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Late Paleozoic tectonic assembly of the Sierra Nevada prebatholithic framework and western Laurentian provenance links based on synthesized detrital zircon geochronology

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ABSTRACT

The Sierra Nevada batholith of California represents the intrusive footprint of composite Mesozoic Cordilleran arcs built through pre-Mesozoic strata exposed in isolated pendants. Neoproterozoic to Permian strata, which formed the prebatholithic framework of the Sierran arc, were emplaced against the tectonically reorganized SW Laurentian continental margin in the late Paleozoic, culminating with final collapse of the fringing McCloud arc against SW Laurentia. Synthesis of 22 new and 135 existing detrital zircon U/Pb geochronology sample analyses clarifies the provenance, affinity, and history of Sierra Nevada framework rocks.

Framework strata comprise terranes with distinct postdepositional histories and detrital zircon provenance that form three broad groups: allochthonous

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Neoproterozoic to lower Paleozoic strata with interpreted sediment sources from Idaho to northern British Columbia; Neoproterozoic to Permian strata parautochthonous to SW Laurentia; and middle to upper Paleozoic deposits related to the fringing McCloud arc. Only three sedimentary packages potentially contain detritus from rocks exotic to western Laurentia: the Sierra City mélange, chert-argillite unit, and Twin Lakes assemblage. We reject previous correlations of eastern Sierra Nevada strata with the Roberts Mountains and Golconda allochthons and find no evidence that these allochthons ever extended westward across Owens Valley. Snow Lake terrane detrital ages are consistent with interpreted provenance over a wide range from the Mojave Desert to central Idaho.

The composite detrital zircon population of all analyses from pre-Mesozoic Sierran framework rocks is indistinguishable from that of the Neoproterozoic to Permian SW Laurentian margin, providing a strong link, in aggregate, between these strata and western Laurentia. These findings support interpretations that the Sierran arc was built into thick sediments underpinned by transitional to continental western Laurentian lithosphere. Thus, the Mesozoic Sierra Nevada arc is native to the SW Cordilleran margin, with the Sierran framework emplaced along SW Laurentia prior to Permian–Triassic initiation of Cordilleran arc activity.

INTRODUCTION

The Mesozoic Sierra Nevada arc of eastern California was built into the truncated and tectonically reorganized margin of SW Laurentia, with pre-Mesozoic strata related to the western Laurentian margin making up the prebatholithic metamorphic framework of the arc (Fig. 1; Davis et al., 1978; Bateman, 1992). Deformed and metamorphosed prebatholithic framework rocks are preserved as structural slivers or infolded with younger arc deposits in isolated host-rock pendants, obscuring the provenance and pre-Mesozoic tectonic history of the Sierran framework (Bateman, 1992; Saleeby and Busby, 1993). New U/Pb detrital zircon geochronology analyses of 23 samples from disrupted pre-Mesozoic strata across the Sierra Nevada and eastern California provide new constraints on the nature of Sierran framework rocks and the tectonic evolution of the SW Laurentian margin prior to Cordilleran arc magmatism. To link Sierran framework rocks to continental margin assemblages, for which relationships to the western Laurentian margin are better documented, we compiled published detrital zircon data from 135 samples of Mesoproterozoic to Permian strata of the SW Laurentian continental margin spanning eastern California, Nevada, Utah, and Arizona. In this study, we sought to determine the following: (1) provenance and age of Sierran framework rocks; (2) affinity of isolated framework rock exposures to larger "framework terranes"; and (3) the postdepositional, prebatholithic histories of these terranes.

Next, we provide an overview of the SW Laurentian continental margin and Sierra Nevada prebatholithic framework, present geochronology and comparisons of methods and results, and then discuss implications of this work for Sierran framework rock provenance, evolution of the SW Laurentian continental margin, and assembly of the Sierran framework terranes.

SW Laurentian Continental Margin

Autochthonous strata are those with current exposures that preserve their original paleogeographic relationships and positions relative to their locus of deposition along the western Laurentian margin. Allochthonous strata are those western Laurentian continental margin deposits with western Laurentian sedimentary provenance that have been significantly displaced relative to the margin segment where they originated. This subtly contrasts with parautochthonous rocks, which are fault-bounded but not significantly displaced relative to their original locus of deposition. Herein, we apply the terms autochthonous, parautochthonous, and allochthonous in reference to SW Laurentia, except where explicitly stated otherwise. We apply the term "exotic" to those rocks, strata, arcs, or terranes that were not formed or deposited within, along, or outboard of the western Laurentian margin. The fringing arc, partially built on exotic rocks, is defined as that arc that was active outboard of, and translated parallel to, the western Laurentian margin prior to accretion.

The Neoproterozoic to Paleozoic history of the western margin of North America can be divided into five distinct phases:

(1) The western margin of the North American craton was created by the breakup of Rodinia that began ca. 750 Ma (Burchfiel and Davis, 1972). The initial breakup of Rodinia may have been marked by deposition of the upper Pahrump Group in eastern California and other intracratonic basin deposits along the length of western Laurentia (Wrucke et al., 2007; Dehler et al., 2010; Yonkee et al., 2014). Detrital zircon geochronology studies show that Neoproterozoic strata of SW Laurentia record a significant provenance shift compared to the underlying, locally sourced Mesoproterozoic strata (Yonkee et al., 2014). Strata autochthonous to SW Laurentia were derived from local, central Laurentian, and Grenville basement rocks, as well as from recycling of

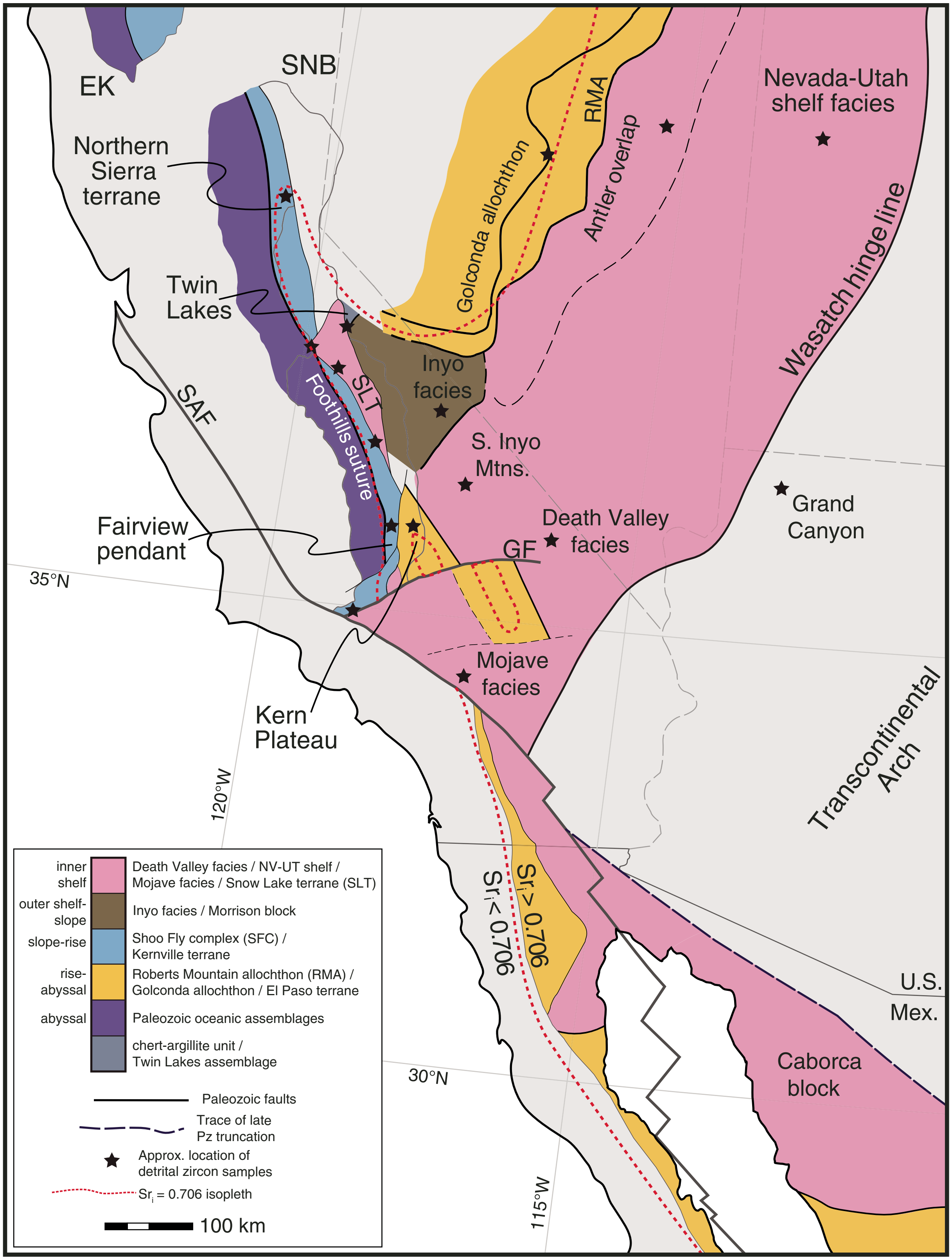

Figure 1. Schematic overview of the geologic and geographic relationships of pre-Mesozoic strata of the SW Cordilleran margin. Extent of Mesozoic Sierra Nevada batholith (SNB) outlined in medium gray. EK—Eastern Klamath Mountains, SAF—San Andreas fault, GF—Garlock fault, NV—Nevada, UT—Utah, Pz—Paleozoic. Figure is modified from Kistler and Ross (1990), Stevens et al. (2005), Crafford (2008), Dickinson (2008), Alsleben et al. (2012), and Chapman et al. (2015).

older strata (Gehrels and Dickinson, 1995). These strata generally show detrital zircon age peaks at ca. 1000–1300 Ma, 1400–1450 Ma, and 1700–1800 Ma (Gehrels and Pecha, 2014; Linde et al., 2014; Mahon et al., 2014; Yonkee et al., 2014; Chapman et al., 2015).

The latest Neoproterozoic–earliest Cambrian rise of the Transcontinental Arch restricted sediment input from eastern Laurentian sources, causing detrital zircon provenance shifts along the western Laurentian continental margin from British Columbia to Mexico (Carlson, 1999; Lewis et al., 2010; Amato and Mack, 2012; Kraft, 2013; Gehrels and Pecha, 2014; Linde et al., 2014, 2017; Yonkee et al., 2014). The timing and expression of this provenance shift vary across SW Laurentia, suggesting complications such as breaching or bypassing of the Transcontinental Arch, recycling from older sediments, or non-Grenville sources of ca. 1100 Ma zircon ages (Linde et al., 2014; Yonkee et al., 2014; Chapman et al., 2015). Ordovician quartz-rich sandstone, including the Eureka Quartzite, was deposited across western Laurentia, bearing the ca. 1850 Ma detrital zircon signature of the then-emergent Peace River Arch in northern British Columbia (Ketner, 1968; Gehrels and Dickinson, 1995; Gehrels et al., 1995; Gehrels and Pecha, 2014).

(2) Starting in the Devonian, the western Laurentian passive margin was subjected to several tectonic events. In SW Laurentia, the Antler orogeny involved the emplacement of deep-water Roberts Mountains allochthon strata over autochthonous shelf deposits in central Nevada (Burchfiel et al., 1992; Gehrels et al., 2000; Linde et al., 2016, 2017). The Roberts Mountains allochthon represents a complex, structurally disrupted allochthon composed of Neoproterozoic to lower Paleozoic deep-water strata with variable provenance ranging from northern British Columbia (main Roberts Mountains allochthon petrofacies, dominated by ca. 1850 Ma detrital zircon ages), to southern Alberta (Harmony Formation), and SW Laurentia (lower Vinini Formation; Gehrels and Pecha, 2014; Linde et al., 2016, 2017). Roberts Mountains allochthon strata are hypothesized to have been transported southward along the western Laurentian margin prior to the Antler orogeny within a complex sinistral transform system linked to the Devonian introduction of exotic rocks into the NW Laurentian margin via a "northwest passage," initiation of the Cordilleran fringing arc, and the subsequent margin-parallel southward transport of exotic terranes, fringing arcs, and distal western Laurentian margin strata (Colpron and Nelson, 2009; Linde et al., 2016). In contrast, it has also been proposed that Roberts Mountains allochthon sediments and other deep-marine deposits were transported southward prior to opening of the Slide Mountain Ocean by sedimentary dispersal through a combination of long-shore currents and turbidite mechanisms, rather than by tectonic transport (Gehrels and Dickinson, 1995; Gehrels et al., 2000; Saleeby and Dunne, 2015).

(3) Sediments shed from the resultant Antler Highlands into inboard foreland basins and the outboard successor Slide Mountain–Golconda Basin in the late Paleozoic, including Antler overlap and Golconda allochthon deposits, show nearly unimodal detrital age distributions remarkably similar to the Roberts Mountains allochthon from which they were derived (Crafford, 2008; Gehrels and Pecha, 2014). Gehrels et al. (2011) documented a shift in sediment sources in Mississippian to Lower Permian Grand Canyon strata that led to an influx of late Mesoproterozoic and progressively younger Neoproterozoic to late Paleozoic zircon to the autochthonous passive margin. Although Gehrels et al. (2011) preferred the Appalachian orogen as the detrital and tectonic source for these provenance shifts, the available data cannot rule out other sources, such as northern and southern circum-Laurentian orogens or fringing arcs outboard of western Laurentia built into far-traveled exotic basement (Colpron and Nelson, 2009; Thomas, 2011).

(4) Truncation of the SW Laurentian continental margin is thought to have begun in the Middle Pennsylvanian with development of a sinistral transform that displaced Mojave cratonic basement and overlying strata southward relative to North America (Stone and Stevens, 1988; Alsleben et al., 2012; Stevens et al., 2015a). However, the timing of this truncation has been proposed to be as young as Jurassic (Anderson, 2015). Two Permian contractional phases are recognized in the Inyo Mountains and other ranges east of the Sierra Nevada. An Early Permian event, involving emplacement of the Last Chance allochthon and creation of a major fault-bend anticline, was followed in the Late Permian to earliest Triassic by development of the Sierra Nevada–Death Valley thrust system (Stevens and Stone, 2002, 2005a, 2005b; Saleeby and Dunne, 2015). A Sierra Nevada–wide Upper Permian to mid-Triassic unconformity with local variation in temporal extent, which suggests considerable uplift and erosion, is likely related to Late Permian transpressive tectonism (Memeti et al., 2010; Cao et al., 2015; Saleeby and Dunne, 2015).

(5) Cordilleran arc magmatism initiated along the truncated SW Laurentian continental margin in the Late Permian in Sonora, the Mojave Desert, and the southeastern Sierra Nevada (Saleeby and Dunne, 2015). The Sonoma orogeny, which resulted in emplacement of the Golconda allochthon in western Nevada, was largely coeval with Late Permian deformation in eastern California (Crafford, 2008). Following the Sonoma orogeny, Cordilleran arc activity was established over an expanded extent along the SW Laurentian margin, coeval with accretion of oceanic assemblages along the Foothills suture at the outboard edge of the consolidated Sierran framework terranes (Miller et al., 1995; Saleeby, 2011; Saleeby and Dunne, 2015).

Exposures of SW Laurentian continental margin strata can be traced across the western North American craton margin to the easternmost Sierra Nevada west of Owens Valley (Figs. 1 and 2). East of Owens Valley, upper Proterozoic to Paleozoic inner-shelf strata of the Death Valley facies are structurally overlain by the outer-shelf Inyo facies across the Last Chance thrust (Stevens and Stone, 2005a; see also Figs. 1 and 2). West of Owens Valley, in the easternmost Sierra Nevada, several pendants preserve parautochthonous Paleozoic slope deposits of the Morrison block (Stevens and Greene, 1999; Stevens and Pelley, 2006). Confirmed exposures of Roberts Mountains allochthon and Golconda allochthon

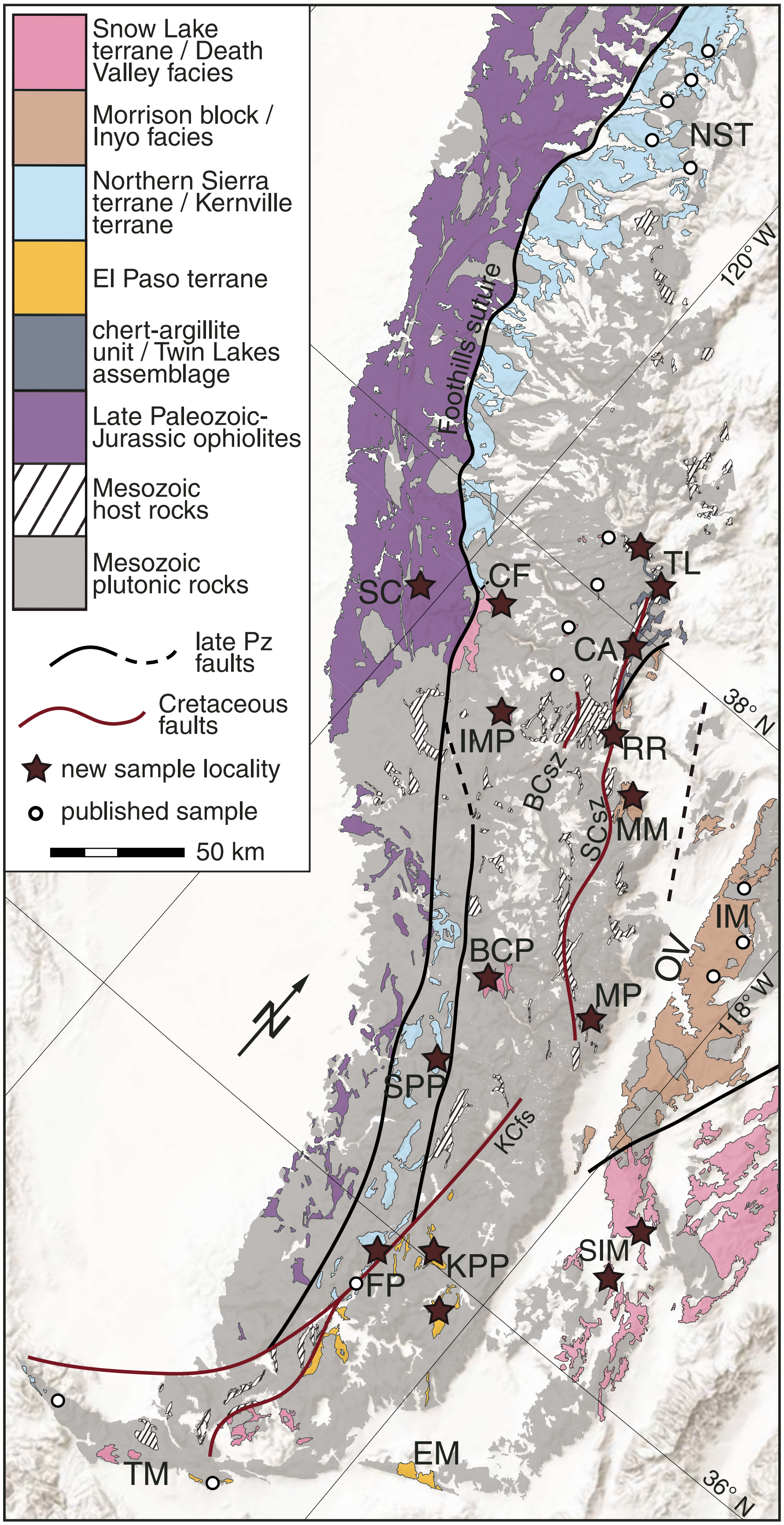

Figure 2. Host-rock exposures within the Sierra Nevada, emphasizing pre-Mesozoic framework rocks as reevaluated in this paper. BCP—Boyden Cave pendant; CA—chert-argillite unit; CF—Crane Flat; EM—El Paso Mountains; FP—Fairview pendant; IM—Inyo Mountains; IMP—Iron Mountain pendant; KPP—Kern Plateau pendants; MM—Mount Morrison; MP—Mount Pinchot; NST—Northern Sierra terrane; OV—Owens Valley; RR—Ritter Range; SC—Sherlock Creek; SIM—southern Inyo Mountains; SPP—Sequoia Park pendant; TL—Twin Lakes; TM—Tehachapi Mountains; BCsz—Bench Canyon shear zone; KCfs—Kern Canyon fault system; LCt—Last Chance thrust; SCsz—Sierra Crest shear zone; Pz—Paleozoic. Geologic contacts and units were adapted from digital *Geologic Map of California* (Jennings et al., 2010).

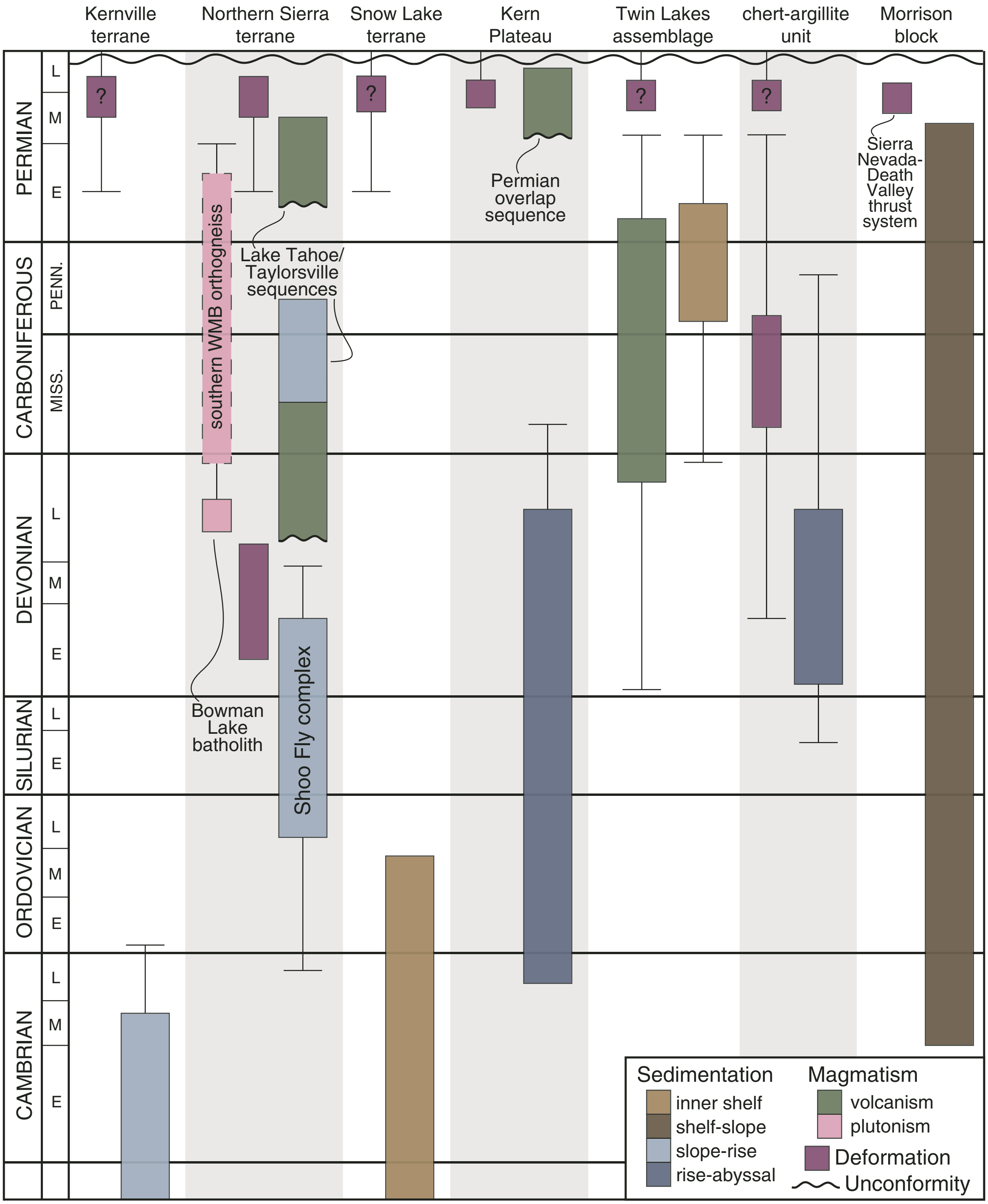

Figure 3. Schematic representation of tectonostratigraphic relations among the Sierra Nevada framework terranes. E—Early, M—Middle, L—Late, WMB—western metamorphic belt. See text for data sources.

strata are preserved as far west as western Nevada (Stevens and Greene, 1999; Crafford, 2008). Both allochthons have been proposed to extend across Owens Valley into the eastern Sierra Nevada (e.g., Schweickert and Lahren, 1987, 2006). However, recent field observations and detrital zircon geochronology contradict these previous correlations (Ardill and Paterson, 2015; Cao, 2015; Cao et al., 2015).

Sierra Nevada Framework Terranes

SSW trends of SW Laurentian continental margin facies are abruptly truncated across Owens Valley in eastern California, where pre-Mesozoic Sierra Nevada framework rocks form NNW-trending, fault-bounded elongated belts (Figs. 1, 2, and 3) that consist of: (1) parautochthonous Paleozoic slope deposits of the Morrison block that are overlain by displaced Paleozoic marine deposits of the chert-argillite unit and Twin Lakes assemblage (Schweickert and Lahren, 1987; Stevens and Greene, 1999; Cao and Paterson, 2015; Cao et al., 2015); (2) deep-water strata of the El Paso terrane, exposed as pendants on the Kern Plateau and extending southeastward into the central Mojave Desert (Davis et al., 1978; Walker, 1988; Dunne and Suczek, 1991; Stevens et al., 2005; Saleeby and Dunne, 2015); (3) displaced shallow-water passive-margin strata of the Snow Lake terrane, previously referred to as the Snow Lake block, exposed discontinuously along the axial Sierra Nevada (Lahren and Schweickert, 1989; Memeti et al., 2010; Chapman et al., 2015); and (4) units in the western metamorphic belt. Pre-Mesozoic rocks of the western metamorphic belt include (1) allochthonous deep-water strata of the lower Paleozoic Shoo Fly complex and Sierra City mélange, as well as overlying upper Paleozoic arc and marine assemblages of the Northern Sierra terrane (Harwood, 1992; Girty et al., 1996); (2) lower Paleozoic structurally complex, thick-bedded, quartzose turbidites of the Kernville terrane (Saleeby and Busby, 1993; Chapman et al., 2012; Saleeby and Dunne, 2015); and (3) more outboard, structurally disrupted Paleozoic ophiolitic basement complexes (Saleeby, 2011). Boundaries between framework terranes are interpreted to be reverse, normal, or transform faults, the details of which are often speculative, due to the lack of fault exposure and overprinting by extensive Mesozoic arc magmatism and deformation (e.g., Engebretson et al., 1985; Paterson et al., 1987, 1989, 2014; Schweickert and Lahren, 1987; Kistler, 1993; Greene and Schweickert, 1995; Tobisch et al., 1995; Tikoff and Saint Blanquat, 1997; Wyld and Wright, 2001; Memeti et al., 2010; Chapman et al., 2012; Cao et al., 2015; Saleeby and Dunne, 2015).

Next, we summarize the stratigraphy, structure, and tectonic significance of each Sierran framework terrane, presented schematically in Figure 3, as well as limited existing detrital zircon geochronology.

Morrison Block

The Morrison block consists of Paleozoic slope-facies strata exposed in host-rock pendants in the easternmost central to southern Sierra Nevada from west of Mono Lake to southeast of Bishop (Fig. 1; Stevens and Greene, 1999). Stevens and Greene (1999) defined a coherent Cambrian to Permian stratigraphy of siliciclastics, ranging from argillite to sandstone to conglomerate, and carbonates with minor chert and calc-silicates. These parautochthonous strata are interpreted as distal equivalents of SW Laurentian inner-shelf deposits, based primarily on correlation of a Middle Devonian submarine fan complex across Owens Valley (Stevens and Pelley, 2006). The earliest deformation identified in the Morrison block, between the Early Permian and earliest Mesozoic, is correlated with the Sierra Nevada–Death Valley thrust system (Stevens and Greene, 2000; Greene and Stevens, 2002).

Chert-Argillite Unit

In the northern Ritter Range pendant, rocks of the Morrison block are structurally overlain by the informally named mid-Paleozoic “chert-argillite unit” (Fig. 2), which consists of a deformed package of chert, siliceous argillite, siltstone, sandstone, and phyllite that define a deep-marine assemblage (Greene et al., 1997). Schweickert and Lahren (1987) and Greene et al. (1997) correlated these deep-water strata to the Roberts Mountains allochthon and Palmetto Formation of western Nevada, interpreting their basal structural contact as the Roberts Mountains thrust. Stevens and Greene (1999) concluded that the chert-argillite unit was structurally juxtaposed with the Morrison block in the Permian to Middle Triassic (Paterson et al., 2014). A published detrital zircon analysis from the chert-argillite unit (Ardill and Paterson, 2015) shows a spread of Archean to Mesoproterozoic ages with major peaks at ca. 1650, 1825, and 2700 Ma, and minor peaks at ca. 435, 1200, 1450, and 1750 Ma. The Silurian maximum depositional age of ca. 435 Ma is younger than the previously inferred Ordovician age (Schweickert and Lahren, 1987; Ardill and Paterson, 2015).

Twin Lakes Assemblage

The chert-argillite unit is juxtaposed with Paleozoic volcanic and sedimentary strata of the Twin Lakes assemblage, which are best exposed in the Twin Lakes area of the Saddlebag Lake pendant (Fig. 2). Strata exposed in the northeastern Twin Lakes area consist of deformed siltstone and quartzite with minor carbonate and calc-silicate rocks, whereas Paleozoic felsic to intermediate volcanics interbedded with both volcaniclastic and siliciclastic shallow-marine strata are exposed just to the west (Cao and Paterson, 2015; Cao et al., 2015). Eight analyzed samples show maximum depositional ages of ca. 320–430 Ma (Cao, 2015; Cao et al., 2015). The composite Twin Lakes assemblage detrital zircon age distribution shows major peaks at ca. 340, 425, and 600, a spread between 900 and 2050 Ma, and a youngest peak age at ca. 300 Ma (Figs. 4 and 5). The spread of Paleoproterozoic to Mesoproterozoic and late Neoproterozoic to Paleozoic detrital ages is inconsistent with previous correlations of this assemblage with the Golconda allochthon (Schweickert and Lahren, 1987).

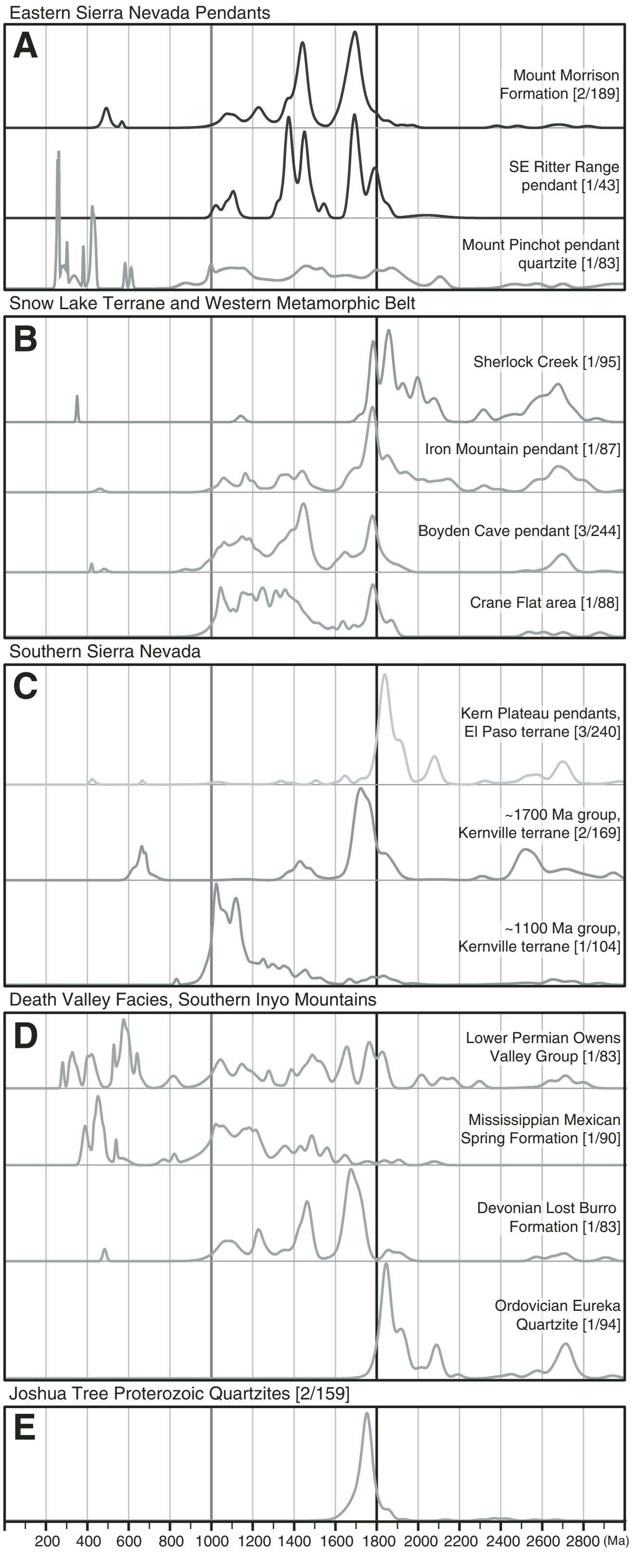

Figure 4. Probability density plots of detrital zircon age distributions from new analyses. First number in brackets denotes number of samples combined to form age distribution; second number indicates total number of zircon ages plotted.

El Paso Terrane

Paleozoic strata exposed in pendants across the Kern Plateau, as well as throughout the El Paso Mountains (Fig. 2) and northern Mojave Desert (Fig. 1), comprise the El Paso terrane (Carr et al., 1984, 1992, 1997; Dunne and Suczek, 1991; Martin and Walker, 1995; Miller et al., 1995; Chapman et al., 2012; Saleeby and Dunne, 2015). Lower to middle Paleozoic strata of Kern Plateau pendants are dominantly very fine-grained argillite and siliciclastics with subordinate chert, mafic volcanics, carbonates, and rare conglomerate, as well as stratiform barite and local serpentinized peridotite and sedimentary serpentinite (Dunne and Suczek, 1991). These strata are interpreted as deep-water, rise facies strata (Dunne and Suczek, 1991; Stevens et al., 2005). In the Bean Canyon pendant of the Tehachapi Mountains and the Kennedy Meadows pendant on the Kern Plateau, these strata appear to rest unconformably on latest Cambrian serpentinized peridotite basement (Chapman et al., 2012; Saleeby and Dunne, 2015). Within some pendants, upper Paleozoic volcanic, volcaniclastic, and sedimentary strata unconformably overlie lower to mid-Paleozoic strata (Dunne and Suczek, 1991; Carr et al., 1997; Chapman et al., 2012). Lower Paleozoic Kern Plateau strata have been correlated with lower Paleozoic metamorphic argillite, schist, carbonates, and mafic greenstone in the western El Paso Mountains (Carr et al., 1997). In the eastern El Paso Mountains, lower Paleozoic fine-grained siliciclastics and carbonates are interpreted to represent an inner rise assemblage overlain by Pennsylvanian to Permian strata (Carr et al., 1984, 1992, 1997; Stevens et al., 2005).

The El Paso terrane has generally been interpreted as a southward-transported, displaced ribbon of the Roberts Mountains allochthon (Davis et al., 1978; Dunne and Suczek, 1991; Stevens et al., 2005; Colpron and Nelson, 2009; Saleeby and Dunne, 2015). However, based on correlation of a Middle Devonian calcareous quartzite in the Mount Morrison pendant in the eastern Sierra Nevada with similar units in the El Paso terrane, including the Kern Plateau, and the lack of Devonian–Mississippian deformation in both areas, Stevens and Pelley (2006) considered the El Paso terrane to represent a displaced fragment of the Morrison block. The age of the earliest deformation recognized in the El Paso Mountains is constrained to Late Permian (Miller et al., 1995; Carr et al., 1997; Stevens et al., 2015c). Carr et al. (1992, 1997) suggested that Mississippian strata resting disconformably on lower Paleozoic deep-water strata in the western El Paso Mountains represent a stratigraphic expression of the Antler orogeny. The lack of any identified Antler-age deformation within the El Paso terrane supports a broad depositional link, rather than a direct tectonic correlation, to the Roberts Mountains allochthon (Saleeby and Dunne, 2015).

Snow Lake Terrane

Shallow-marine strata exposed in axial central and southern Sierra Nevada pendants (Figs. 1 and 2) have been interpreted as a displaced terrane referred to as the Snow Lake block (Lahren and Schweickert, 1989; Schweickert and Lahren, 1991). Following

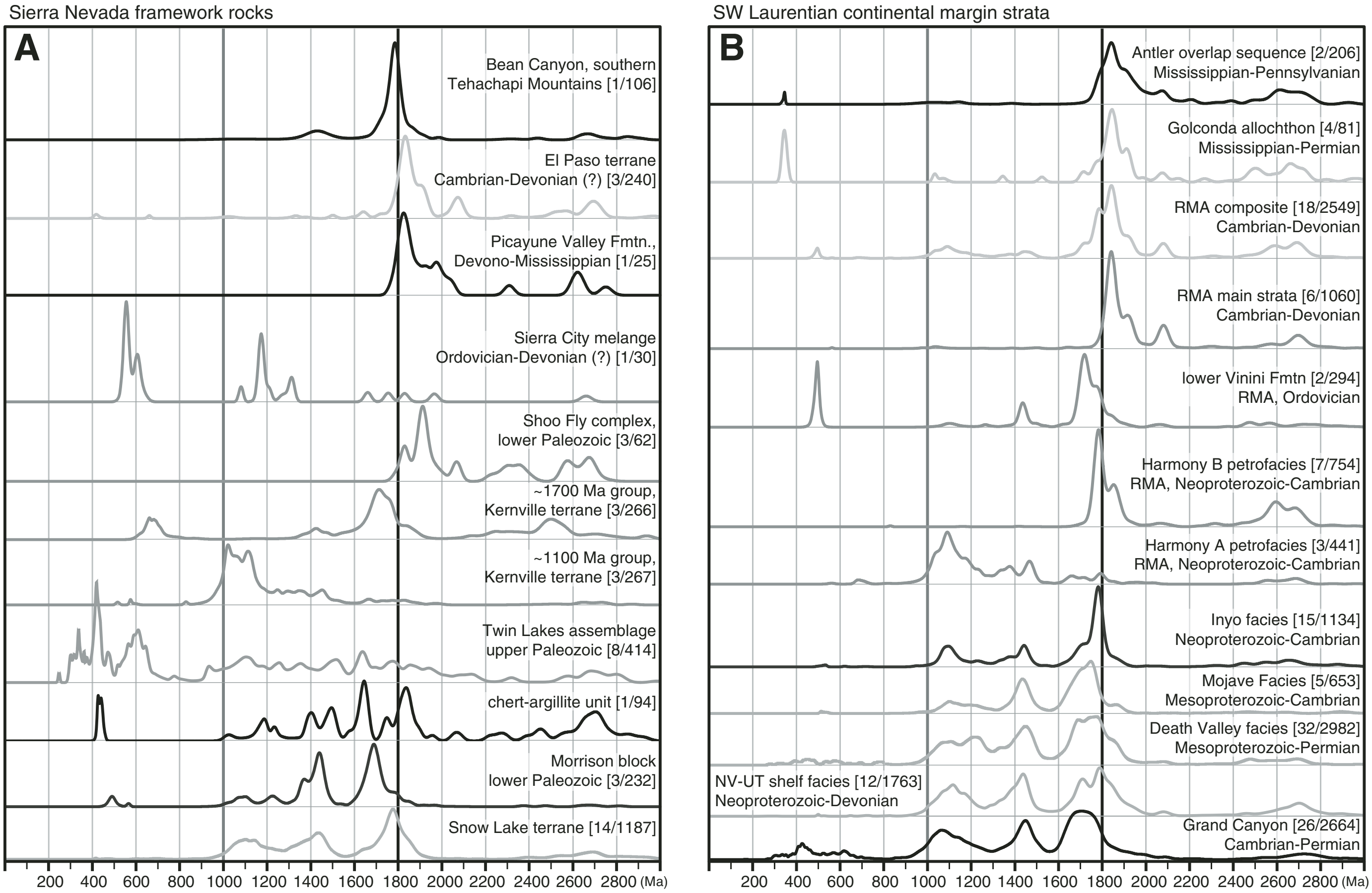

Figure 5. Probability density plots of compiled detrital zircon age distributions of SW Laurentian continental margin and pre-Mesozoic Sierra Nevada metamorphic framework terrane. Labels are same as Figure 4. Fmtn.—Formation; RMA—Roberts Mountains allochthon; NV—Nevada; UT—Utah.

Chapman et al. (2015) and Saleeby and Dunne (2015), we herein use the term Snow Lake terrane to refer to this parautochthonous or possibly allochthonous terrane instead. Snow Lake terrane strata consist of quartzite, quartzofeldspathic schist, carbonates, and calc-silicate layers interpreted as multiply deformed and metamorphosed Neoproterozoic to Ordovician shallow-marine shelf deposits (Lahren and Schweickert, 1989; Grasse et al., 2001; Memeti et al., 2010; Chapman et al., 2015). These strata are unconformably overlain by infolded Jurassic marine metasedimentary strata (Memeti et al., 2010, 2012). At least one pre-Jurassic deformation episode has been identified in Snow Lake terrane pendants (Lahren and Schweickert, 1989; Memeti et al., 2010, 2012). Detrital zircon ages from nine Snow Lake terrane samples are similar to detrital zircon age distributions of autochthonous Neoproterozoic to Ordovician SW Laurentian passive-margin strata (Grasse et al., 2001; Memeti et al., 2010). Snow Lake terrane detrital zircon age distributions show peaks with varied relative proportions at ca. 1000–1200, 1450, and 1750 Ma, with a spread of Archean ages. Two samples from the May Lake pendant show a unique distribution with a single major peak at ca. 1800 Ma and scattered Archean and ca. 700 Ma ages. This ca. 1800 Ma–dominated detrital zircon age distribution is similar to other Peace River Arch–derived Ordovician sandstone across western Laurentia (Gehrels and Dickinson, 1995; Memeti et al., 2010).

The timing, tectonic setting, and structural mechanisms of Snow Lake terrane emplacement are uncertain. Lahren and Schweickert (1989) proposed that the Snow Lake terrane represented a block of the Neoproterozoic to Cambrian Mojave facies stratigraphy displaced up to 400 km northward from apparently similar Neoproterozoic to Cambrian strata in the Mojave Desert along the cryptic Mojave–Snow Lake fault of inferred Cretaceous age (Grasse et al., 2001; Wyld and Wright, 2001). However, Jurassic strata that overlie Snow Lake terrane strata are part of the widespread Sierran marine overlap sequence and differ significantly from Triassic to Jurassic terrestrial strata that overlie the Neoproterozoic to Paleozoic Mojave facies shelf strata in both depositional setting and detrital zircon provenance (Saleeby et al., 1978; Saleeby and Busby, 1993; Memeti et al., 2010, 2012; Chapman et al., 2015; Paterson et al., 2017). Maximum depositional ages of these unconformably overlying Jurassic marine strata indicate Early Jurassic exhumation of the Snow Lake terrane (Memeti et al., 2010; Chapman et al., 2015). Chapman et al. (2015) proposed a model in which the Snow Lake terrane represents a part of the Death Valley facies that was exhumed from the east along an Early Jurassic cryptic low-angle detachment. This model is consistent with several observations, including: (1) Jurassic exhumation of the Snow Lake terrane; (2) isotopic compositions of plutons intruding the Snow Lake terrane, Mojave facies, and Death Valley facies; and (3) restoration of ~75 km of Late Cretaceous to Paleogene dextral slip between the Inyo Mountains and easternmost Snow Lake terrane exposures (Chapman et al., 2015).

Northern Sierra Terrane

The Northern Sierra terrane constitutes the most inboard terrane of the western metamorphic belt (Fig. 2). The lower Paleozoic Shoo Fly complex, the structurally lowest assemblage within the Northern Sierra terrane, consists of four imbricated thrust sheets (Hanson et al., 1988; Girty et al., 1996). The three structurally lowest allochthons show similar detrital zircon age distributions with ages >1800 Ma, typical of allochthonous Roberts Mountains allochthon units and Ordovician sandstone derived from the Peace River Arch region (Harding et al., 2000). The structurally highest allochthon, the Sierra City mélange, shows a spread of ages that cluster at ca. 420, 600, and 1100–1300 Ma, along with a spread of >1600 Ma ages (Grove et al., 2008). The age of the Shoo Fly complex is broadly constrained by limited Middle to Late Ordovician marine fossils, ca. 370 Ma plutonism, and Late Devonian marine fossils at the base of the overlying Taylorsville Sequence (Hanson et al., 1988; Harwood, 1992; Cecil et al., 2012). The Shoo Fly complex is unconformably overlain by Upper Devonian to Lower Mississippian marine sediments and arc volcanics, which are unconformably overlain by Lower Permian marine volcanics, volcaniclastics, and sedimentary strata (Harwood, 1988, 1992; Girty et al., 1996). Eleven analyzed zircon grains from the basal unit of the Permian arc assemblage do not constitute a representative sample population that can robustly characterize the underlying complex age distribution. Eight of 11 grains form a cluster at ca. 350 Ma (Spurlin et al., 2000). The Northern Sierra terrane is bounded on the west by a polyphase structural zone shown on Figure 1 as the Foothills suture (Saleeby et al., 1989; Saleeby, 2011).

Timing of earliest Shoo Fly complex deformation is best constrained by Late Devonian intrusions and mid-Paleozoic strata unconformably overlying tilted Shoo Fly complex strata (Saleeby et al., 1987; Hanson et al., 1988; Harwood, 1988; Girty et al., 1996). Despite the presence of a stratigraphically higher Pennsylvanian to Lower Permian unconformity, no corresponding Pennsylvanian to Early Permian deformation has been recognized (Harwood, 1988, 1992). Folding and thrusting of lower to upper Paleozoic strata below the uppermost Permian–Mesozoic unconformity indicate that all Paleozoic rocks of the Northern Sierra terrane record some pre-Mesozoic deformation (Harwood, 1988, 1992).

The Northern Sierra terrane extends southward within the western metamorphic belt, where Schweickert (1981) correlated multiply deformed, interlayered Paleozoic quartzite, quartz–mica schist, and phyllite plus sparse carbonates and graphitic schist with the Shoo Fly complex (Merguerian, 1985; Bhattacharyya, 1986; Bateman and Krauskopf, 1987; Dodge and Calk, 1987). Multiply deformed orthogneiss bodies exposed northwest of the Crane Flat area (Fig. 2) are dated at ca. 375–275 Ma (Sharp et al., 1982). These intrusions predate all but the oldest deformation identified in this region (Merguerian and Schweickert, 1987). Another set of pre-Mesozoic structures deforms both Paleozoic strata and orthogneiss, predating tectonic juxtaposition with the Calaveras complex (Bhattacharyya, 1986). Schweickert and Lahren (1991) noted that strata exposed in the southernmost western metamorphic belt are lithologically similar to Snow Lake terrane strata, but they distinguished them as Shoo Fly complex based on sparse primary textures that suggested deep-marine protoliths and the presence of pre-Mesozoic orthogneiss as well as more intense deformation (Merguerian and Schweickert, 1987).

Kernville Terrane

Pre-Mesozoic quartzite, siliceous and carbonaceous argillite, subordinate calc-silicates, carbonates, mafic schist, and rare bedded barite, exposed south of ~37°N in a belt of pendants west of the Snow Lake terrane and El Paso terrane exposures (Fig. 2), form the Kernville terrane (Hinthorne, 1974; Saleeby and Busby, 1993; Chapman et al., 2012; Saleeby and Dunne, 2015). The dominant quartzite is interpreted as channel facies turbidites (Saleeby and Dunne, 2015). Kernville terrane strata are interpreted to have been deposited in slope to inner rise environments along the western Laurentian margin (Schweickert and Lahren, 1991; Saleeby and Dunne, 2015).

Zones of relatively low Mesozoic strain within Kernville terrane rocks preserve fabrics and structures oriented at high angles to the regional Sierran orogenic grain, attesting to a significant pre-Mesozoic deformational event (Saleeby and Busby, 1993; Saleeby and Dunne, 2015). One quartzite sample from the Fairview pendant shows a major peak at ca. 1000–1200 Ma with a spread back to ca. 1600 Ma, and a minor peak at ca. 1800 Ma (Saleeby, 2011). Another sample from the Fairview pendant shows major peaks at ca. 675 and 1550–1700 Ma, with a spread of ca. 2200–2500 Ma ages and a minor peak at ca. 1425 Ma (Saleeby, 2011).

The western boundary of the Kernville terrane with the more outboard western metamorphic belt ophiolite belt is coincident with the initial $^{87}Sr/^{86}Sr_{(i)} = 0.706$ isopleth within the hosting batholith and forms the southern segment of the Foothills suture, the accretion locus of Panthalassan abyssal lithosphere along the reorganized SW Laurentian margin (Saleeby, 2011; Saleeby and Dunne, 2015). The initial Sr = 0.706 isopleth also corresponds to the Foothills suture along the southern Northern Sierra terrane. The basement of the western metamorphic belt outboard of the Northern Sierra and Kernville terranes consists of Paleozoic and Mesozoic ophiolitic complexes that represent Panthalassan abyssal lithosphere (Saleeby et al., 1989; Saleeby, 2011).

METHODS

Geochronology

U-Pb geochronology of zircon was conducted by laser ablation–inductively coupled plasma–mass spectrometry at the Arizona LaserChron Center (Gehrels et al., 2008). Detailed sample preparation and geochronology methods are presented in Supplementary File A in the GSA Data Repository.[1] Analyzed zircon grains with a U/Th ratio above 10 were filtered out prior to plotting and statistical comparison to exclude a small number of likely metamorphic zircon grains. Analyses with greater than 20% discordance or 10% reverse discordance were filtered out to exclude effects of Pb-loss or other disturbances of isotopic ratios. Maximum depositional ages were determined from the youngest coherent cluster of three detrital grain ages rather than isolated individual youngest ages (Gehrels, 2014). U/Pb geochronology isotopic data for all new analyses are presented in Supplementary File B in the GSA Data Repository (see text footnote 1).

Compilation

We compiled previously published detrital zircon U-Pb ages from the western North American Cordillera, extending the compilation of Chapman et al. (2012, 2015) to include published analyses from Mesoproterozoic to Permian strata from California, Nevada, Utah, and Arizona (Fig. 1). These data were generated by multiple researchers using multiple methods at multiple facilities. Methodological choices such as discordance cutoff, filtering of high U/Th analyses, and exclusion of grain ages younger than known depositional ages vary by study, depend on the particular data set, and are somewhat subjective (Gehrels, 2014). We have chosen to follow the decisions of the original studies rather than compile the complete isotopic data for each analysis and apply a uniform filter to the entire data set. It is particularly important to note that the number of zircon grains analyzed per compiled sample varies from tens to hundreds of zircon. Although detrital zircon age groups are identifiable for analyses with $n \leq \sim 100$, the relative proportions of these populations are not necessarily indicative of the underlying age distribution (Gehrels, 2014).

Our compilation contains analyses of 157 samples from pre-Mesozoic strata (12,207 analyzed grains). It includes: 14 samples from the Snow Lake terrane (Grasse et al., 2001; Memeti et al., 2010; this study); 3 samples from the El Paso terrane (this study); 13 samples from the eastern Sierra Nevada metamorphic pendants (Cao, 2015; Cao et al., 2015; this study); 7 samples from southern Sierra Nevada metamorphic pendants (Saleeby, 2011; Chapman et al., 2012; this study); 15 samples from the Inyo facies (MacLean et al., 2009; Chapman et al., 2015); 12 samples from the Nevada-Utah shelf facies (Gehrels and Dickinson, 1995; Stewart et al., 2001; Gehrels and Pecha, 2014; Linde et al., 2014); 2 samples from the Antler overlap sequence (Gehrels and Dickinson, 1995, 2000; Gehrels and Pecha, 2014); 32 samples from the Death Valley facies (Stewart et al., 2001; MacLean et al., 2009; Schoenborn et al., 2012; Gehrels and Pecha, 2014; Mahon et al., 2014); 5 samples from the Mojave facies (Grasse et al., 2001; Stewart et al., 2001; Barth et al., 2009; Gehrels and Pecha, 2014; this study); 26 samples from Grand Canyon cratonic strata (Gehrels et al., 2011); 18 samples from the Roberts Mountains allochthon (Smith and Gehrels, 1994; Gehrels and Dickinson, 1995; Gehrels et al., 2000; Gehrels and Pecha, 2014; Linde et al., 2016, 2017); 4 samples from the Golconda allochthon (Riley et al., 2000); and 6 samples from the Northern Sierra terrane and western metamorphic belt (Harding et al., 2000; Spurlin et al., 2000; this study). Detailed sample information and detrital zircon age data are given in Supplementary File C in the GSA Data Repository (see text footnote 1).

Multidimensional Scaling

Multidimensional scaling (MDS) applied to detrital zircon geochronology represents a potentially powerful exploratory data-analysis method (Chapman et al., 2012, 2015; Vermeesch, 2013; Vermeesch and Garzanti, 2015). MDS uses pairwise dissimilarity measures of sample distributions to create n-dimensional coordinates for each sample, thereby producing an n-dimensional map on which similar detrital zircon sample populations plot closer together and dissimilar populations plot farther apart (Vermeesch, 2013). MDS takes an $N \times N$ (where N is the number of samples or populations) matrix of pairwise dissimilarities and fits a set of n-dimensional coordinates to each sample such that the pairwise Euclidean distances between samples minimize some chosen parameter with respect to the input dissimilarities (Vermeesch, 2013). The resulting n-dimensional coordinates are then plotted on a number of axes equal to the number of dimensions chosen at the beginning of the process. The values plotted on each axis have no meaningful units: The kth axis simply represents the coordinates of each point in the kth dimension as computed through MDS. As the input remains the same regardless of the number of dimensions chosen, going from two- to three-dimensional plots ultimately allows MDS to fit the distances between the coordinates with an additional degree of freedom. A classic example of the application of MDS is the recreation of a geographic map of major U.S. cities given a matrix of pairwise distances between these cities. MDS finds coordinates for each city that minimize "strain" between the given and resulting intercity distances.

We made the following methodological choices in the MDS analysis applied to this compilation: (1) restricting MDS to two

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[1] GSA Data Repository Item 2018256—Supplemental File A: Analytical methods of zircon geochronology; Supplemental File B: Table DR1—Zircon geochronology isotopic data; and Supplemental File C: Sample information and detrital age data for all compiled analyses (with multiple tables)—is available at www.geosociety.org/datarepository/2018/, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

dimensions for ease of presentation, (2) combining multiple sample analyses to form composite distributions where appropriate, and (3) calculating dissimilarity using the Kolmogorov-Smirnov (K-S) statistic. It is important to note that these choices assume that all data display similar analytical uncertainty, which is not true for our compiled data set. Considering this, we evaluated the impact of different probability density estimation methods and found that MDS results were robust with respect to the chosen estimation method, indicating that violating the above assumption is unlikely to significantly alter MDS analyses of this data set. To create these MDS maps, we used the MATLAB application *MuDisc* (Vermeesch, 2013).

RESULTS

New Geochronology

Morrison Block

Three samples from Morrison block strata (Fig. 4A) all show similar detrital ages. Two samples from the Middle Devonian Mount Morrison Formation (samples RTF01, RTCL01) have nearly identical detrital age distributions. The composite distribution shows major peaks at ca. 1450 and 1700 Ma, with minor peaks at ca. 500, 1100, and 1250 Ma. Sample VT15-12-A, from unnamed fine-grained slaty argillite exposed on the western slope of Deadman Crest in the Ritter Range pendant, included within the Morrison block by Stevens and Greene (1999), shows major peaks at ca. 1400 and 1700 Ma, with minor peaks at ca. 1100, 1800, and 2050 Ma. Two Mesozoic ages significantly younger than independent depositional age constraints were excluded from further analysis. An additional sample, from the Mount Aggie Formation in the Mount Morrison pendant (RTMG01), was excluded from further consideration due to a limited sample size and a significant proportion of aberrant Late Cretaceous ages, likely sourced from or disturbed by coeval intrusions.

Mount Pinchot Pendant

A fine-grained, gray quartzite from the southwestern part of the Mount Pinchot pendant (Fig. 4A) shows a younger dominant spread between ca. 250 and 450 Ma, with peaks at ca. 255 and 425 Ma. An older spread is centered on peaks at 1100, 1500, and 1850 Ma, with a subordinate scatter between 2000 and 3000 Ma. One analyzed grain that yielded a Late Cretaceous age was excluded. The youngest age peak at ca. 255 Ma provides a latest Permian maximum depositional age.

Kern Plateau Pendants

Three samples from the southern Sierra Nevada Kern Plateau pendants (Fig. 2) show similar detrital age distributions and thus have been plotted as a composite in Figure 4. The composite distribution shows a major peak at ca. 1850 Ma and minor peaks at ca. 2100, 2550, and 2700 Ma (Fig. 3C). The youngest age peak (two grains) at ca. 425 Ma does not provide a robust maximum depositional age. One grain, yielding an age of 213 Ma, was excluded because it is significantly younger than the minimum depositional age given by crosscutting relationships from coeval proximal intrusions (Saleeby and Dunne, 2015). One of these samples, K-D23-10, from the Kennedy pendant shows eight detrital ages between ca. 420 and 1500 Ma with no distinct grouping of more than two ages. Although sample K-D23-10 shows several detrital zircon ages that are not found in the other two Kern Plateau samples, the three sample detrital age distributions are overwhelmingly similar and essentially indistinguishable. Thus, we prefer to treat the detrital ages of all three samples as a composite distribution.

Snow Lake Terrane

Three samples from mature, thick, cross-bedded quartzite in the Boyden Cave pendant of the south-central Sierra Nevada (Fig. 2) show similar detrital age distributions and have been grouped together. Their composite distribution shows a dominant spread from ca. 1000 to 1500 Ma, centered on ca. 1150 and 1450 Ma, with another major peak at ca. 1775 Ma and minor peaks at ca. 1650 and 2700 Ma (Fig. 4B). Fine-grained, gray quartzite adjacent to meta-chert mélange with local calc-silicates and skarn deposits of the central Sierra Nevada Iron Mountain pendant shows a major peak at ca. 1790 Ma with minor peaks at ca. 1050, 1150, 1350, 1450, and 2700 Ma. The minimum age of 461 ± 17 Ma defined by a single grain is herein considered inconclusive.

Kernville Terrane

Two samples from 1- to 3-m-thick feldspathic quartzite beds within the Fairview pendant, interpreted as turbidite channel fills, and one sample from an ~10-m-diameter quartzite block hosted in argillite matrix from the Sequoia Park pendant define a set of two distinct detrital age distributions, one dominated by ages at ca. 1100 Ma (07SS10) and the other dominated by ca. 1750 Ma ages (09-KK-3 and 081103E). The first distribution shows major peaks at ca. 1050 and 1125 Ma, with subordinate spread from ca. 1200 to 1850 Ma (Fig. 4C). The second composite distribution shows a major peak at ca. 1750 Ma, with minor peaks at ca. 675, 1450, 1850, 2500, and 2700 Ma, and a youngest age peak of three grains providing a maximum depositional age at ca. 625 Ma.

Western Metamorphic Belt

Mature, white to reddish weathering, medium-grained quartzite with interbedded schist of the southern western metamorphic belt, found along Highway 120 just NW of Crane Flat in the western central Sierra Nevada (Fig. 2), showed a detrital age distribution with a dominant peak between ca. 1000 and 1450 Ma, a narrower major peak at ca. 1775 Ma, a minor peak at ca. 1650 Ma, and a spread of ages >2400 Ma (Fig. 3B). This sample comes from the quartzite and schist of Pilot Ridges, rocks previously mapped as part of the Shoo Fly complex (Bateman and Krauskopf, 1987; Dodge and Calk, 1987). The similarity of these detrital age peaks to new and published Snow Lake terrane strata detrital ages in the Boyden Cave, Iron Mountain, Quartzite Peak, and Benson Lake pendants calls into question their previous correlation with the Shoo Fly complex, which we discuss further below.

A sample of fine-grained, gray quartzite, associated with phyllite and marble in a tectonic slice in the Sherlock Creek area within the Sullivan Creek terrane, showed major peaks at ca. 1775 and 1850 Ma, with minor peaks at ca. 2000 and 2650 Ma (Fig. 4B). The youngest grain, at ca. 350 Ma, does not constitute a robust cluster and does not constrain a maximum depositional age. Fusulinids and other shallow, warm-water fossils found within this structural sliver provide a Late Mississippian age (Herzig and Sharp, 1992).

Southern Inyo Mountains

Four samples from Ordovician, Devonian, Upper Mississippian, and Lower Permian strata in the southern Inyo Mountains (Fig. 2) show a progression of detrital zircon age distributions (Fig. 4D). These strata are herein grouped with the Death Valley facies. For a more thorough examination of their depositional setting through time, see Stone et al. (1989). The Ordovician Eureka Quartzite (sample 09-TCH-2) shows a major peak at ca. 1850 Ma, with minor peaks at ca. 2100 and 2700 Ma. The Devonian Lippincott Member of the Lost Burro Formation (09-TCH-1) shows major peaks at ca. 1475 and 1675 Ma, with minor peaks at ca. 1100 and 1250 Ma. A single youngest age at ca. 485 Ma does not provide a robust constraint on maximum depositional age. The detrital age distribution of the Upper Mississippian Mexican Spring Formation (09-CM-699) displays a shift to younger ages and a general change in relative proportions of Proterozoic ages. The distribution shows major peaks at ca. 385, 450, 1050, and 1200 Ma and minor peaks at ca. 550, 800, 950 1350, and 1500 Ma. The youngest age peak is defined by five grains at ca. 385 Ma. The detrital ages of the Lower Permian Santa Rosa Flat unit 2 of the Owens Valley Group (09-CM-676) also record a greater spread of younger detrital ages. The sample distribution shows a spread of ca. 300–650 Ma ages, with peaks at ca. 325, 425, and 575 Ma, additional peaks at ca. 1050, 1150, 1500, 1650, 1775, and 1825 Ma, and a scatter of ages between 2000 and 2800 Ma. Two Late Triassic ages were excluded from further consideration because they are significantly younger than independent constraints on the depositional age of this unit (Stevens et al., 2015b). The youngest age peak is defined by three grains centered at ca. 305 Ma, which is somewhat older than the Late Permian depositional age of this unit.

Joshua Tree National Park

Two samples from Proterozoic quartzite from the Joshua Tree area in the Mojave Desert, which show very similar unimodal detrital ages with a major peak at ca. 1750 Ma, have been plotted together (Fig. 4E). The youngest robust age cluster is at ca. 1640 Ma, giving a latest Paleoproterozoic maximum depositional age.

MDS Results

MDS was performed on our compilation of new and published sample detrital zircon U-Pb ages (Figs. 5 and 6). The resultant MDS plot (Fig. 6) shows a first-order banana-shaped structure. The opposing tips of this structure are defined by a cluster of samples dominated by a major peak at ca. 1850 Ma on the bottom right and samples dominated by a major peak at ca. 1100 Ma on the bottom left. The main body of this structure is a cloud defined by the spread of samples from autochthonous SW Laurentian continental margin strata. Both tips of the structure show a spread toward the main cloud, with the ca. 1100 Ma tip overlapping the autochthonous cloud. The ca. 1850 Ma group forms a distinct cluster composed of Paleozoic allochthonous strata and their overlap assemblages. Upper Paleozoic samples, excluding the Golconda allochthon and Antler overlap sequence, form a small cloud somewhat distinct from the main autochthonous body due to their spread of younger detrital ages. The main body shows a second-order structure with a spread of samples between a well-defined end member of Mesoproterozoic sediments and Neoproterozoic–Cambrian Inyo facies strata that show a nearly unimodal ca. 1750 Ma peak, and the group of Neoproterozoic–Cambrian strata with a large proportion of 1000–1300 Ma ages. Considerable overlap between autochthonous strata and the Snow Lake terrane is indicative of the general similarity between their detrital age distributions. The spread within the main body is attributable to the variable proportions of major peaks and presence of different minor peaks in sample distributions.

Several other second-order patterns of the positions of sample distributions belonging to individual facies/terranes with respect to the first- and second-order structures described here were also evident: (1) The Kernville terrane, southern Tehachapi Mountains pendants south of the Garlock fault, Northern Sierra terrane, Roberts Mountains allochthon, Death Valley facies, Nevada-Utah shelf facies, and Inyo facies all show some analyzed sample distributions that plot within or near the ca. 1100 Ma–dominated tip. These points are indicative of a widespread pattern evident in detrital zircon age signatures across the western Laurentian margin (Linde et al., 2014). (2) The Snow Lake terrane, Nevada-Utah shelf facies, and Death Valley facies all have samples with known or inferred Ordovician depositional ages that plot within the ca. 1850 Ma allochthonous strata cluster. (3) Sample distributions of all autochthonous Devonian strata show a tight cluster within the field of strata autochthonous to SW Laurentia, indicative of their impressive similarity. (4) The eastern Sierra Nevada chert-argillite unit sample (ChA) and three samples from the Kernville terrane and Tehachapi Mountains (FV2, FV3, ThBC) plot between the edge of the Inyo facies domain and the allochthonous group tip. The Kernville terrane and Tehachapi Mountains samples lack the prominent peak at ca. 1850 Ma representative of the allochthonous terranes, but they share dominant ca. 1600–1800 Ma ages with autochthonous strata. These three southern Sierra Nevada samples show a shared

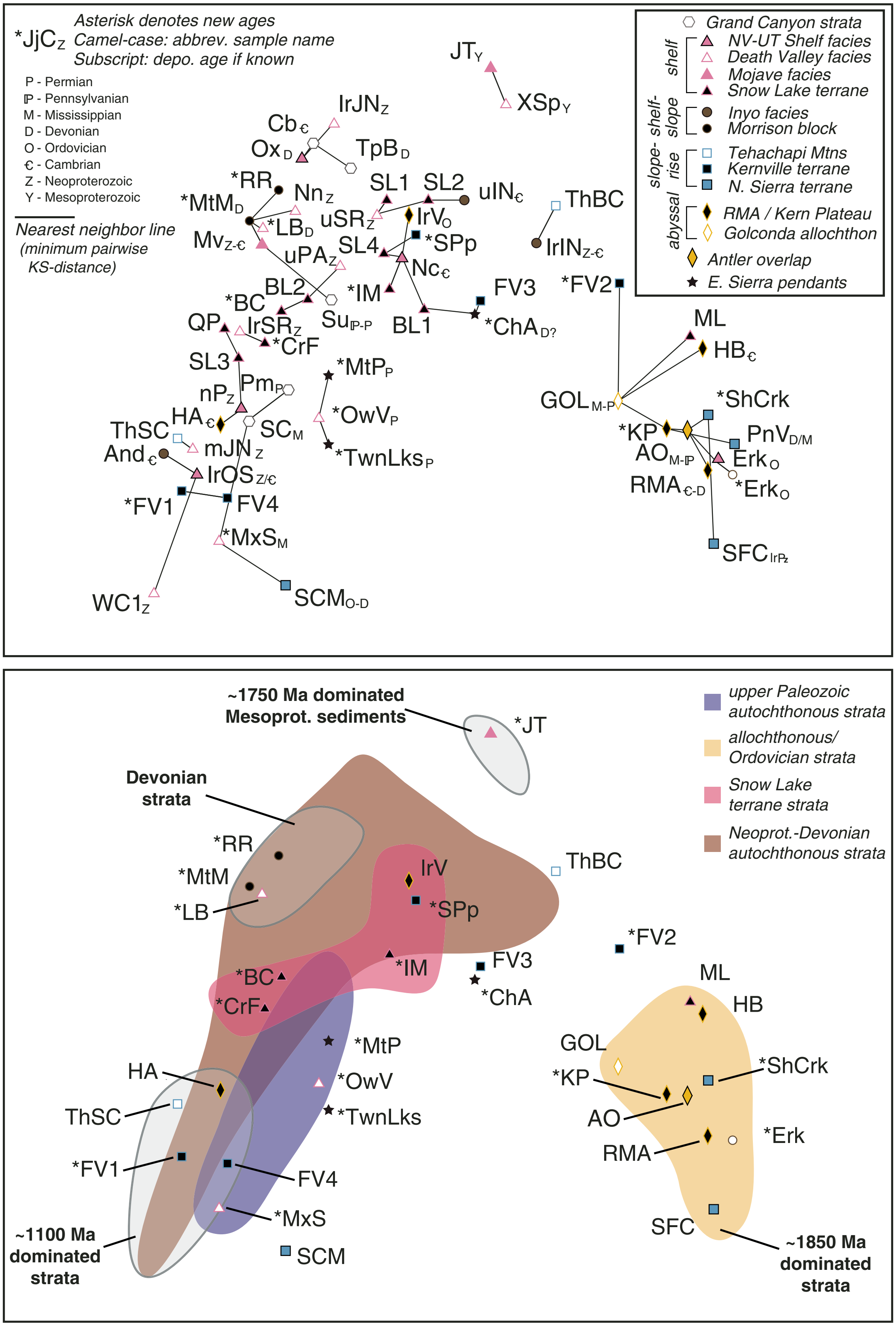
*JjC Z
Asterisk denotes new ages
Camel-case: abbrev. sample name
Subscript: depo. age if known
P - Permian
ℙ - Pennsylvanian
M - Mississippian
D - Devonian
O - Ordovician
Є - Cambrian
Z - Neoproterozoic
Y - Mesoproterozoic
Nearest neighbor line
(minimum pairwise
KS-distance)
Grand Canyon strata
shelf
NV-UT Shelf facies
Death Valley facies
Mojave facies
Snow Lake terrane
slope- shelf-slope
Inyo facies
Morrison block
rise
Tehachapi Mtns
Kernville terrane
N. Sierra terrane
abyssal
RMA / Kern Plateau
Golconda allochthon
Antler overlap
E. Sierra pendants
JT Y
XSp Y
IrJN Z
Cb Є
Ox D
TpB D
*RR
Nn Z
*MtM D
*LB D
Mv Z-Є
SL1
SL2
uIN Є
uSR Z
IrV O
*SPp
SL4
uPA Z
Nc Є
ThBC
IrIN Z-Є
*BC
BL2
*IM
Su ℙ-P
BL1
FV3
*ChA D?
*FV2
QP
IrSR Z
*CrF
SL3
*MtP P
Pm P
nP Z
HA Є
SC M
*OwV P
ThSC
mJN Z
And Є
*TwnLks P
IrOS Z/Є
*FV1
FV4
*MxS M
WC1 Z
SCM O-D
ML
HB Є
GOL M-P
*ShCrk
*KP
PnV D/M
AO M-ℙ
Erk O
RMA Є-D
*Erk O
SFC IrPz
~1750 Ma dominated
Mesoprot. sediments
*JT
upper Paleozoic
autochthonous strata
allochthonous/
Ordovician strata
Snow Lake
terrane strata
Neoprot.-Devonian
autochthonous strata
Devonian
strata
*RR
*MtM
*LB
IrV
*SPp
ThBC
*FV2
*BC
*IM
FV3
*ChA
*CrF
ML
HB
*MtP
GOL
HA
*OwV
*ShCrk
*KP
ThSC
*TwnLks
AO
*Erk
RMA
*FV1
FV4
*MxS
SFC
~1100 Ma
dominated
strata
SCM
~1850 Ma
dominated
strata

Figure 6.

minor peak at ca. 650 Ma, which is relatively uncommon in Neoproterozoic–lower Paleozoic Laurentian margin strata.

DISCUSSION

Provenance of Sierra Nevada Framework Rocks

Our new detrital zircon data and compilation of previous work provide key constraints on the evolution of the SW Laurentian continental margin and the nature and assembly of Sierran framework terranes. Next, we integrate multiple lines of evidence to best resolve these issues.

Morrison Block

Three samples from Morrison block strata exposed in the Mount Morrison and Ritter Range pendants show detrital zircon age distributions that are consistent with other Neoproterozoic to lower Paleozoic rocks autochthonous to SW Laurentia (Fig. 5). Detrital zircon ages from two samples of the Mount Morrison Formation are nearly identical to ages from the coeval shelf-facies Lippincott Member of the Lost Burro Formation, corroborating the correlation of these units by Stevens and Pelley (2006). These ages further support the interpretation of the fault-bounded Morrison block strata as parautochthonous slope facies equivalents to more inboard, Paleozoic autochthonous strata, which derived detritus from either recycled shelf deposits or central Laurentian basement (Stevens and Greene, 1999; Stevens and Pelley, 2006).

Figure 6. Multidimensional scaling (MDS) plot of compiled data. Top panel shows relationships between all new and published single sample, and composite detrital age distributions. Bottom panel shows relationships of key detrital age distributions to fields defined by the plotted extent of compiled data grouped by paleogeographic affinity and provenance, with symbols same as top panel. See text for more thorough discussion of data structure; more information on compiled samples is available in Supplementary File C (see text footnote 1). KS—Kolmogorov-Smirnov. Sample abbreviations: TwnLks—Twin Lakes assemblage composite, ChA—TP-8 (chert-argillite unit), MtM—Mount Morrison Formation composite, RR—VT15-12-A, MtP—S-1822 (Mount Pinchot pendant); SL1—SLP-Sterling1, SL2—SLP-13, SL3—SLP-Zabriskie1, SL4—SLP-21, BL1—BP-M-314, BL2—RE-242, ML—May Lake pendant composite, CrF—SP-1, QP—SN7131, IM—He-8, BC—Boyden Cave pendant composite; KP—Kern Plateau strata composite; SPp—09-KK-3, FV2—081103E, FV3—91SS32, FV1—07SS10, FV4—89SS4; ThSC—08SE258, ThBC—08BC60; uIN—upper Inyo facies units composite, And—Andrews Mountain Member composite, lrIN—lower Inyo facies units composite; Mv—Mojave facies Neoproterozoic–Cambrian strata composite, JT—Joshua Tree quartzite composite; Ox—Oxyoke Canyon Sandstone, Erk—Eureka, Nc—upper Neoproterozoic to lower Cambrian shelf composite, lrOS—SP-01-COM, nP—Neoproterozoic NV-Utah shelf composite; OwV—09-C19-676, MxS—09-CM-699, LB—09-TCH-1, *Erk—09-TCH-2; WC1—WC1, uSR—upper Stirling Quartzite composite, lrSR—NR30, mJN—J39, lrJN—J14A, Nn—Noonday Dolomite composite, uPA—upper Pahrump Group composite, XSp—Crystal Spring Formation composite; Pm—lower Grand Canyon Permian units composite, Su—Supai Group composite, SC—Surprise Canyon composite, TpB—Temple Butte composite, Cb—Grand Canyon Cambrian units composite; lrV—lower Vinini Formation composite, RMA—Roberts Mountains allochthon main facies composite, HA—Harmony A composite, HB—Harmony B composite; GOL—Golconda allochthon composite; PnV—Picayune Valley Formation, ShCrk—MR-5, SCM—Sierra City mélange, SFC—Shoo Fly complex composite; AO—Antler overlap composite.

Chert-Argillite Unit

The detrital ages of the chert-argillite unit (Ardill and Paterson, 2015) do not match ages from other autochthonous or allochthonous strata presently exposed in SW Laurentia (Figs. 4, 5, and 6). The observed detrital ages and Silurian maximum depositional age are inconsistent with previous stratigraphic correlations of this unit with Ordovician Roberts Mountains allochthon strata that predict a unimodal ca. 1850 Ma–dominated detrital zircon age distribution. These new detrital zircon data are significantly different than any detrital zircon ages from Roberts Mountains allochthon strata such as the lower Vinini or Harmony Formations (e.g., Linde et al., 2016, 2017), and they are thus inconsistent with correlation to any Roberts Mountains allochthon strata.

It is rare to observe a detrital age distribution with a spread of Paleoproterozoic–Mesoproterozoic age peaks throughout autochthonous western Laurentian margin strata south of Alaska until mid-Paleozoic time (Gehrels et al., 2011; Kraft, 2013; Gehrels and Pecha, 2014; this study). The detrital age distribution of the chert-argillite unit, including the ca. 435 Ma youngest age peak, most closely resembles that of deep-water Devonian Yreka subterrane (Eastern Klamath Mountains) strata interpreted to have received detritus from exotic rocks, as well as Devonian strata of southern British Columbia (Grove et al., 2008; Colpron and Nelson, 2009; Kraft, 2013; Gehrels and Pecha, 2014). The post mid-Silurian, deep-water chert-argillite unit was likely deposited farther north along the western margin of Laurentia, where it received detritus from varied basement rocks or continental margin deposits likely including exotic or fringing arc sources. The similarity of chert-argillite unit detrital zircon ages to those from Yreka subterrane units, along with the proposed connection to the NW Laurentian margin, exotic detritus, and fringing arcs, suggests that these strata represent an isolated sliver of strata correlative to mid-Paleozoic rocks of the Eastern Klamath–Northern Sierra terrane.

Twin Lakes Assemblage

The detrital age distribution of the Twin Lakes assemblage, with a youngest cluster between 300 and 350 Ma (peak ca. 330 Ma), spread of ages between 300 and 650 Ma, and a continuous spread between 900 and 2000 Ma, is distinct from all other Sierran pre-Mesozoic rocks that we have sampled (Fig. 5). Similar detrital age distributions are found in Lower Permian strata of the southern Inyo Mountains and the Grand Canyon (Fig. 7; Gehrels et al., 2011). Detrital zircon age populations of ca. 325 Ma grains are also present in various areas to the northwest, including the Mississippian Bragdon Formation and

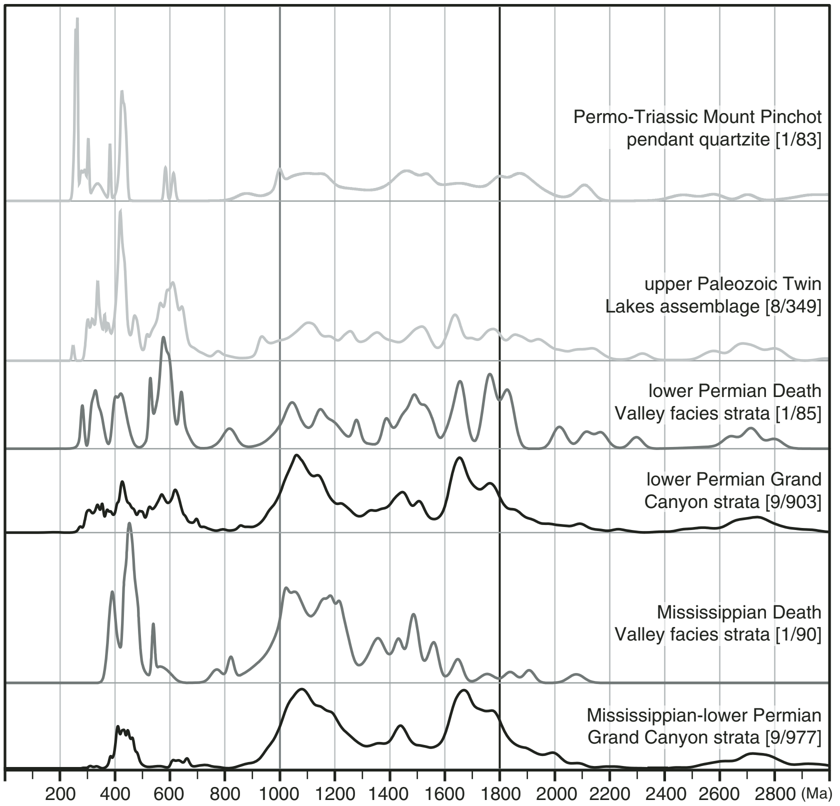

Figure 7. Probability density plots of SW Cordilleran upper Paleozoic strata detrital age distributions. Grand Canyon data are from Gehrels et al. (2011).

Pennsylvanian–Lower Permian Baird Formation in the eastern Klamath Mountains, and the Lower Permian Arlington Formation of the Northern Sierra terrane (Gehrels and Miller, 2000; Spurlin et al., 2000). Detrital zircons with ca. 435 Ma ages are also found in the nearby chert-argillite unit.

Three models for the original locus of deposition of the Twin Lakes assemblage may be proposed: (1) along the SW Laurentian margin as an outboard equivalent of Lower Permian Grand Canyon and southern Inyo Mountains strata; (2) farther north along the western Laurentian margin, on the inboard side of the Slide Mountain Ocean; or (3) on the Slide Mountain Ocean side of the fringing McCloud arc system.

Several important considerations bear weight on these three paleogeographic models: (1) the interbedded shallow-marine siliciclastic and volcaniclastic sediments, and felsic to intermediate volcanics of the Twin Lakes assemblage require deposition near a volcanic source, likely an arc. As no Devonian to Permian arc built into the autochthonous SW Laurentian margin has been documented, it is difficult to place the Twin Lakes assemblage along SW Laurentia at the time of its deposition. (2) In Pennsylvanian to Early Permian time, the outboard western Laurentian margin was dominated by slope-abyssal facies strata deposited within the Slide Mountain Ocean that are characterized by ca. 1850 Ma detrital age peaks (Stevens, 1991; Gehrels and Dickinson, 2000; Riley et al., 2000; Gehrels and Pecha, 2014). (3) Paleogeographic reconstructions place the fringing McCloud arc, built onto oceanic crust, exotic basement, and slivers of western Laurentian margin strata, as the outboard boundary of the Slide Mountain Ocean (Metcalf et al., 2000; Colpron and Nelson, 2009; Saleeby, 2011; Stevens, 2012). (4) As the geometry, origin, and opening direction of the Slide Mountain Basin and position of fringing arcs relative to the western Laurentian margin are not well constrained (compare Colpron and Nelson [2009] to Stevens [2012]), it is possible that some detritus shed from western Laurentia may have reached the proximal side of the fringing arc. Nappes of the McCloud arc exposed in SE Alaska and western British Columbia contain abundant interbeds of relatively mature siliciclastics and carbonates, at least some turbiditic, suggesting that the Slide Mountain Basin was traversed by Laurentian margin detritus to be deposited within the fringing-arc stratigraphy (Rubin et al., 1990; Saleeby, 2000). Given these considerations, we favor model 3.

Mount Pinchot Pendant

The eastern Sierra Nevada Mount Pinchot pendant quartzite sample (Fig. 4A) shows a spread of Proterozoic detrital ages matching upper Paleozoic strata across SW Laurentia. Sparse Neoproterozoic ages and more restricted late Neoproterozoic to Paleozoic ages, particularly limited at ca. 600 Ma, contrast with all Lower Permian strata, suggesting a change in provenance following the Early Permian (Fig. 7). Ages older than 650 Ma may also be recycled from the underlying assembled Sierran framework terranes or the proximal SW Laurentian margin strata (Fig. 5). We interpret proximal Permian–Triassic magmatism as the source of the youngest ages in these strata. These detrital zircon ages were derived from strata that presumably unconformably overlie strata correlated with the Neoproterozoic–Cambrian Inyo facies stratigraphy (Bartley et al., 2001; Stevens et al., 2005). Thus, at least some Mount Pinchot pendant strata represent a Permian–Triassic sequence. This inferred relationship parallels that of similar, coeval deposits exposed in the El Paso Mountains and possibly the Kern Plateau, suggesting that a Permian–Triassic overlap sequence is more widespread than previously recognized (Walker, 1988; Dunne and Suczek, 1991; Saleeby and Dunne, 2015).

Kern Plateau Pendants

Deep-marine strata of the Kern Plateau pendants show a detrital zircon age distribution dominated by ca. 1850 Ma ages, consistent with all other allochthonous deep-water deposits and autochthonous Ordovician sandstone. Ages for all these strata are most compatible with derivation from the Peace River Arch in northern British Columbia (Figs. 5 and 6; Gehrels et al., 2000; Linde et al., 2016, 2017). Given stratigraphic similarities to deep-marine Roberts Mountains allochthon strata documented by Dunne and Suczek (1991), the new detrital zircon data further support the interpretation of Saleeby and Dunne (2015) that the Kern Plateau pendants are exposures of a tectonic ribbon of abyssal-rise facies strata and oceanic lithospheric basement emplaced within the Pennsylvanian–Permian sinistral truncation transform of the SW Laurentian margin. Structural and isotopic evidence suggests that El Paso terrane strata record a postdepositional structural history divergent from that of the Roberts Mountains allochthon and were not deformed nor emplaced as part of the Roberts Mountains allochthon, but were rather emplaced along with their oceanic lithosphere basement (Kistler and Ross, 1990; Miller et al., 1995; Saleeby and Dunne, 2015). The lack of Antler deformation across all Sierran prebatholithic framework rocks is inconsistent with previous interpretations of the El Paso terrane as a displaced block of the highly deformed Antler allochthon itself. This interpretation, based on detrital zircon provenance, contrasts with previous alternative correlations to Morrison block strata (Stevens and Pelley, 2006). The lack of detrital zircon data from El Paso terrane strata in the El Paso Mountains precludes definitively extending the above provenance interpretation to the entire El Paso terrane. Nonetheless, we consider this a likely valid hypothesis with readily testable predictions.

Snow Lake Terrane

New analyses from the Boyden Cave and Iron Mountain pendants are consistent with previously published Snow Lake terrane detrital ages, suggesting ultimate derivation from Laurentian basement terranes (Grasse et al., 2001; Memeti et al., 2010; Chapman et al., 2015). This confirms the interpretation of these pre-Mesozoic strata as part of the Snow Lake terrane (Schweickert and Lahren, 1991; Saleeby and Busby, 1993; Memeti et al., 2010, 2012; Paterson et al., 2014; Saleeby and Dunne, 2015). The new Crane Flat area quartzite sample comes from rocks previously interpreted as part of the Shoo Fly complex (Merguerian and Schweickert, 1987; Memeti et al., 2010). However, our new detrital ages show a greater similarity to other shallow-water passive-margin deposits (Figs. 4, 5, and 6), suggesting that the Crane Flat area quartzite, phyllite, and marble are most plausibly interpreted as highly deformed Neoproterozoic to lower Paleozoic Snow Lake terrane strata. As our understanding of the Kernville terrane stratigraphy and existing detrital zircon data from Kernville strata are limited, it is also possible that the detrital zircon ages from the Crane Flat area are similar to some undocumented Kernville terrane strata detrital zircon age distributions.

The criteria presented by Schweickert and Lahren (1991) for differentiating rocks of the southern Shoo Fly complex from the Snow Lake terrane, discussed above, are not explicitly met in the southernmost western metamorphic belt. The isolated Crane Flat area outcrops record deformation histories and intensity similar to other Snow Lake terrane exposures (Bhattacharyya, 1986; Saleeby and Busby, 1993). Due to limited exposure and acute deformation, it is uncertain if Crane Flat area strata are continuous with strata intruded by middle to upper Paleozoic orthogneiss to the north. However, no Paleozoic orthogneiss bodies, typical of the Shoo Fly complex just to the north, have been recognized in the immediate Crane Flat area or farther south (Bhattacharyya, 1986). Together, the new analyses from the Boyden Cave pendant, Iron Mountain pendant, and Crane Flat show that the map extent of the Snow Lake terrane extends farther south and west of what Schweickert and Lahren (1991) originally defined as the “Snow Lake block” (see Figs. 2 and 4B).

These new and previously published ages are similar to detrital ages of Neoproterozoic to Devonian autochthonous shallow-water continental margin strata of SW Laurentia as far north as central Idaho (Figs. 5 and 6), which are thought to have been derived from central and eastern Laurentian cratonic basement with minor input from Neoproterozoic to Cambrian W Laurentian magmatism (Yonkee et al., 2014; Chapman et al., 2015; Beranek et al., 2016). In aggregate, none of these regions is distinguishable as a closer match to the Snow Lake terrane than others (Yonkee et al., 2014; Beranek et al., 2016). However, our detrital zircon age compilation does not support previous stratigraphic correlations of specific Snow Lake terrane exposures with the late Neoproterozoic to Cambrian Mojave facies stratigraphy (e.g., Lahren and Schweickert, 1989) or alternative correlations with the well-established and well-dated stratigraphies of the Death Valley, Inyo, or Nevada-Utah shelf facies (Fig. 6). Only Snow Lake pendant strata correlated with the Mojave facies Zabriskie Quartzite show a large proportion of ca. 1100 Ma detrital ages (Memeti et al., 2010), whereas published detrital ages from the Mojave facies would predict that no such ca. 1100 Ma–dominated detrital zircon age distribution should be found in Snow Lake pendant stratigraphy. The alternative stratigraphic correlations also predict ca. 1100 Ma–dominated detrital zircon age distributions at stratigraphic levels that are inconsistent with detrital zircon ages from Snow Lake pendant strata. Thus, we cannot constrain the original locus of deposition of the Snow Lake terrane to a narrower range than the Mojave Desert to central Idaho.

Kernville Terrane

Three new and two previously published analyses (Saleeby, 2011; Chapman et al., 2012) from distal Kernville terrane strata show two distinct detrital signatures: one dominated by 1000–1200 Ma ages with a subordinate spread from ca. 1200 to 1850 Ma, and another with a major peak at ca. 1700 Ma and minor peaks at ca. 675, 1450, 1850, and 2500 Ma (Figs. 5 and 6). The first group is dominated by Grenville-aged grains and matches strata throughout the western Laurentia margin. The second group of Kernville terrane strata shows detrital ages similar to the Inyo facies and the Harmony B petrofacies of the Roberts Mountains allochthon (Fig. 8). The minor ca. 675 and 1450 Ma age components found throughout this second group are conspicuously absent in Harmony B detrital ages, whereas the ca. 675 Ma ages are present in Harmony A strata (Linde et al., 2017). The Grenville ages absent in this second group are a minor component in almost all Inyo facies strata (Chapman et al., 2015). Three provenance models for the Kernville terrane may be proposed: (1) an along-strike continuation of the rise facies Shoo Fly complex; (2) a rise facies equivalent of Neoproterozoic–Cambrian shelf and slope deposits autochthonous to the SW Laurentian margin that was accreted onto or interleaved with other Sierra Nevada framework terranes; or (3) original deposition farther north, potentially between southern Idaho and southern Canada prior to southward transport and emplacement.

Several considerations bear weight on these provenance models: (1) The clear distinction between two groups of detrital age distributions, with one dominated by ca. 1100 Ma ages, seen throughout rocks with affinity to the southern and central portions of the western Laurentian margin, provides a broad constraint on the Kernville terrane locus of deposition. (2) The outer shelf Inyo facies is markedly depleted in Grenville ages relative to more proximal shelf deposits. It is possible that the Grenville-aged zircons had simply not reached more distal deposits. (3) Some late Neoproterozoic–aged grains thought to be derived from magmatic activity within Idaho have been identified throughout Neoproterozoic–lower Paleozoic strata across the southern and central portions of the western Laurentian margin (Kraft, 2013; Gehrels and Pecha, 2014; Yonkee et al., 2014; Chapman et al., 2015; Linde et al., 2017). (4) Though all three samples of the ca. 1700 Ma group share a minor peak at ca. 675 Ma, they show slightly different major peaks at ca. 1650, 1700, and 1750 Ma, and they differ in the location and abundance of pre–1800 Ma ages (Fig. 8). The presence of significant ca. 1500–1650 Ma ages, rare outside of Belt basin and Lemhi subbasin strata of northern Montana and Idaho (Ross and Villeneuve, 2003; Yonkee et al., 2014; Link et al., 2016), provides another possible link to a northern sediment source region for the Kernville terrane. (5) Kernville terrane detrital ages are significantly different than the limited data available from the Shoo Fly complex and are incompatible with a shared provenance.

The dissimilarity between Kernville terrane detrital ages and Shoo Fly complex data indicates that the Shoo Fly complex and Kernville terrane are not continuous along-strike equivalent belts and were derived from distinct source areas along the western Laurentian margin. Given the potential sources for ca. 675 and 1500–1650 ages in the Idaho area (Link et al., 2016) and the presence of ca. 1450 and 1700 Ma grains in strata deposited in this region, we favor model 3, with sediment sources in the Idaho and southern Canada regions.

Western Metamorphic Belt

The sample from the Sherlock Creek area (Fig. 2) within the western metamorphic belt Calaveras complex shows a detrital age distribution that is similar to all other deep-water passive-margin facies (Figs. 4B, 5, and 6). Given the mixed quartzite, marble, and phyllite stratigraphy as well as the Late Mississippian fossil age and position within the structurally complex Sullivan Creek terrane, we interpret these strata as a structural sliver of Shoo Fly complex overlap deposits similar to the Picayune Valley Formation of the Northern Sierra terrane that was faulted into this part of the western metamorphic belt during early Mesozoic deformation.

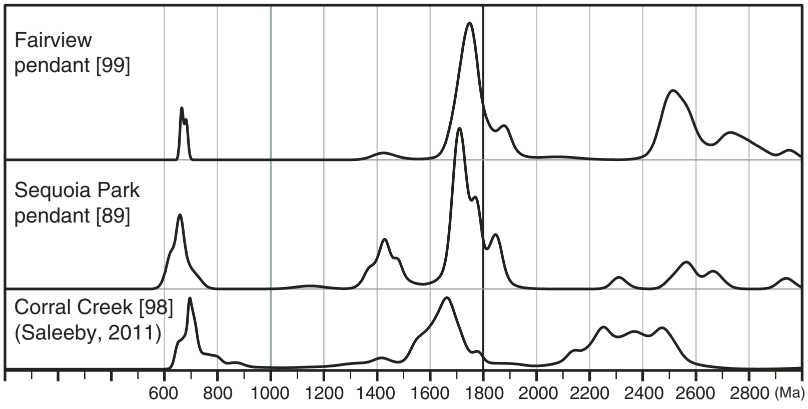

Figure 8. Probability density plots of Kernville terrane ca. 1700 Ma group sample detrital age distributions. Note the shared ca. 700 Ma minor peak, variable major peaks between 1650 and 1750 Ma, and varied pre–2100 Ma ages.

Southern Tehachapi Mountains Pendants

Detrital zircon ages of two samples from pre-Mesozoic strata exposed in isolated, displaced pendants of the Tehachapi Mountains (Fig. 2), presented in Chapman et al. (2012), have been previously correlated with strata of the southern Sierra Nevada, from which they may have separated within Late Cretaceous detachment sheets. One sample from a quartzite in the Bean Canyon pendant south of the Garlock fault, showing a major peak at ca. 1800 Ma and minor peaks at ca. 1450 and 2700 Ma (Fig. 9), was previously correlated with rocks of the El Paso terrane. Although our compilation shows that these detrital ages are more similar to Inyo facies detrital age distributions (Fig. 6), the ca. 487 Ma mafic/ultramafic complex that lies nonconformably beneath the principal siliciclastic section reported by Chapman et al. (2012) precludes correlation with the Inyo facies. Another sample from the Salt Creek pendant in the San Emigdio Mountains, which shows major peaks at ca. 1100 and 1450 Ma and minor peaks at ca. 600 and 1700 Ma (Fig. 9), was previously correlated with the ca. 1000–1200 Ma–dominated samples from the Kernville terrane. Salt Creek pendant carbonates, quartzites, and quartzofeldspathic gneisses and schists may have been deposited in slope to inner-shelf settings. Given that Grenville-age detrital distributions are found in all continental margin facies of SW Laurentia, detrital zircon geochronology and stratigraphic comparisons cannot provide a firm correlation for these strata (Fig. 6).

Joshua Tree National Park

Quartzite in isolated exposures in the Joshua Tree area show detrital ages very similar to the Mesoproterozoic Crystal Springs Formation of Death Valley and an even closer match to the latest Paleoproterozoic Pinto Mountains Group of the Transverse Ranges (Barth et al., 2009; Mahon et al., 2014).

Evolution of the SW Laurentian Margin

Our compiled data, integrated with other tectonic constraints, indicate several important connections between the western Laurentian margin and Sierran framework terranes that shed light on the tectonic evolution and development of depositional systems across Laurentia:

(1) Complications in timing and expression of the widespread influx and subsequent paucity of late Mesoproterozoic detrital zircon ages in Neoproterozoic–Cambrian strata across the western Laurentian margin decrease their utility as a "golden spike" for uplift of the Transcontinental Arch (Linde et al., 2014; Yonkee et al., 2014). This shift in detrital zircon age populations with stratigraphic position is clearly expressed within our compilation and MDS results (Fig. 6): A stark decrease in ca. 1100 Ma detrital zircon ages occurs twice in the Neoproterozoic to lower Cambrian Death Valley facies stratigraphic succession, once in the Nevada-Utah shelf facies, and is not observed in the Mojave facies (MacLean et al., 2009; Schoenborn et al., 2012; Gehrels and Pecha, 2014; Linde et al., 2014; Mahon et al., 2014; Yonkee et al., 2014). Neoproterozoic to Cambrian Inyo facies strata record little Grenville-age input, with the exception of the lower Cambrian Andrews Mountain Member of the Campito Formation (Chapman et al., 2015). Despite this, the reorganization of sediment transport and depositional systems indicated by these shifting detrital zircon age populations indicates proximity to the southern and central parts of the western Laurentian margin in Neoproterozoic to Cambrian time. This Neoproterozoic–Cambrian provenance contrasts with the ca. 1100 Ma ages abundant in the Ordovician–Devonian Sierra City mélange, which we propose reflect the mid-Paleozoic introduction of detritus derived from exotic rocks into western Laurentian depositional systems (Colpron and Nelson, 2009; Gehrels and Pecha, 2014).

(2) Devonian cratonic, shelf, and slope facies strata autochthonous to southwestern Laurentia show very similar detrital zircon age distributions, suggesting that sediment networks were interconnected across the SW Laurentian passive margin at this time. This contrasts with the Devonian Slaven Chert of the Roberts Mountains allochthon, which shows detrital zircon ages typical of the Cambrian–Devonian main Roberts Mountains allochthon facies (Linde et al., 2016). This contrast further supports the hypothesis that Roberts Mountains allochthon strata, with the

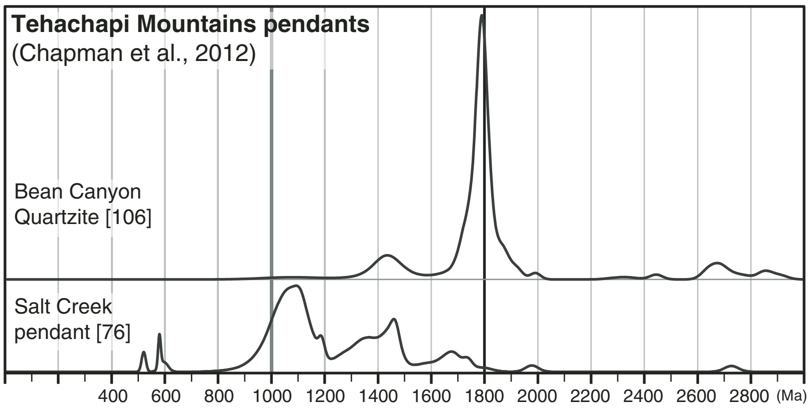

Figure 9. Probability density plots of isolated Tehachapi Mountains pendant strata sample detrital age distributions.

exception of the lower Vinini Formation, are not equivalents of coeval, proximal deposits of this section of the western Laurentian margin and were likely transported parallel to the margin prior to accretion during the Antler orogeny (Suczek, 1977; Wallin, 1990; Wright and Wyld, 2006; Colpron and Nelson; 2009; Linde et al., 2016, 2017).

(3) The Roberts Mountains thrust does not extend across Owens Valley into the eastern Sierra Nevada (Figs. 1, 2, and 3). Detrital zircon ages and emplacement timing constraints are inconsistent with correlation of the chert-argillite unit and the Twin Lakes assemblage with the Roberts Mountains and Golconda allochthons, respectively (Figs. 4, 5, 6, and 7). As discussed herein, continental rise strata of the Kern Plateau are unlikely to represent a tectonic sliver of the Roberts Mountains allochthon itself. Thus, there is no evidence to support the presence of an offset lateral extension of the Roberts Mountains thrust in the southern Sierra Nevada framework.

(4) New data from middle to upper Paleozoic strata of the southern Inyo Mountains (Fig. 4D) suggest that a barrier to sediment transport from the Antler Highlands was long-lived and extensive. Southern Inyo Mountains strata show detrital ages very similar to coeval units exposed within the Grand Canyon (Fig. 7), in sharp contrast with Antler overlap detrital distributions (Figs. 5 and 6).

(5) Given the Twin Lakes assemblage detrital zircon ages and the presence of similar ages in upper Paleozoic strata of accreted terranes to the north, we propose that upper Paleozoic arcs built onto far-traveled or exotic basement outboard of western Laurentia and translated parallel to the margin may have provided at least some of the Neoproterozoic–Paleozoic zircon (Fig. 7). As is the case for other upper Paleozoic strata across the western Laurentian margin, detrital zircon data alone from the Twin Lakes assemblage cannot discriminate between eastern and northern Laurentian orogens, such as the Appalachian and Franklinian orogens, as well as fringing arcs outboard of western Laurentia, as sediment sources (Thomas, 2011).

Exotic Rocks in the Sierra Nevada

Truly exotic rocks or strata that received sediments from exotic terranes or basement are rare in the Sierra Nevada. Only two packages, the Sierra City mélange and chert-argillite unit, can currently be conclusively identified as exotic, with the Twin Lakes assemblage potentially having been built onto, or received sediment from, exotic rocks. Furthermore, the proposed link between the chert-argillite unit and strata found in the Eastern Klamath Mountains provides new constraints on the timing of accretion of the fringing McCloud arc. Emplacement of the chert-argillite unit over Morrison block strata is locally constrained in the northern Ritter Range pendant between deposition of youngest Morrison block strata and the Permian–Triassic Sierra Nevada–wide unconformity (Stevens and Greene, 1999; Barth et al., 2011; Cao et al., 2015). This timing overlaps with several proposed Permian to Permian–Triassic tectonic events, including the Sonoma orogeny, emplacement of the Last Chance allochthon, and the Sierra Nevada–Death Valley thrust system activity. These Permian tectonic events may have been driven by the initiation of Slide Mountain Ocean closure (Saleeby, 2011; Saleeby and Dunne, 2015), emplacement of Sierran framework terranes within the SW Laurentian continental margin truncation transform, final collapse of the McCloud arc against the truncated SW Laurentian margin, or some combination of these events.

Snow Lake Terrane and Western Metamorphic Belt Boundaries

The similarity of the Crane Flat sample detrital zircon ages to Snow Lake terrane detrital zircon ages suggests that the boundaries among the Snow Lake terrane, Shoo Fly complex, Kernville terrane, and Calaveras complex in the central Sierra Nevada need to be reevaluated (Fig. 1). Reassigning metasediments of the Crane Flat area to the Snow Lake terrane suggests that, at least locally, the western bounding structure of the Snow Lake terrane is the Calaveras–Shoo Fly fault, a segment of the Foothills suture (Saleeby, 2011; Saleeby and Dunne, 2015). Although it is unclear whether any Shoo Fly complex or Kernville terrane strata lie between the Crane Flat area Snow Lake terrane rocks and the Calaveras complex to the west, the Snow Lake terrane apparently intervenes, or was interleaved between, the Shoo Fly complex and Kernville terrane in the area near Crane Flat. It is possible that Crane Flat area strata were structurally juxtaposed with the Shoo Fly complex during the Pennsylvanian–Permian truncation of the SW Laurentian margin and assembly of the Sierran framework. Such a fault would have been truncated by the Foothills suture to the west, and it would have an orientation oblique to the Sierran trend, like those seen in zones of low Mesozoic strain in the Kernville terrane (Saleeby and Dunne, 2015). The timing of such syntruncation juxtaposition of Snow Lake terrane and Shoo Fly complex strata is constrained between the ca. 275 Ma age of the youngest orthogneiss exposed north of Crane Flat (Sharp et al., 1982) and Permian–Triassic development of the Calaveras–Shoo Fly fault (Saleeby, 2011). Alternatively, this juxtaposition may have occurred during Early Jurassic extensional attenuation of the Sierran metamorphic framework (Saleeby and Dunne, 2015).

Snow Lake Terrane Emplacement Models

Current models of Snow Lake terrane provenance and emplacement contrast with the models of tectonic assembly of all other Sierra Nevada framework terranes (Table 1; Fig. 1). Both the Mojave–Snow Lake fault southern source model (Lahren and Schweickert, 1989) and the model of Early Jurassic extensional denudation of the lower plate of the Last Chance–eastern Sierra thrust system, leading to emplacement from the east (Chapman et al., 2015), are consistent with Snow Lake terrane detrital zircon data. However, as discussed herein, those detrital zircon ages are similar to those of autochthonous shelf strata exposed as far south as the Mojave Desert and as far north as central Idaho. We propose

TABLE 1. SUMMARY OF PROVENANCE AND PALEOGEOGRAPHIC AFFINITY INTERPRETATIONS FOR SIERRA NEVADA METAMORPHIC FRAMEWORK ROCKS

	Depositional environment	Depositional age	Original locus of deposition	Paleogeographic affinity	Detrital zircon age peaks (Ma)
Morrison block	Slope facies	Paleozoic	SW Laurentia	Parautochthonous	Ca. 1100, 1350–1450, 1700
Chert-argillite unit	Abyssal	Devonian?	Uncertain	Exotic/fringing?	Ca. 435, 1400–1500, 1650, 1850, 2700
Twin Lakes assemblage	Shallow-marine siliciclastic and volcanogenic strata	Devonian–Permian?	Proximal to McCloud arc	Exotic/fringing?	Ca. 350, 425, 600, 1000–2000
Kern Plateau pendants	Rise to abyssal	Cambrian–Devonian	N British Columbia	Allochthonous	Ca. 1850
Snow Lake terrane	Shelf facies	Neoproterozoic–Ordovician?	California–central Idaho	Parautochthonous allochthonous	Ca. 1000–1200, 1450, 1750
Northern Sierra terrane	Slope-rise	Paleozoic	N British Columbia/ McCloud arc	Allochthonous/fringing	Ca. 1850 (SFC)/ca. 600, 1100 (SCM)
Kernville terrane	Slope-rise	Neoproterozoic–Ordovician?	S British Columbia central Idaho	Allochthonous	Ca. 700, 1700/ca. 1100

SCM—Sierra City mélange; SFC—Shoo Fly complex.

a third model for the origin of the Snow Lake terrane consistent with the northern provenance of the other Sierran framework terranes. In this model, the Snow Lake terrane originated from the Idaho area, separated from the margin before or during the opening of the Slide Mountain Ocean. The timing and tectonic environment in which shelf strata could have separated from the Idaho region are unclear and difficult to constrain. Subsequently, the Snow Lake terrane was entrained into the Pennsylvanian–Permian transform with the other Sierran framework terranes prior to final juxtaposition along the truncated SW Laurentian continental margin.

Several considerations constrain models for the paleogeographic affinity and postdepositional history of the Snow Lake terrane: (1) Given the dissimilarity between Mesozoic strata unconformably overlying the Snow Lake terrane and those in a similar position above Neoproterozoic to Paleozoic shelf facies in the Mojave Desert region, motion along a cryptic Mojave–Snow Lake structure would have to predate the Middle Jurassic (Memeti et al., 2010, 2012; Chapman et al., 2015). We interpret the depositional age of these central Sierra Nevada Jurassic strata as an exhumation age for the Snow Lake terrane (Chapman et al., 2015). (2) Chapman et al. (2015) restored ~75 km of post–Early Jurassic dextral displacement across Owens Valley to align the Snow Lake terrane with the Death Valley facies. The Jurassic Independence dike swarm is one of the principal offset markers used to argue for ~65 km of Late Cretaceous or younger dextral displacement across Owens Valley, along with the Late Cretaceous Golden Bear dike and Coso dike swarm (Kylander-Clark et al., 2005; Bartley et al., 2007). On the other hand, the Independence dike swarm is more widespread than previously thought and thus lacks utility as a piercing point (Chapman et al., 2015; Saleeby and Dunne, 2015). Polon et al. (2016) suggested that the Golden Bear and Coso dikes are also more widespread than previously thought and, thus, do not provide strong constraints on the magnitude or timing of dextral displacement across Owens Valley. Late Triassic timing of dextral displacement across Owens Valley, predating the proposed timing of Snow Lake terrane emplacement, is equally plausible (Stevens and Stone, 2002). (3) At least one set of pre–Early Jurassic structures developed in the Snow Lake terrane may correspond to pre-Mesozoic deformation evident in all other pre-Mesozoic framework terranes. The Snow Lake terrane may have participated in the pre-Mesozoic tectonic assembly of the Sierran framework terranes against the truncated margin. (4) The potential pre-Triassic juxtaposition of the Shoo Fly complex and Snow Lake terrane near Crane Flat further suggests that the Snow Lake terrane participated in the pre-Mesozoic tectonic assembly of the Sierran prebatholithic framework.

Considering together these observations and lines of reasoning, we cannot definitively distinguish between the model of Chapman et al. (2015) and the new model proposed herein for the original locus of deposition and postdepositional history of the Snow Lake terrane. However, these models make distinct predictions about the boundary separating Crane Flat Snow Lake terrane and Shoo Fly complex strata in the western metamorphic belt, the age and kinematics of pre-Jurassic Snow Lake terrane deformation, and the relationship of Snow Lake terrane strata to the early Paleozoic stratigraphy and paleogeography of the Idaho region, which could be tested with future work.

Tectonic Assembly of the Sierran Metamorphic Framework

The tectonic regime in which allochthonous and exotic Sierran framework rocks were translated southward, roughly parallel to the western Laurentian margin, is difficult to constrain, with the exception of the Shoo Fly complex forming part of the basement of the middle to late Paleozoic Northern Sierra–Eastern Klamath fringing arc. We favor a model derived from those of Stevens (2012) and Saleeby and Dunne (2015), as follows (Fig. 10):

(1) Neoproterozoic to mid-Paleozoic strata of the future Sierran framework terranes were dispersed southward from their

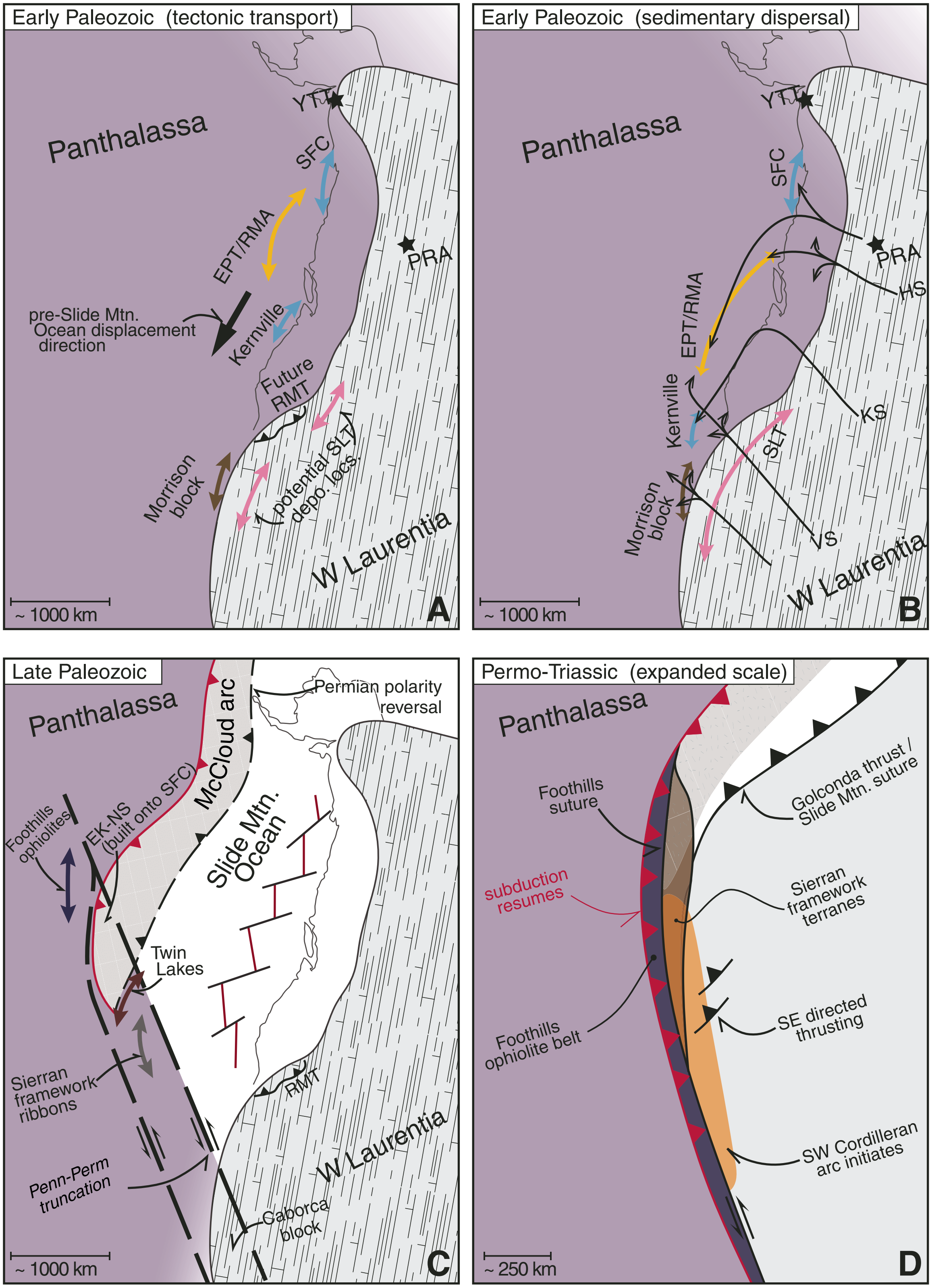
Early Paleozoic (tectonic transport)
Panthalassa
YTT
SFC
EPT/RMA
PRA
pre-Slide Mtn.
Ocean displacement
direction
Kernville
Future
RMT
Morrison
block
potential SLT
depo. locs.
W Laurentia
~ 1000 km
A
Early Paleozoic (sedimentary dispersal)
Panthalassa
YTT
SFC
PRA
HS
EPT/RMA
Kernville
KS
SLT
Morrison
block
VS
W Laurentia
~ 1000 km
B
Late Paleozoic
Panthalassa
McCloud arc
Permian polarity
reversal
Foothills
ophiolites
EK-NS
(built onto SFC)
Slide Mtn.
Ocean
Twin
Lakes
Sierran
framework
ribbons
RMT
W Laurentia
Penn-Perm
truncation
Gaborca
block
~ 1000 km
C
Permo-Triassic (expanded scale)
Panthalassa
Foothills
suture
Golconda thrust /
Slide Mtn. suture
subduction
resumes
Sierran
framework
terranes
Foothills
ophiolite belt
SE directed
thrusting
SW Cordilleran
arc initiates
~ 250 km
D

Figure 10.

source regions along the western Laurentian margin. Uncertainty exists as to the relative, or potentially exclusive, roles of (a) post-Silurian tectonic transport of the Sierran framework strata southward following deposition directly outboard of their interpreted source regions (Fig. 10A; Colpron and Nelson, 2009; Kraft, 2013; Linde et al., 2016, 2017) versus (b) primary deposition south of their source regions, prior to the opening of the Slide Mountain Ocean (Fig. 10B; Gehrels and Dickinson, 1995; Saleeby and Dunne, 2015). The latter interpretation, within the context of our detrital zircon age data, requires significant southward sedimentary dispersal of detritus that formed the Roberts Mountains allochthon, El Paso terrane, and Kernville terrane. The same may be hypothesized for Shoo Fly complex strata of the Northern Sierra terrane. Alternatively, the Shoo Fly complex may have been rifted from its original locus of deposition along with the Yukon-Tanana terrane to the north (Fig. 10A; Pecha et al., 2016) to be subsequently incorporated into the fringing arc basement. A sedimentary transport–dominated model does not require cryptic large-offset fault systems with few field constraints. On the other hand, a tectonic transport–dominated model is consistent with the paucity of early Paleozoic detrital zircon ages in autochthonous Neoproterozoic to Devonian strata (Fig. 5; Gehrels and Pecha, 2014; Pecha et al., 2016). Tectonic transport would have occurred within the complex subduction–rifting–sinistral transform tectonic environment proposed to have accommodated the margin-parallel transit of the fringing arc and exotic rocks as well as opening of the Slide Mountain Ocean (Colpron and Nelson, 2009; Linde et al., 2016, 2017).

(2) Rifting related to opening of the Slide Mountain Ocean displaced the McCloud arc, exotic terranes, and western Laurentian strata further outboard (Fig. 10C). This placed the future Sierra Nevada framework terrane strata within the marginal Slide Mountain Ocean, outboard of its axial spreading centers but inboard of the fringing McCloud arc, which was built into exotic terranes, slivers of the western Laurentian margin, and Cambrian–Ordovician Panthalassan abyssal lithosphere.

(3) Sierran framework strata were subsequently entrained as ribbons in the Pennsylvanian–Permian SW Laurentian continental truncation transform and successively interleaved along the truncated margin (Fig. 10C; Saleeby and Dunne, 2015). Late Paleozoic truncation progressed until polarity-reversed, east-vergent McCloud arc subduction led to collapse of the fringing arc against the western Laurentia margin, which initiated with accretion of the Northern Sierra terrane against the truncated SW Laurentian continental margin (Davis et al., 1978; Saleeby, 2011).

(4) The Permian–Triassic was characterized by initiation of accretion of Panthalassan abyssal rocks and arc magmatism (Fig. 10D; Saleeby, 2011; Saleeby and Dunne, 2015), as well as deposition of a southern Sierra Nevada–Mojave Desert Permian–Triassic overlap sequence that stretched at least as far north as the Mount Pinchot pendant.

It is uncertain whether the Sierran framework terranes were transported and emplaced as coherent crustal slices that were underpinned by mantle lithosphere or if they were rootless nappes and/or strike-slip ribbons. Based on isotopic data and the remnants of nonconformably underlying oceanic basement and fault slices, the El Paso terrane appears to have been transported with abyssal Panthalassan oceanic basement that was never incorporated into the fringing arc (Kistler and Ross, 1990; Dunne and Suczek, 1991; Miller et al., 1995; Chapman et al., 2012; Saleeby and Dunne, 2015). Both the Kernville terrane and Shoo Fly complex contain mafic ± ultramafic fault slices that could represent fragments of original underlying oceanic basement, but unlike parts of the El Paso terrane, local stratigraphic successions that appear to depositionally overlie underlying basement are lacking. Abundant isotopic data on batholithic plutons that cut the Snow Lake terrane strongly suggest that it was rooted into, or at least was still in structural succession with, mature continental lithosphere (Kistler and Peterman, 1973; DePaolo, 1981; Chen and Tilton, 1991). This suggests that if the Snow Lake terrane moved into its current position as a strike-slip ribbon, it did so at least partially coupled to its lithospheric underpinnings. Alternatively, if the Snow Lake terrane is effectively in situ, having been exhumed from beneath the Last Chance and related thrust systems in the early Mesozoic, the batholithic isotopic signature of its Proterozoic basement was derived from appreciably attenuated Laurentian continental crust. Thus, the Sierran framework terranes were likely emplaced with at least some of their original basement preserved.

Aggregate Sierra Nevada Detrital Zircon Signature

Figure 11 compares the aggregate detrital zircon age distributions of pre-Mesozoic Sierra Nevada framework terrane strata to SW Laurentian continental margin strata. The close

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Figure 10. Schematic Paleozoic paleogeographic reconstructions. (A) Tectonic transport model for the early Paleozoic. Double-ended colored arrows indicate ranges of original locus of deposition for Sierran framework terrane strata directly outboard of their source regions, emphasizing position both along and across strike of the W Laurentian margin. (B) Alternative sediment dispersal model for the early Paleozoic. Black arrows indicate dispersal pathways for sediments from source regions to loci of deposition. HS—Harmony Formation source region; KS—Kernville Terrane source region; VS—lower Vinini Formation source region. (C) Late Paleozoic paleogeography. The fringing McCloud arc is shown in its likely middle to late Paleozoic position. The Twin Lakes assemblage locus of deposition is placed relative to the McCloud arc rather than the western Laurentian continental margin. Distance between fringing McCloud arc and western Laurentian margin is largely schematic. (D) Permian–Triassic initiation of the arc following collision of the fringing arc. Smaller extent and expanded scale focusing on SW Laurentia. EPT—El Paso terrane; EK-NS—Eastern Klamaths–Northern Sierra; PRA—Peace River Arch; RMA—Roberts Mountains allochthon; RMT—Roberts Mountains thrust; SFC—Shoo Fly complex; SLT—Snow Lake terrane; YTT—Yukon-Tanana terrane. Figure is modified from Stevens et al. (2005), Colpron and Nelson (2009), Saleeby and Dunne (2015), Linde et al. (2016, 2017), and Pecha et al. (2016).

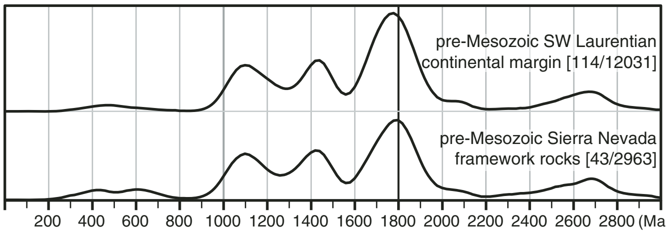

Figure 11. Kernel density estimate plots of composite distributions of all ages from SW Laurentian continental margin strata and Sierra Nevada pre-Mesozoic framework rocks. These plots show that the aggregate detrital zircon age distribution of pre-Mesozoic strata inboard of the arc is indistinguishable from that of Sierra Nevada framework rocks, indicating the western Laurentian affinity of the Sierran framework terranes. Although relative proportions of coeval detrital zircon age distribution peaks may differ, these variations are likely attributed to bias resulting from spatially and stratigraphically irregular sampling rather than fundamental differences in the underlying age distributions.

correspondence in the location and relative proportions of the two age distributions in Figure 11 clearly indicates that pre-Mesozoic Sierra Nevada metamorphic framework strata share a common sedimentary provenance with the western Laurentian margin and were ultimately derived from the Laurentian cratonic basement. Although small differences are apparent between the two distributions shown in Figure 11, they likely reflect bias due to spatially and stratigraphically irregular sampling rather than true differences in the detrital zircon age populations of the sampled strata. This observation indicates a tectonic and paleogeographic setting for the Sierran framework consistent with models in Saleeby and Dunne (2015) and Figure 10. Importantly, the similarity of the aggregate distributions strongly contradicts models of a Cordilleran mobile belt, inclusive of the Sierran framework, that place its origin in the distal Panthalassa ocean basin above a west-dipping subduction zone, and its en-masse accretion to the Cordilleran margin in the Late Cretaceous (e.g., Sigloch and Mihalynuk, 2013).

To further characterize the aggregate Sierra Nevada detrital zircon signature, we plotted U-Th ratios of all our new zircon grain analyses in Figure 12. Over 92% of our new analyses, including those grains that did not pass the U-Th ratio filter, show U/Th < 5. Generally, the main cloud of analyses shows maximum U-Th ratios of ~3 for Archean grains, with the maximum increasing to ~5 for upper Paleoproterozoic grains, decreasing to ~4 for Mesoproterozoic ages, and further declining to ~3 for grains younger than ca. 1000 Ma. Broadly, these observations indicate that the detrital zircon provenance signature of Sierran framework sediment sources was dominated by primary magmatic zircon growth rather than subsequent tectonic events and associated metamorphism (Gehrels, 2014).

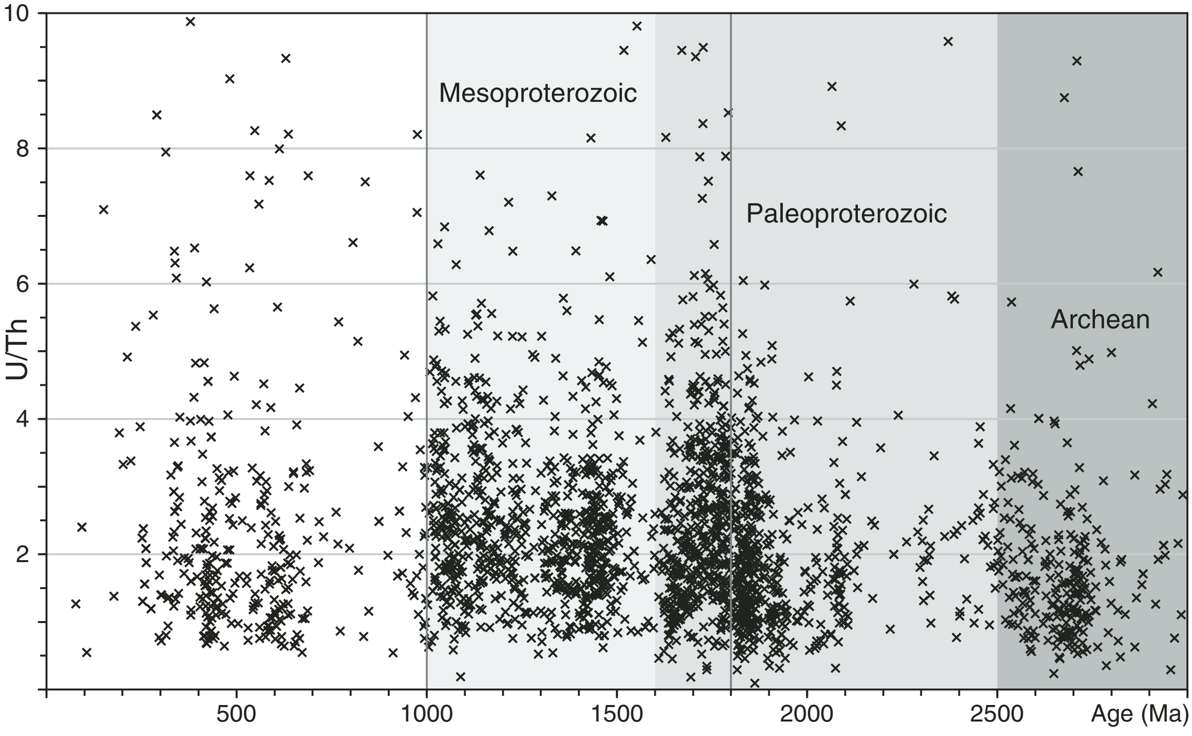

Figure 12. U/Th vs. age plot of new Sierra Nevada framework detrital zircon analyses as well as Twin Lakes assemblage and chert-argillite unit data. Only 81 new analyses of the total 2487, or just over 3%, had U-Th ratios greater than 10, with the bulk of analyses showing U/Th values less than 5, indicating that these detrital zircon ages reflect source-rock crystallization events.

CONCLUSIONS

Sierra Nevada framework terranes outboard of the Morrison block represent western Laurentian margin strata allochthonous to the SW Laurentian continental margin and subordinate interleaved exotic rocks, with the Snow Lake terrane as a potential exception. These allochthonous strata were emplaced along the truncated SW Laurentian margin as the Sierran prebatholithic metamorphic framework within the late Paleozoic SW Laurentian continental truncation transform. Only the eastern Sierra Nevada chert-argillite unit and Twin Lakes assemblage, as well as Sierra City mélange, display exotic detrital zircon provenance. Detrital zircon geochronology and field observations preclude the presence of offset slices of the Roberts Mountains and Golconda allochthons within the Sierra Nevada, indicating these allochthons are unlikely to have ever extended across Owens Valley. New and published detrital zircon data from Snow Lake terrane strata are consistent with a wide range of SW Laurentian provenance and original loci of deposition from the Mojave Desert to central Idaho.

Our compilation of SW Laurentian detrital zircon ages and application of exploratory data analysis reveal successive changes in detrital zircon age populations of Mesoproterozoic to upper Paleozoic strata that are related to evolving Laurentian tectonics. This compilation also highlights unambiguous provenance links between Sierra Nevada metamorphic framework strata and the western Laurentian passive margin, indicating their shared sediment sources in Laurentian cratonic basement provinces. These observations confirm that the Mesozoic Sierra Nevada arc was built into western Laurentian margin strata, which were emplaced along the SW Laurentian margin prior to Permian–Triassic arc initiation. Thus, the Mesozoic Sierra Nevada arc is native to the SW Cordilleran margin.

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