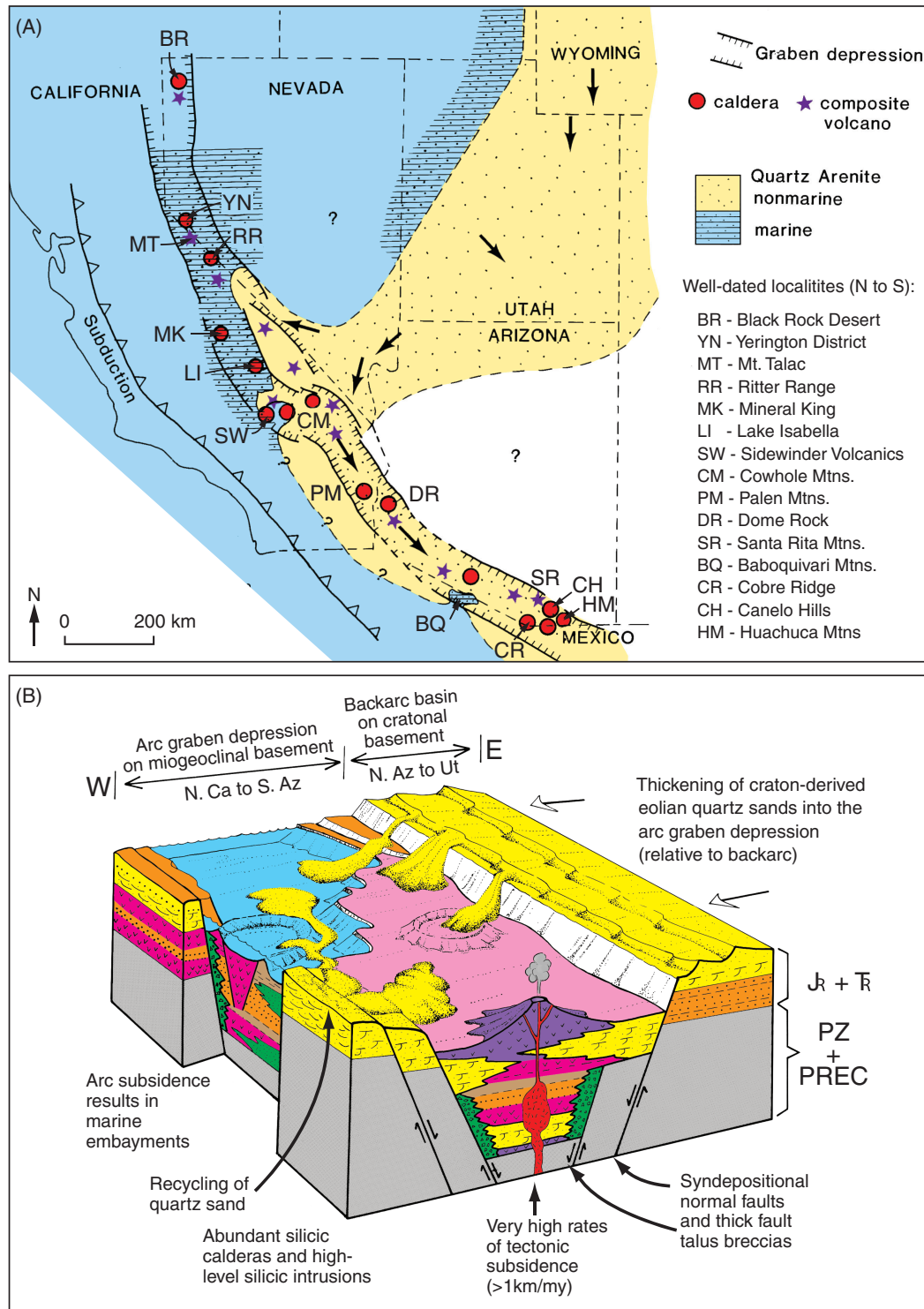


Fig. 19.3. Late Triassic to Middle Jurassic extensional continental arc “graben depression” in the SW US (Busby-Spera, 1988). (A) Paleogeographic map of the arc. (B) Evidence for extensional continental arc origin, summarized for the region shown in Figure 19.3A (Busby-Spera, 1988; Busby et al., 1990). Variations in basins fills, from submarine to nonmarine environments, are summarized in Figure 19.6A and 6B. N. Ca to S. Az = northern California to southern Arizona; N. Az to Ut = northern Arizona to Utah.

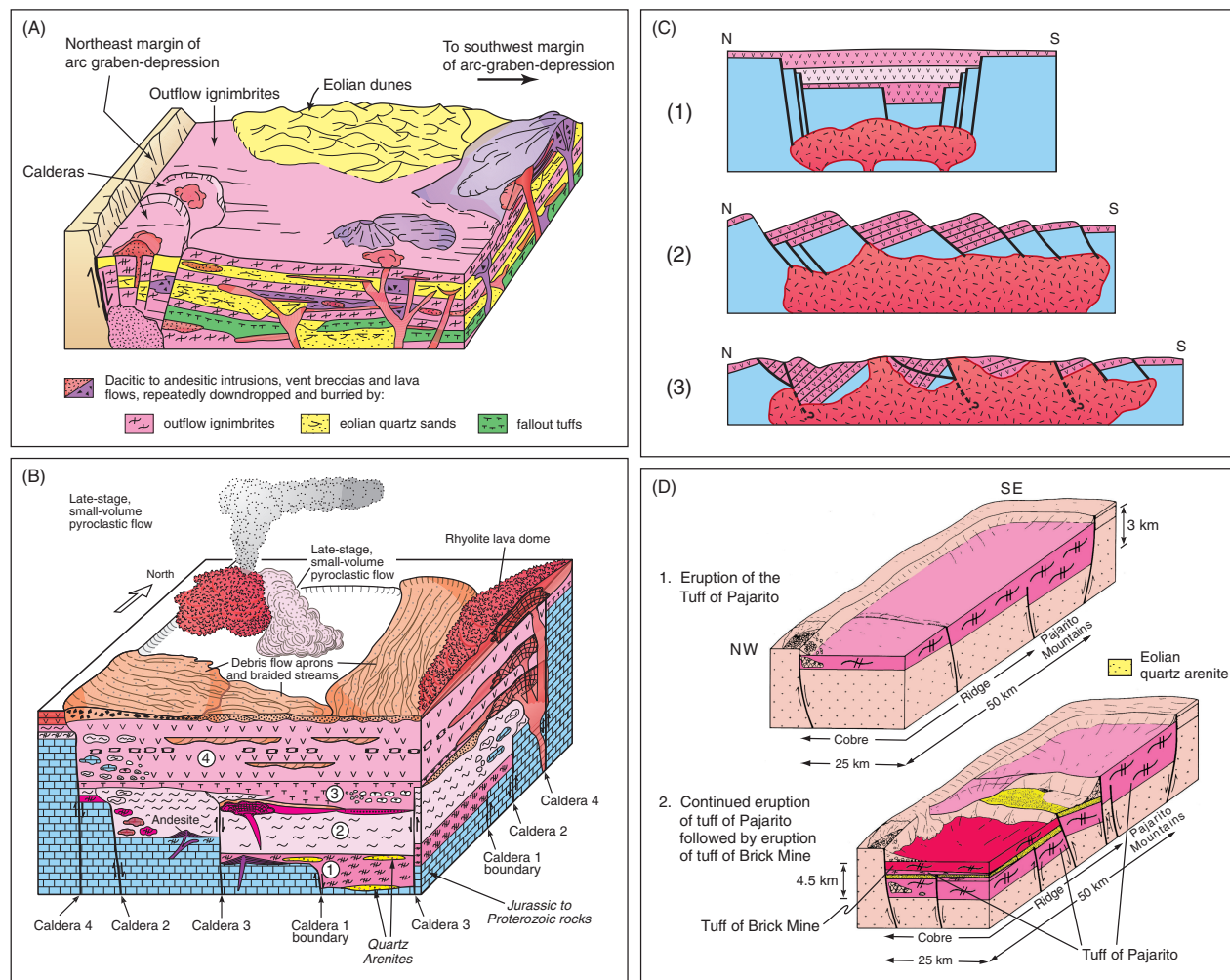
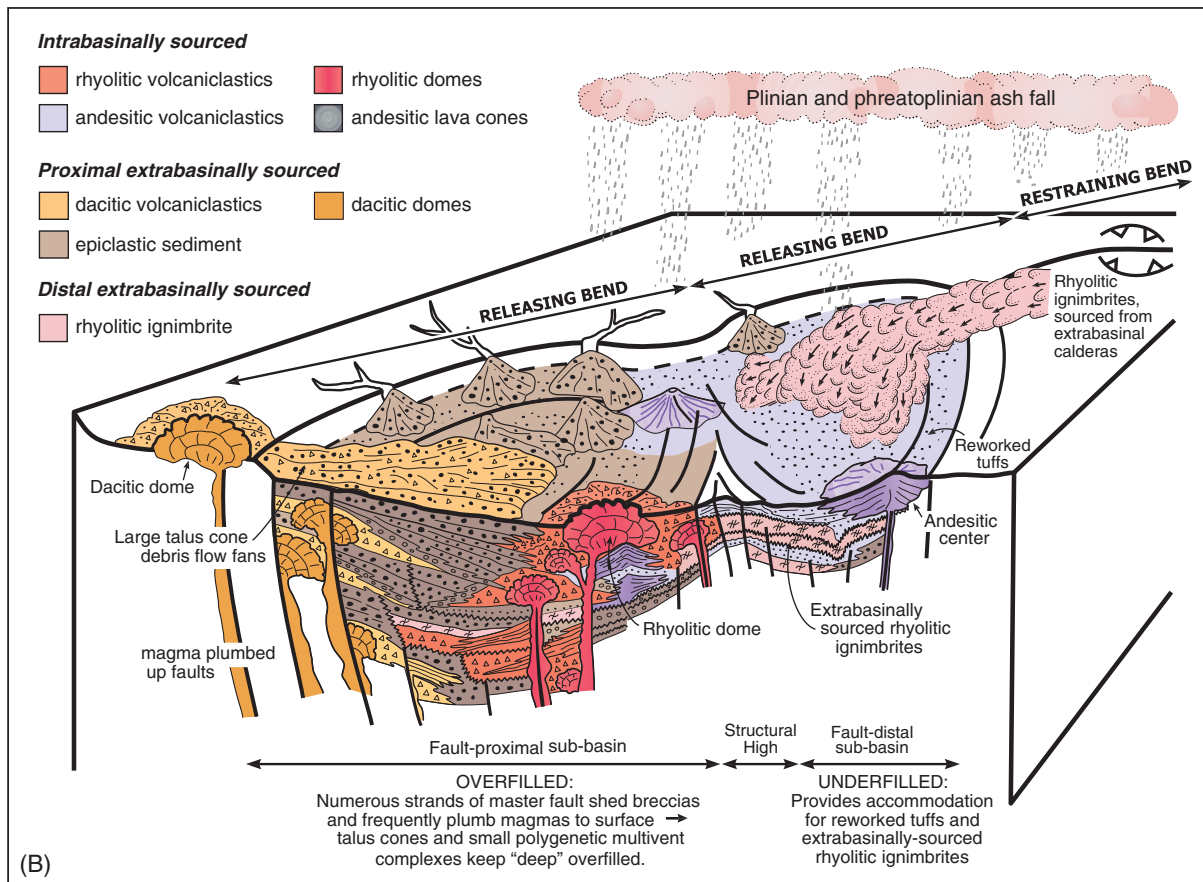
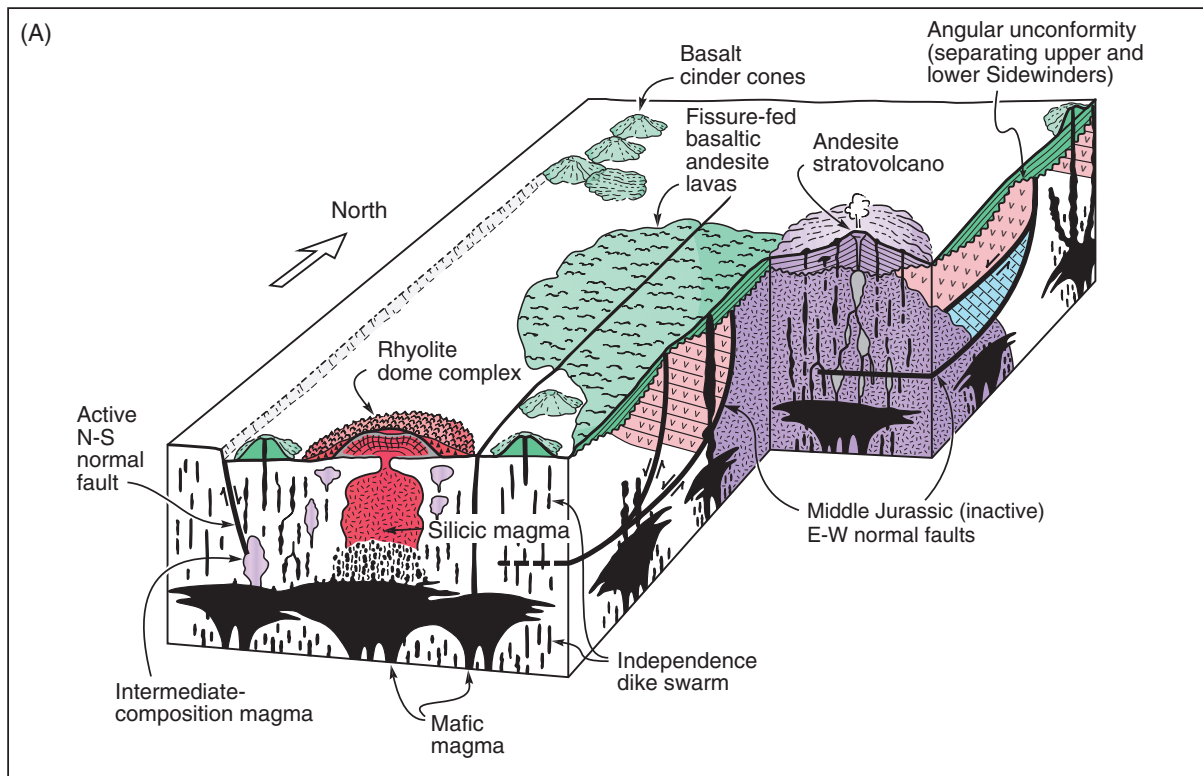


Fig. 19.4. Structural and stratigraphic styles of basins in the early-stage low-lying extensional continental arc (Triassic to Middle Jurassic, Arizona and California). (A) Northern margin of the extensional arc “graben depression,” Santa Rita Mountains area of southern Arizona (schematic; location “SR” on Figure 19.3A), from Riggs and Busby-Spera (1990). (B) Accommodation in a nested caldera complex, Lower Sidewinder volcanic series, central Mojave Desert (location SW on Figure 19.3A; Schermer and Busby, 1994). (C) Syn-magmatic extension and batholith unroofing (interpretive cross sections) showing Lower Sidewinder volcanic series calderas and associated batholithic rocks (1) getting offset by normal faults during ongoing batholith emplacement, (2) leading to partial unroofing of the batholith (3) prior to eruption of Upper Sidewinder volcanic series in a transtensional setting (Figure 19.5A). (Location SW on Figure 19.3A; from Schermer and Busby, 1994.) (D) Rectilinear “graben caldera” or “volcano-tectonic depression” controlled by regional-scale normal faults: Middle Jurassic Cobre Ridge caldera, southern Arizona (location CR, Figure 19.3A; Riggs and Busby-Spera, 1991).

The NW end of the caldera collapsed in two stages, recorded by deposition of eolian quartz sands during an eruptive hiatus of the tuff of Pajarito (ignimbrite), followed by eruption of the tuff of Brick Mine (ignimbrite; source unknown). The large, rectilinear, complex collapse characteristics of the Cobre Ridge caldera are similar to those of the Altiplano-Puna Volcanic Complex, where bigger eruptive centers are complex, large-scale structures influenced by tectonic grain. These are

referred to as “volcano-tectonic depressions” by de Silva and Gosnold (2007), following the terminology of van Bemmelen (1949). I thus agree with Dickinson and Lawton (Dickinson and Lawton 2001, p. 485) that “the influence of regional tectonics on local caldera collapse cannot be excluded” for the Cobre Ridge caldera. There may have been more “graben calderas” like the Cobre Ridge caldera in the early stages of subduction under the SW US, but geometries cannot



generally be reconstructed well, due to dismemberment by synvolcanic extension, or later (Cretaceous) shortening.

Nested caldera complexes provided accommodation for thick sequences within the early-stage low-lying extensional continental arc. For example, in the present-day Mojave Desert, the Lower Sidewinder volcanic series is dominated by four nested subaerial calderas that provided local accommodation for a >4 km aggregate thickness of ignimbrites, megabreccias, andesite lava flows, craton-derived eolian quartz arenites, and volcanoclastic sedimentary rocks (including fluvial and debris flow deposits; Figure 19.4B). Syn-magmatic normal faulting dropped these calderas down against their plutonic roots, which were unroofed by extension (Figure 19.4C). These plutons were then disconformably overlain by arc volcanic rocks erupted in a Late Jurassic transtensional regime (Figure 19.5A; Schermer and Busby, 1994).

Late Jurassic transtensional arc

Late Jurassic sinistral transtensional continental arc basins formed along the axis of earlier Jurassic extensional continental arc basins in Arizona and southern California (Figure 19.1B and Table 19.1; Saleeby and Busby-Spera, 1992; Schermer and Busby, 1994; Busby et al., 2005). The plate-margin-scale Independence dike swarm, which is 500 km long, was emplaced in the California segment of the arc (Figure 19.1B) at ≈ 148 Ma, and the structural levels of exposure in the Mojave Desert affords a unique view of the dike swarm's eruptive as well as hypabyssal intrusive equivalents (Figure 19.5A; Schermer and Busby, 1994). The Upper Sidewinder Volcanic Series (Figure 19.5A) is a broadly bimodal, alkalic suite of dikes, lavas, and vent breccias with compositions that include trachybasalt, basalt to basaltic andesite and comendite, comeditic trachyte, and rhyolite, consistent with an arc rift origin (see references in Schermer and Busby, 1994). Plutonic rocks show oxygen isotope evidence for deep

penetration of meteoric water, indicating arc rifting, as they do in the Middle Jurassic plutons of the region (Solomon and Taylor, 1991).

Silicic giant continental calderas continued to form in this setting (as in the extensional arc), but they were not as widespread (Table 19.1); instead, they appear to be restricted to symmetrical basins at releasing stepovers. For example, three Jurassic calderas in southern Arizona, first identified by Lipman and Hagstrum (1992), were inferred by Busby et al. (2005) to have formed along the sinistral Sawmill Canyon fault zone where strands of the fault progressively stepped westward in a releasing geometry. These calderas were then dismembered along the fault zone so their original shape (circular vs. rectangular) cannot be discerned.

In contrast with releasing stepover basins and calderas, releasing bends produce asymmetrical basins, with frequent but small-volume eruptions from multiple fault-controlled vents (Figure 19.5B and Table 19.1; Busby and Bassett, 2007). Releasing bend basins along transform plate boundaries have been studied for many decades, including Crowell's (1974, 1982, 2003) classic studies of the Ridge Basin, which formed in the early history of the San Andreas fault zone. In contrast, very little is known about the characteristics of releasing bend basins in magmatic arcs. For this reason, the structural, stratigraphic and volcanological characteristics of a Late Jurassic transtensional arc basin are summarized here (Figure 19.5B), and contrasted with those of the Early to Middle Jurassic extensional arc. Before we can make those comparisons, however, we must consider the stratigraphic consequences of major climate change induced by large-scale translation of North America.

The Late Jurassic change in arc tectonic style, from extension to sinistral transtension, was apparently triggered at least in part by the opening of the Gulf of Mexico, which resulted in development of sinistral strike-slip faults in the upper plate, and oblique subduction under California and Arizona (Figure 19.1B). This was accompanied by rapid northward drift of North America out of the horse latitudes into temperate ones (Busby

Fig. 19.5. Structural and stratigraphic styles of basins in the early-stage low-lying transtensional continental arc (Late Jurassic, Mojave and Sonora Deserts of California and Arizona). (A) The Late Jurassic Upper Sidewinder volcanic series of the central Mojave Desert (Schermer and Busby, 1994) provides a view of the plate-margin scale Independence dike swarm (see dikes on Figure 19.1B) and its plutonic and eruptive equivalents. (B) The Late Jurassic Santa Rita Glance Conglomerate of southern Arizona (Busby and Bassett, 2007) provides a view of an intra-arc strike-slip basin. This contrasts with the older, purely extensional basins (Figure 19.4) mainly by having reverse-slip faults coeval with normal-slip faults, extremely deep unconformities, and a much higher proportion of epiclastic sediment (see text).

et al., 2005; Figure 19.1B). Paleomagnetic data show that SW North America was translated about 15 degrees northward, from equatorial latitudes, between about 185 and 160 Ma, and even more rapidly, another 13 degrees further northward, between about 152 and 150 Ma (Busby et al., 2005). By the end of the Jurassic, eolian sedimentation was replaced by fluvial sedimentation, as shown by sedimentary sequences in both backarc regions (now on the Colorado Plateau) and within the arc (Busby et al., 2005). The style of volcanism in the arc also changed radically, from a “dry” eruptive style recorded by welded and ultrawelded ignimbrites (similar to the modern Basin and Range), to a “wet” eruptive style, typified by eruptions through lakes, which produce phreato-plinian fall and nonwelded ignimbrites (similar to Taupo Volcanic Zone today; Busby et al., 2005). Thus, the Late Jurassic arc basin fill shown in Figure 19.5B lacks eolian sediment, and instead contains “sandstones” (Drewes, 1971), which are actually fluvially reworked tuffs made of delicate glass shards and euhedral crystals. The phreato-plinian tuffs are extremely widespread, very distinctive deposits made up of finely laminated or convolute-laminated white to pink porcellanite. These were the effects of major tectonically induced climate change on basin fill.

Tectonically controlled differences between Late Jurassic transtensional arc basins and the older (Early to Middle Jurassic) extensional arcs basin are numerous (Table 19.1; Busby et al., 2005). The transtensional arc basin shown in Figure 19.5B is asymmetric, with a dominant basin-bounding strike-slip fault on one side, and a much less regionally significant fault on the other side. Detailed stratigraphic analysis shows that the high-angle intrabasinal faults alternated between normal-slip and reverse-slip separation with time, and some faults with dip-slip separation were active synchronously with faults showing reverse-slip separation elsewhere in the basin; this is typical of strike-slip basins (see full discussion with references in Bassett and Busby, 2005). The basin fill thins dramatically away from the major strike-slip fault, because subsidence is greatest adjacent to it. Furthermore, vent-related deposits (rhyolitic lava domes and andesitic lava cones) and their feeders decrease away from the strike-slip fault, because the faults they exploit are more abundant near it. Talus cone and alluvial fan deposits (“epiclastic sediment”; Fig. 19.5) are restricted to the “deep” end of the basin, near

the strike-slip fault. These deposits include blocks or boulders up to 4 m across at distances of up to 2 km from the strike-slip fault. Dacite domes sited on the strike-slip fault repeatedly shed block-and-ash flows into the deep end of the basin. The end of the basin adjacent to the strike-slip fault is “overfilled”, due to high epiclastic sediment supply from the strike-slip fault, and abundant intrabasinal volcanism. The “underfilled” end of the basin (distal from the strike slip fault) provided accommodation for fluvially reworked tuffs, as well as extrabasinally sourced pyroclastic flows that were erupted from calderas at releasing stepovers.

The cross-sectional view of the transtensional arc basin fill (perpendicular to the master fault) shows numerous erosional unconformities of two types (shown as zigzagging black lines on the sides of the block diagram, in Figure 19.5B): (1) distal to the strike-slip fault lie symmetrical erosional unconformities, 200–600 m deep, with paleo-slope gradients of 20–25°; these are interpreted to represent deep river canyons that were carved into the basin during uplift events at restraining bends. (2) Proximal to the strike-slip fault lie highly asymmetrical unconformities with extreme vertical relief (460–910 m) and very high paleo-slope gradients (40–71° on the side adjacent to the strike-slip fault; Figure 19.5B). These represent fault scarps and paleo-landslide scars created during basin uplift (inversion) events that occurred as the basin moved along restraining bends of the strike-slip fault (Busby and Bassett, 2007). By analogy, basin cannibalization has been imaged seismically in an active strike-slip basin of offshore New Zealand, where one end of a basin is upthrust and has landslide scars, and the other edge is downdropped and contains slide deposits (Barnes et al., 2001). This is consistent with the fact that landside blocks are common in Late Jurassic basin fill deposits elsewhere in basins along the Sawmill Canyon fault zone (Busby et al., 2005). Because basin fills are destroyed at restraining bends, partial preservation of the basin fill is only possible in overall transtensional systems (Bassett and Busby, 2005).

We include Late Jurassic transtensional arc basins in the “early-stage low-lying” category (Table 19.1) because the arc volcanic rocks in southern Arizona and northern Mexico are at least in part overlain by the Early Cretaceous Mural limestone, which was deposited during an eustatic high sea level stand in a seaway that was probably connected through the Chihuahua trough to the

Gulf of Mexico (Figure 19.1B; Dickinson et al., 1986, 1987, 1989).

SUMMARY OF EARLY-STAGE LOW-LYING CONTINENTAL ARC BASINS

Key features of the Early to Middle Jurassic early-stage low-lying extensional and Late Jurassic trans-tensional continental arc are summarized in Figure 19.6 and Table 19.1.

Subsidence in the extensional arc was uniformly fast and continuous along syndepositional normal faults (Busby-Spera, 1988; Busby-Spera et al., 1990; Riggs and Busby-Spera, 1990; Riggs et al., 1993; Haxel et al., 2005). Shallow marine and deep marine deposits dominated in the north (Figure 19.1A), where the arc was built across thinned continental crust and transitional crust, while nonmarine deposits dominated in the south, where the arc was built upon the craton. In the marine realm (Figure 19.6A), welded ignimbrites were deposited in deepwater calderas, and turbidite fans were built of resedimented silicic pyroclastic debris. Steam explosions contributed to the fragmentation of eruptive products, producing hyaloclastite lavas and hyalotuffs. In the nonmarine realm, large-volume welded ignimbrites dominate the volcanic deposits (Figure 19.6B), with smaller andesitic centers located along fault strands (Figure 19.4B). Craton-derived supermature sediment was ponded in the arc graben depression throughout this time, as eolianites on the nonmarine realm, and as shelfal and turbiditic sandstones in the marine realm. Silicic calderas were large and numerous in both marine and nonmarine settings, and epiclastic sedimentation was minimal, due to burial of fault scarps by abundant pyroclastic debris, although landslide megabreccias were shed from normal faults.

In contrast, releasing-bend basins of the early stage transtensional arc (Figure 19.6C) experienced rapidly alternating uplift and subsidence, or “porpoising,” that is, the result of temporal alternations between subsiding releasing bends and uplifting restraining bends along a strike-slip fault. Unlike extensional basins, individual intrabasinal faults alternated between normal- and reverse-slip over time, and reverse faults operated in some parts of a basin at the same time that normal faults were active in another part. Uplift events produced numerous large-scale unconformities, in the form of deep paleocanyons

and huge landslide scars, while giant slide blocks of “cannibalized” basin fill accumulated in subsiding areas (Figure 19.6C; Bassett and Busby, 2005; Busby and Bassett, 2007). Erosion of pop-up structures along restraining bends yielded an impressive epiclastic sediment supply. Releasing-bend basins lack silicic calderas, and instead have multiple monogenetic centers sited along fault strands.

Releasing stepover basins of the early stage transtensional arc lack reverse faults and epiclastic sediments, because there are no adjacent pop-up structures to supply them (Figure 19.6B). Some segments are dominated by silicic calderas and ignimbrite outflow deposits, while other segments are dominated by broadly bimodal dike swarms that act as feeders to lava flows, lava domes, and small stratocones or cinder cones.

LATE-STAGE HIGH-STANDING CONTINENTAL ARC BASINS

In this section, I describe late-stage high-standing continental arc basins of the western US, dividing them into two types: (1) those formed by extension of the “Nevadaplano” during Eocene to Miocene slab rollback (Figure 19.2A), and (2) those formed by transtension as the Sierra Nevada microplate began to calve off the western edge of the Nevadaplano at 12 Ma (Walker Lane belt, Figure 19.2B). Features of these basins are summarized in Table 19.1.

Eocene to Miocene extensional arc

During Late Cretaceous to Paleocene time, the Cretaceous arc terrane was unroofed to batholithic levels across the broad uplift referred to as the “Nevadaplano,” with “paleochannels” or “paleocanyons” hundreds of m deep carved into it (shown as unconformity 1 on Figure 19.7). The approximately N-S paleo-drainage divide for these channels lay at the crest of the Nevadaplano, in eastern Nevada (Figure 19.2A); channels on the west flank of the divide extended westward from there all the way to the Great Valley of California, as shown by the paleochannel fills consisting of ignimbrites erupted near the crest of the Nevadaplano (Henry, 2008; see sequence 1 on Figure 19.7). These paleo-channels are better preserved and exposed in the Sierra Nevada than they are in the Basin and Range to the east, where they are disrupted by faults and buried beneath basins.

LOW-LYING CONTINENTAL ARC

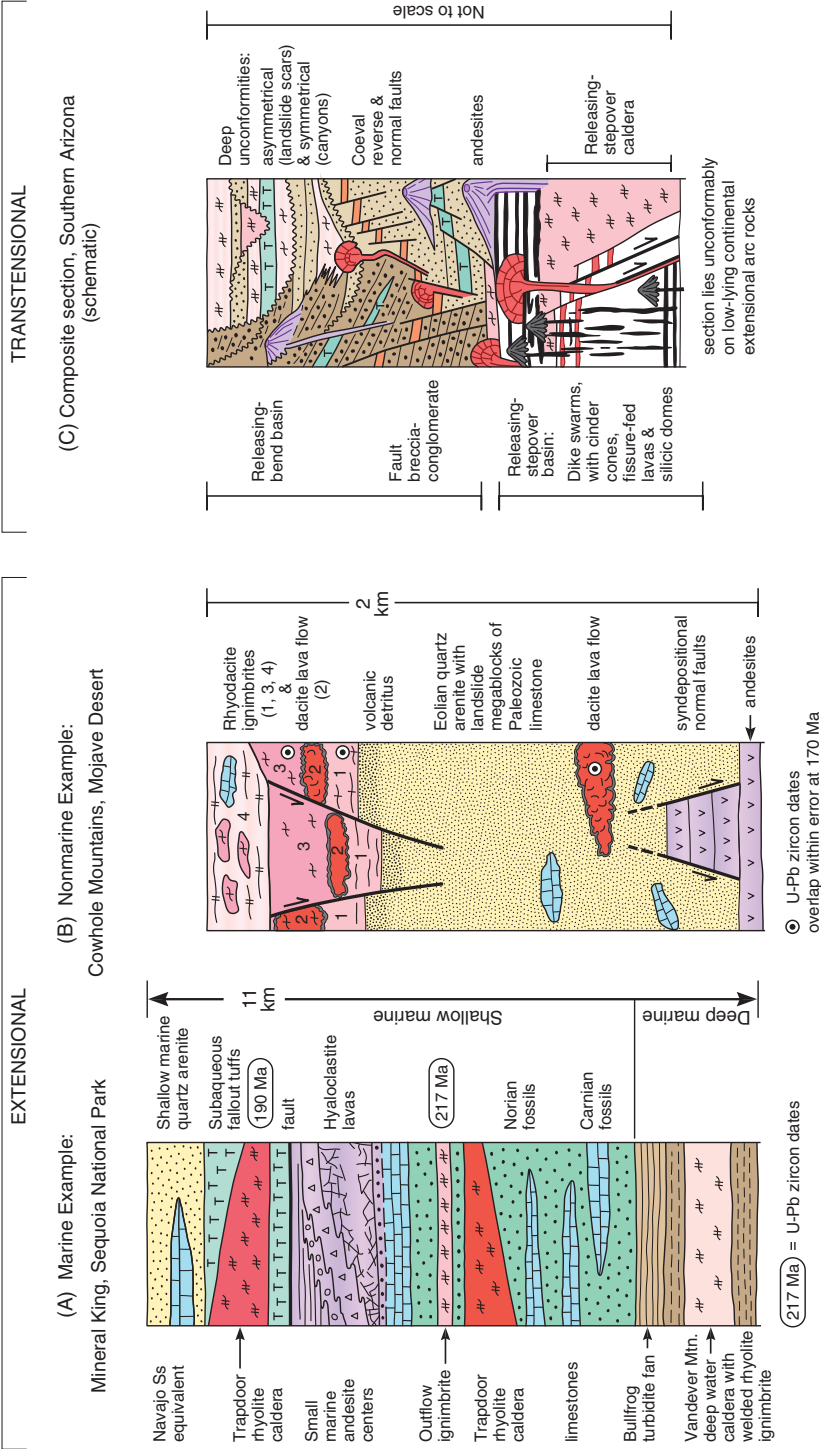


Fig. 19.6. Representative measured stratigraphic sections from the early-stage, low-lying extensional continental arc (a and b), and composite stratigraphic column for the early-stage, low-lying transtensional continental arc (c). (A) Marine facies at Mineral King, Sequoia National Park, California (location MK on Figure 19.3A). An 11 km-thick deep marine to shallow marine section includes giant continental calderas and outflow ignimbrites, small andesite stratocones, turbidite fans, and very thick shallow marine successions that indicate rapid tectonic subsidence, including limestones and tempestites. All of the sedimentary material is reworked from volcanic sources, except for the quartz arenites with limestone lenses at the top of the section; these may be the shallow marine equivalents of the Navajo Sandstone, and represent wind-blown sands reworked by marine currents (Busby-Spera, 1983, 1984a, 1984b, 1985, 1986; Kokelear and Busby, 1992). (B) Nonmarine facies in the Cowhole Mountains, eastern Mojave Desert (location CM on Figure 19.3A; from Busby et al., 2002). Silicic lava flows and ignimbrites are interstratified with >800 m thick eolian quartz arenite, recording ponding of craton-derived supermaturation sand within the arc graben depression (Figure 19.3). Like column A, erosional unconformities are absent, probably due to uniformly high subsidence rate, and epiclastic sediment is absent, probably due to burial of fault scarps by pyroclastic debris, although landslide megablocks were shed from fault scarps (Busby et al., 2002). (C) Low-lying continental transtensional arc basins include two types: (1) releasing-bend basins, characterized by “porpoising” basins with coeval/alternating normal-slip and reverse-slip faults, numerous small monogenetic volcanic centers, deep unconformities, and abundant epiclastic sediment (Busby and Bassett, 2007); and (2) releasing stepover basins, dominated by giant continental calderas and dike swarms/effusive complexes with broadly bimodal alkalic compositions (Schermer and Busby, 1994).

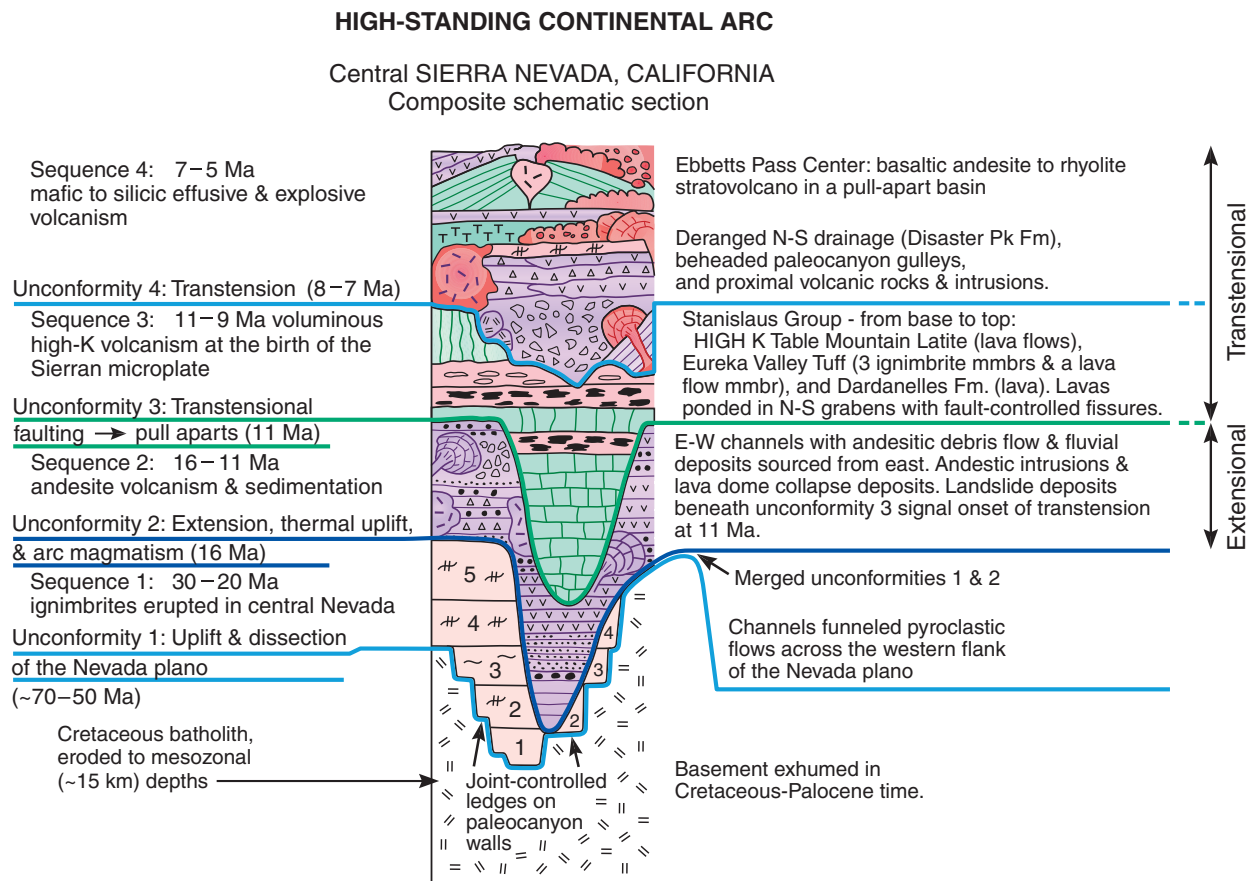


Fig. 19.7. Composite stratigraphic column (schematic) for late-stage, high-standing extensional and transtensional continental arc basins: Unconformity-bounded Ancestral Cascades arc sequences preserved in paleocanyons and grabens of the central Sierra Nevada, western Walker Lane belt, California (generalized from Busby et al., 2008a, 2008b; Busby and Putirka, 2009; Busby et al., 2009a, 2009b). The paleocanyons were carved in Late Cretaceous-Paleocene time (unconformity 1), into the western flank of the “Nevadaplano,” a Altiplano-like plateau that formed in response to low angle subduction. These paleocanyons funneled ignimbrites westward from their arc source calderas in central Nevada, to central California (sequence 1). Grabens formed in response to extension and thermal uplift that accompanied the southwestward sweep of arc magmatism, as the subducting slab fell back to steeper depths during Eocene to Miocene time (Figure 19.2A). Unconformity 2 records arrival of the arc front into eastern California-western Nevada at 16 Ma, and sequence 2 is dominated by andesite volcanic rocks. Unconformity 3 and sequence 3 records the onset of transtensional calving of the Sierra Nevada microplate (Figure 19.2A) off the western edge of the Nevadaplano (see text). Unconformity 4 corresponds to a third phase of arc uplift and extension, followed by development of large volcanic centers along the faults (sequence 4, see text). Further discussion in text.

Thus, Sierran paleochannels provide the best opportunity to understand the paleogeography of the western flank of the Nevadaplano, and its Cenozoic history (Busby et al., 2008a, 2008b; Busby and Putirka, 2009; Hagan et al., 2009).

Ignimbrites that gradually accumulated over a long period (from <30 to 20 Ma) were deeply dissected along unconformity 2 prior to the first pulse of arc volcanism, dated at 16–13 Ma (Fig. 19.7). Recent stable isotope work has shown that the southwestward sweep of the arc through Idaho and Nevada was accompanied by synchronous extension and increase in surface elevation,

interpreted to record thermal effects as the Farallon slab fell back (Horton and Chamberlain, 2006; Kent-Corson et al., 2006; Mulch et al., 2007). Evidence for extension at the onset of arc volcanism in the Sierra Nevada (Figure 19.7) is summarized by Busby and Putirka (2009). Therefore, I infer that unconformity 2 (Figure 19.7) records uplift and extension as the arc front swept westward into what is now the western Walker Lane belt and eastern Sierra Nevada (Figure 19.2).

Sequence 2 consists of andesitic arc volcanic rocks, including shallow-level intrusions, block-and-ash-flow tuffs, volcanic debris flow deposits,

fluvial deposits, and minor lava flows (Figure 19.7). Volcanic centers were generally small, and sited along faults (Busby and Putirka, 2009). In the northern Sierra Nevada, however, sequence 2 rocks include the Lovejoy basalt (Figure 19.2A), which is the largest effusive eruptive unit in California (150 km^3). It erupted from a fissure along the Honey Lake fault zone (Garrison et al., 2008), which is one of the longest faults of the Walker Lane belt. The Lovejoy basalt flowed down the westernmost flank of the Nevadaplano through channels and spread out into California's Central Valley (Figure 19.2A). Although this fissure eruption probably records the onset of Sierra Nevada range front extension (Busby and Putirka, 2009), extension was not significant enough to disrupt the E-W paleocanyon/paleochannel systems, as shown by abundant 16–11 Ma fluvial sandstones that were sourced from the east (sequence 2, Figure 19.3). In contrast, the transtension discussed below (sequences 3 and 4, Figure 19.7) caused disruption of the ancient E-W drainage systems.

12 Ma to present-day transtensional arc

Unconformity 3 and sequence 3 strata of the central Sierra Nevada (Figure 19.7) record the onset of transtensional calving of the Sierra Nevada microplate off the western edge of the Nevadaplano, in the thermally weakened axis of the Ancestral Cascades arc (Figure 19.2B; Busby and Putirka, 2009). At about 12–11 Ma, transtension resulted in synvolcanic tilting of strata about normal faults, producing angular unconformities, and uplift resulted in deep erosional unconformities (Busby et al., 2008a). Huge landslides were unleashed, with individual blocks up to 1.6 km long (Busby et al., 2008a). This was immediately followed by voluminous high-K volcanism (sequence 3, Figure 19.7). These high-K volcanic rocks erupted within the Ancestral Cascades arc, and include the type locality of “latite” lava flows (Table Mountain Latite of Ransome, 1898), as well as distinctive, widespread trachydacite ignimbrites (Eureka Valley Tuff). Transtension enabled the transport and eruption of deep, low melt-fraction magmas high in K_2O , recording the birth of the Sierra Nevada microplate (Putirka and Busby, 2007).

The processes and products that signal the birth of the Sierra Nevada microplate include (Busby and Putirka, 2009, 2010a,b; Busby et al., accepted):

- (1) *Extreme effusive eruptions along fault-controlled fissures, including intermediate-composition fissure eruptions of “flood lava.”*

These “flood andesites” were erupted from 8 to 12 km-long fissures within volcanotectonic grabens that currently lie along the Sierra Nevada range crest and range front at Sonora Pass (Figure 19.8). The fissure vents for the “flood andesite” consist of massive (nonstratified) cinder rampart deposits, 100–200 m thick, with angular dense blocks up to 5 m across dispersed in a red matrix of unsorted scoria lapilli, bombs and ash. The Table Mountain Latite (Figure 19.7) was largely ponded to thicknesses of 300–400 m in the grabens, but some of it escaped westward out of the graben into an ancient paleochannel, where it is <50 m thick (Figure 19.8). That paleochannel funneled flows westward across the unfaulted Sierra Nevada block. One individual lava flowed at least 130 km westward (Gorny et al., 2009; Pluhar et al., 2009), an extremely unusual distance for an andesite, with a volume of 20 km^3 (the largest-volume intermediate-composition lava flow that I am aware of). The $>200 \text{ km}^3$ Table Mountain Latite lava flow field was erupted in only 28–230 kyr, between about 10.4 and 10.2 Ma (Busby et al., 2008a; Hagan, 2010; Busby and Putirka, 2010a, 2010b). Although most of the faults shown in Figure 19.8 have been reactivated since the Table Mountain Latite was erupted, at least half the displacement on them took place before and/or during eruption of the Table Mountain Latite (Hagan, 2010; Koerner, 2010; Busby et al., accepted).

- (2) *Development of large volcanic centers at sites of maximum displacement on releasing transtensional stepover faults.*

The Little Walker Caldera (Figure 19.8) formed at the site of maximum extension in the Table Mountain Latite volcanotectonic lava complex (Busby et al., 2008a; Hagan, 2010). The caldera erupted three large-volume ignimbrite sheets (Eureka Valley Tuff, Figure 19.7) at ~9.5–9.4 Ma. During Eureka Valley Tuff eruptions from the caldera, trachyandesitic to basaltic lavas continued to erupt from cinder cones along faults that emanated northwestward beyond the caldera, but trachydacitic lavas were also erupted from the faults; the latter are indistinguishable in composition from the Eureka Valley Tuff (Koerner and Busby, 2009; Hagan, 2010). One trachydacite vent along the

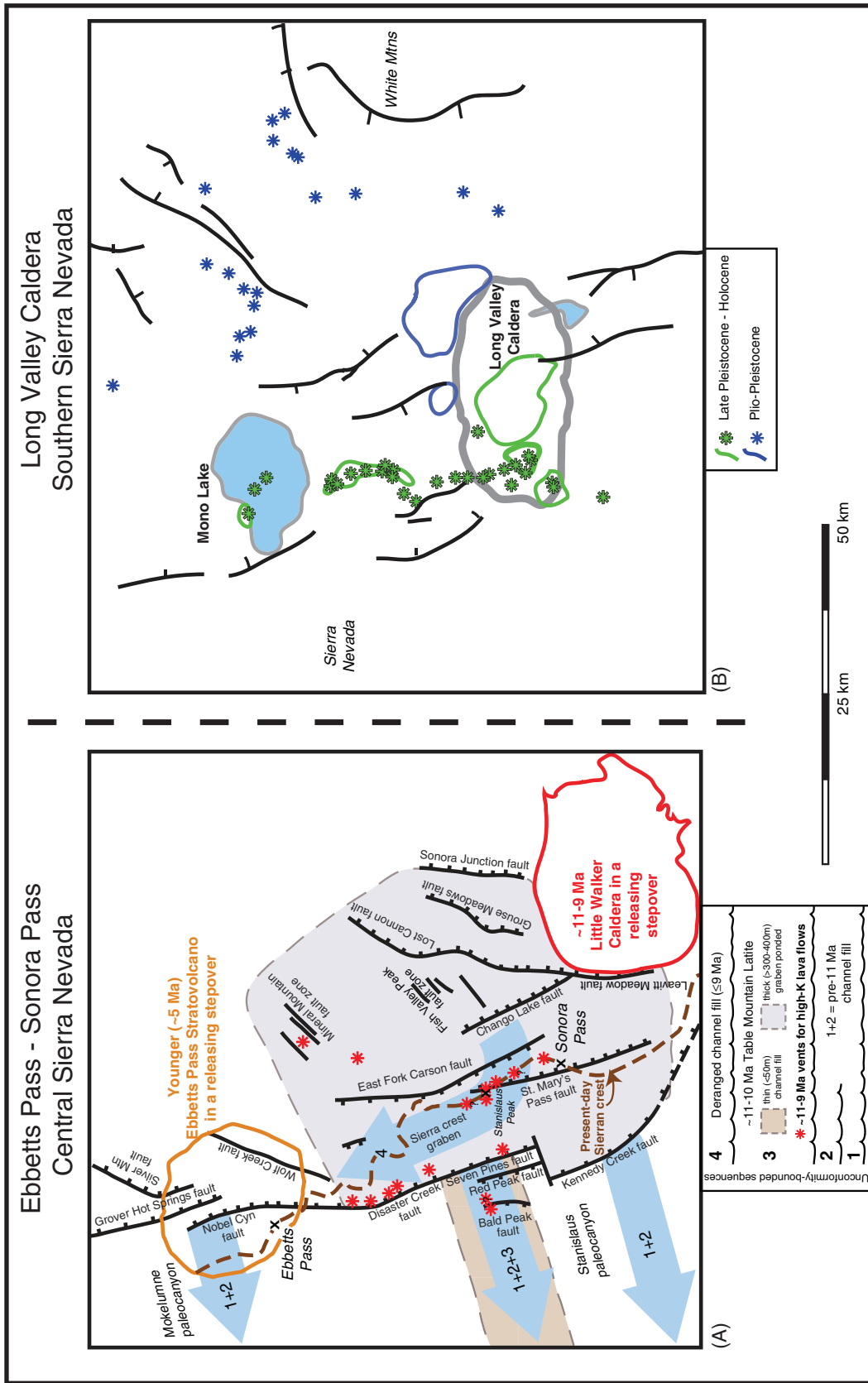


Fig. 19.8. Major volcanic centers at transensional stepovers along the eastern boundary of the Sierra Nevada microplate, showing analogues between the 11–9 Ma Little Walker Caldera (A, based on mapping of Busby et al., in press) and the Pliocene to Recent Long Valley Caldera (B, from Bursik, 2009). Locations shown on Figure 19.2B. In both, NNW-trending normal faults have a variable component of right-lateral motion, and NE-trending faults have a left-lateral component of motion; lava flow vents lie along these faults; and the calderas are elongated E-W probably due to extension. In the Miocene arc example (a), extreme effusive eruptions occurred along fault-controlled fissures, including intermediate-composition fissure eruptions of “flood lava.” These were largely ponded near-vent in synvolcanic grabens. Progressive derangement of ancient, long E-W drainage systems of the Nevadaplano by the N-S grabens is recorded in the stratigraphy (sequences 1–4, described in Figure 19.7). Modern drainages east of the present-day Sierran crest (shown in a) run N-S. A younger arc volcanic center at a transtensional stepover is also shown, the newly discovered Ebbetts Pass stratovolcano (sequence 4, Figure 19.7; Busby and Putirka, 2009; Hagan, 2010; see text).

Mineral Mountain fault zone (Figure 19.8) consists of a tuff ring built of pyroclastic surge deposits, while a nearby vent consists of an intrusion that passes upward into a lava dome. Trachydacites were erupted from vents as far as 15 km west of the Little Walker caldera, from the Bald Peak–Red Peak faults (Figure 19.8). These structural and volcanological relations are similar to those of the nearby Quaternary Long Valley Caldera, where the Inyo-Mono chain emanates northward from the caldera along faults (Figure 19.8); like the 11–9 Ma Little Walker Caldera, continental lithosphere is being ruptured along a releasing bend (Bursik, 2009), although the region is no longer above a subducting slab (due to northward migration of the triple junction, Figure 19.2A).

- (3) *Derangement of ancient E-W drainage systems, by development of north-south grabens that acted as funnels for lavas and fluvial channels.*

Oligocene and pre-12 Ma Miocene deposits are very well represented in paleochannels that flowed westward across the central Sierra Nevada (sequences 1 and 2, Figure 19.8). However, few sequence 3 lava flows flowed into these paleochannels, because they were trapped in N-S grabens (Figure 19.8). Sequence 3 pyroclastic flows are better represented in the E-W paleochannels than the lava flows are, because they are by nature more mobile, but they are thicker and more extensive in the N-S grabens, relative to the fill of the E-W paleochannels. However, sequence 4 deposits (Figure 19.7) are entirely restricted to N-S paleochannels that follow N-S grabens. For example, the Disaster Creek fault sector of the Sierra Crest graben lacks any units older than the Stanislaus Group (sequence 3), in contrast with the ancient paleochannels at Sonora Pass and Ebbetts Pass which also contain sequences 1 and 2 (Figure 19.8). This is because this sector of the graben lies between the two paleocanyons, consistent with its formation at 11 Ma. Sequence 3 high-K volcanic rocks in the Disaster Creek segment of the Sierran Crest graben are deeply incised (unconformity 4, Figure 19.7) and overlain by sequence 4 fluvial deposits within an inset N-S paleochannel >3 km wide and 400 m deep, with paleocurrent indicators of south to north flow (Disaster Peak Formation, Figure 19.7). In contrast, the Stanislaus paleocanyon west of the Sierra Crest graben apparently lacks sequence 4 strata (Figure 19.8), because it was beheaded.

Today, the Little Walker River drains south to north along the eastern boundary of the area shown in Figure 19.8, and the head of the East Fork Carson River lies in the Sierra Crest graben along the East Fork Carson fault (Figure 19.8).

The region covered by volcanic rocks erupted from the Sonora Pass region at the birth of the plate boundary appears to be greater than that affected by any other arc volcanic centers along the plate boundary. However, two other large arc volcanic centers at transtensional stepovers have been identified: the ~5 Ma Ebbetts Pass stratovolcano and the modern Lassen Volcanic Center (Figure 19.2B).

The Ebbetts Pass Center is a composite cone/stratovolcano that formed at a releasing normal fault stepover (Busby and Putirka, 2009; Hagan, 2010). Radially dipping basal basaltic andesite to andesite lava flows and scoria fall deposits define an early center 10 km in diameter; then the core of this was intruded by silicic plugs, while the edifice grew to a diameter of at least 18 km through eruptions of silicic block-and-ash-flow tuffs. Rhyolite welded ignimbrites, lava flows and intrusions, as well as two pyroxene dacites, also occur at with this center. The Ebbetts Pass Center evidently occupies a deep pull-apart basin, since a thick (~500 m), section of sequence 3 (Stanislaus Group) strata drop abruptly out of view beneath it (Busby et al., 2009b).

The Lassen Volcanic Center (Figure 19.2B) represents a modern analogue to the Ebbetts Pass Center of the ancestral Cascades arc; it is a Cascade arc volcano sited on normal and transtensional faults along the NE margin of the Walker Lane belt (Muffler et al., 2008; Janik and McLaren, 2010). At Lassen, 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).

CONTRASTS AND COMPARISONS BETWEEN LATE-STAGE AND EARLY- STAGE CONTINENTAL ARC BASINS

Now that I have described the late-stage basins, I will summarize the similarities and differences between the four continental intra-arc basin types described in this chapter: (1) early-stage low-lying extensional, (2) early-stage low-lying transtensional,

(3) late-stage high-standing extensional, and (4) late-stage high-standing transtensional.

Both types of late-stage high-standing continental arc basins contrast with both types of early-stage low-standing continental arc basins in three important ways (Table 19.1). First, marine deposits are absent, because late-stage basins are built upon pre-thickened crust that takes millions or tens of millions of years to thin by extension. Second, late-stage basins are not accessible to craton-derived sediment, because they are elevated above the rest of the continent. Third, late-stage basins differ markedly from early-stage basins by forming atop a deeply eroded substrate; they rest on exhumed basement rocks, and eruptive products are funneled through canyons carved during the preceding phase of crustal shortening (Table 19.1).

Early-stage low-standing extensional continental arc basins contrast with all three other basin types in three ways: (1) they preserve much thicker sections, with higher subsidence rates, than any of the other three basin types; (2) they lack erosional unconformities in their fill, due to uniformly continuous and fast subsidence in long, wide, continuous grabens; and (3) epiclastic debris is rare in their fill, because fault scarps and horst blocks are buried by pyroclastic debris (Table 19.1). This suggests that rapid stretching of the lithosphere in early-stage low-standing extensional continental arcs produces subsidence that outpaces thermally induced surface uplift, so that footwall blocks subside to become buried by pyroclastic debris, rather than undergoing erosion. In addition, early-stage low-standing extensional continental arc basins are commonly floored by superacrustal rocks, because volcanism is not preceded by uplift, although basement rocks uplifted by earlier orogenic events may be present in the floor.

Late-stage extensional continental arc basins are similar to early-stage extensional arc basins in having “supervolcano” silicic caldera fields (Table 19.1). However, in the late-stage examples, these are largely restricted to areas of pre-thickened crust (along the crest of the Nevadaplano, Figure 19.2A), while in the early-stage example, they occur everywhere in the arc (Figure 19.3A).

Transtensional basins of the early and late stages are similar in three ways: (1) they have calderas at releasing stepovers, (2) the proximity of pop-ups to basins results in preservation of abundant landslide deposits, and (3) their fill contains abundant erosional unconformities (Table 19.1). The early-stage transtensional basins described here apparently

formed in proximity to more restraining bends than the late-stage ones described here did, because they contain more epiclastic debris; however, this is not a difference that is inherent to the high-standing versus low-standing nature of the arc. The biggest difference between early-stage and late-stage transtensional basins lies in the fact that the late-stage ones lack marine strata, and were built upon a landscape that was deeply dissected by river canyons, which provided extra accommodation space for arc strata (in addition to faulting).

CONCLUSIONS

This chapter made a first attempt to identify distinguishing features of extensional and transtensional continental arc basins formed during the early stages of subduction, and contrast them with basins formed in the late stages of subduction. This chapter also illustrates some of the variety of continental arc basin architectures and fills present in the western US. However, our understanding of continental arc basins remains limited, relative to other basin types, because of difficulties inherent in their study. The geologist who studies them must be conversant in both sedimentary and volcanic geology, as well as structural geology and igneous petrology. Volcanic stratigraphy is notoriously complex, with rapid primary lateral variation, commonly overprinted by alteration or metamorphism, and disrupted by intrusions. Non-marine basins dominate, so fossil age controls are rare, and isotopic dating can be hindered by alteration and metamorphism. Nonetheless, this basin type is important for providing constraints on the tectonic evolution of a region. Although Quaternary arc rocks are less altered and deformed than older ones, they do not provide a time-integrated and deeper structural view as Mesozoic to Cenozoic arcs described here do.

The geologic aspect of continental arcs has been neglected relative to geochemical and geophysical aspects (Hildreth, 2007). The perception still exists that a magmatic arc consist of “one or two single-file chains of evenly spaced stratovolcanoes” (p. 1), when, in fact, the best studied continental arc in the world, the Quaternary Cascades, includes more than 2,300 volcanoes, with fewer than 30 stratovolcanoes (Hildreth, 2007). The complexity of the Quaternary chain is reflected in the variety of continental arc rocks preserved in the Phanerozoic geologic record.

ACKNOWLEDGMENTS

I would like to acknowledge the hard work of students and postdoctoral researchers who have worked with me on the geology of continental arc rocks: Nancy Riggs, Kari Bassett, Elizabeth Schermer, Jeanette Hagan, Ben Fackler Adams, Noah Garrison, Steve DeOreo, Alice Koerner, Carolyn Gorny, Ben Melosh, and Dylan Rood. Colleagues who have collaborated with me to do lab work on these rocks include James Mattinson, Keith Putirka, Chris Pluhar, Phil Gans, and Paul Renne. I would also like to thank UCSB Scientific Illustrator Dottie McLaren for assisting me with preparation of Figures 19.4B, 19.5A, 19.5B, 19.6, and 19.7; her work shows an unusual blend of attention to scientific detail and intuitive artistic rendering of geologic processes. I would like to thank Princeton University for giving me the financial and intellectual support to begin this work as a PhD student 33 years ago. I also thank my three daughters for accompanying me in the field over the past 24 years.

I thank Ken Ridgeway and Antonio Azor for their very helpful reviews of this manuscript. This work was supported by NSF grant EAR- 071181 (to Busby), and NSF grant EAR- 0711276 (to Busby and Putirka).

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