

# A crucial geologic test of Late Jurassic exotic collision versus endemic re-accretion in the Klamath Mountains Province, western United States, with implications for the assembly of western North America

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## ABSTRACT

Differing interpretations of geophysical and geologic data have led to debate regarding continent-scale plate configuration, subduction polarity, and timing of collisional events on the western North American plate margin in pre-mid-Cretaceous time. One set of models involves collision and accretion of far-traveled “exotic” terranes against the continental margin along a west-dipping subduction zone, whereas a second set of models involves long-lived, east-dipping subduction under the continental margin and a fringing or “endemic” origin for many Mesozoic terranes on the western North American plate margin. Here, we present new detrital zircon U-Pb ages from clastic rocks of the Rattlesnake Creek and Western Klamath terranes in the Klamath Mountains of northern California and southern Oregon that provide a test of these contrasting models. Our data show that portions of the Rattlesnake Creek terrane cover sequence (Salt Creek assemblage) are no older than ca. 170–161 Ma (Middle–early Late Jurassic) and contain 62–83% Precambrian detrital zircon grains. Turbidite sandstone samples of the Galice Formation are no older than ca. 158–153 Ma (middle Late Jurassic) and contain 15–55% Precambrian detrital zircon grains. Based on a comparison of our data to published magmatic and detrital ages representing

provenance scenarios predicted by the exotic and endemic models (a crucial geologic test), we show that our samples were likely sourced from the previously accreted, older terranes of the Klamath Mountains and Sierra Nevada, as well as active-arc sources, with some degree of contribution from recycled sources in the continental interior. Our observations are inconsistent with paleogeographic reconstructions that are based on exotic, intra-oceanic arcs formed far offshore of North America. In contrast, the incorporation of recycled detritus from older terranes of the Klamath Mountains and Sierra Nevada, as well as North America, into the Rattlesnake Creek and Western Klamath terranes prior to Late Jurassic deformation adds substantial support to endemic models. Our results suggest that during long-lived, east-dipping subduction, the opening and subsequent closing of the marginal Galice/Josephine basin occurred as a result of *in situ* extension and subsequent contraction. Our results show that tectonic models invoking exotic, intra-oceanic archipelagos composed of Cordilleran arc terranes fail a crucial geologic test of the terranes’ proposed exotic origin and support the occurrence of east-dipping, pre-mid-Cretaceous subduction beneath the North American continental margin.

## INTRODUCTION

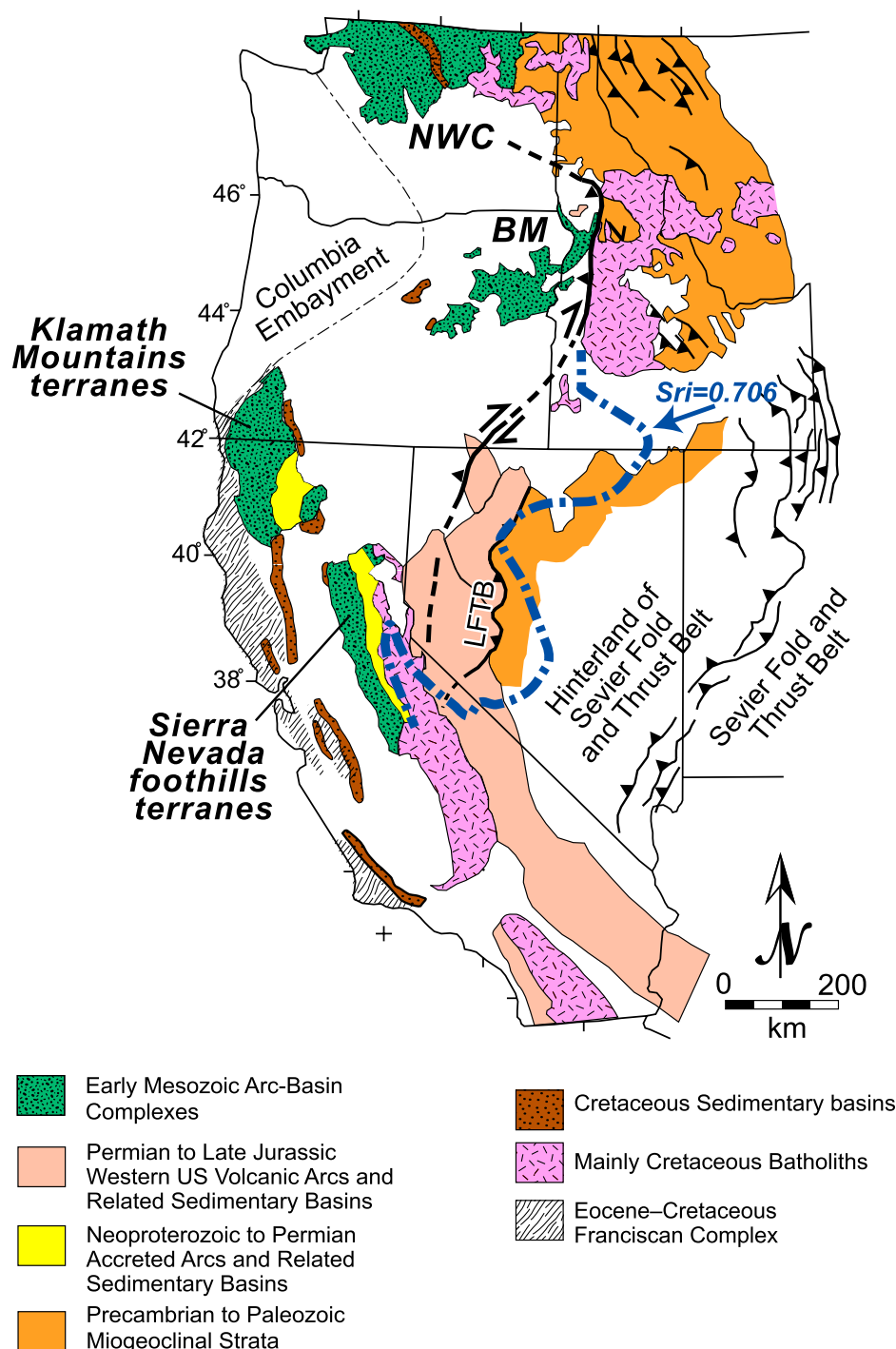
The relationships among deformation, magmatism, and sedimentation are essential to our understanding of fundamental orogenic processes along active continental margins (e.g.,

Dewey and Bird, 1970; Ingersoll, 2012; Ben-Avraham et al., 1981; McCann and Saintot, 2003; Dickinson, 2004). The terrane concept was originally introduced to aid in unraveling the complex evolution of orogens based on distinctions in the deformational, magmatic, and sedimentary histories of seemingly disparate elements (i.e., terranes; e.g., Irwin, 1972; Helwig, 1974; Coney et al., 1980; see Colpron and Nelson, 2014). Due to advances in faunal, isotopic, geochemical, paleomagnetic, and geochronological analysis, many terranes originally considered “suspect” or “exotic” and of unclear relationship to adjacent terranes are now recognizable as having developed as adjacent, locally linked tectonic elements (e.g., English and Johnston, 2005; Nokelberg et al., 2005; LaMaskin et al., 2011; see Colpron and Nelson, 2014).

Even with a rich history of investigation, there is significant contemporary controversy regarding the key processes of deformation, magmatism, and sedimentation during the early Mesozoic assembly of terranes in the western North American Cordillera (Fig. 1), with implications for global plate reconstruction models, continent-scale plate configuration, and subduction polarity (e.g., Shephard et al., 2013; Sigloch and Mihalynuk, 2013, 2017, 2020; Liu, 2014; Monger, 2014; LaMaskin et al., 2015; Yokelson et al., 2015; Gray, 2016; LaMaskin and Dorsey, 2016; Matthews et al., 2016; Lowey, 2017, 2019; Gehrels et al., 2017; Boschman et al., 2018a, 2018b; Monger and Gibson, 2019; Pavlis et al., 2019, 2020). Contemporary debate arises from differences in interpretations of geophysical and

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**Figure 1.** Simplified Mesozoic and early Cenozoic geology of the western United States, modified from Wyld et al. (2006). BM—Blue Mountains Province; LFTB—Luning-Fence-maker thrust belt; NWC—northwest Cascades; Sri—initial strontium isopleth.

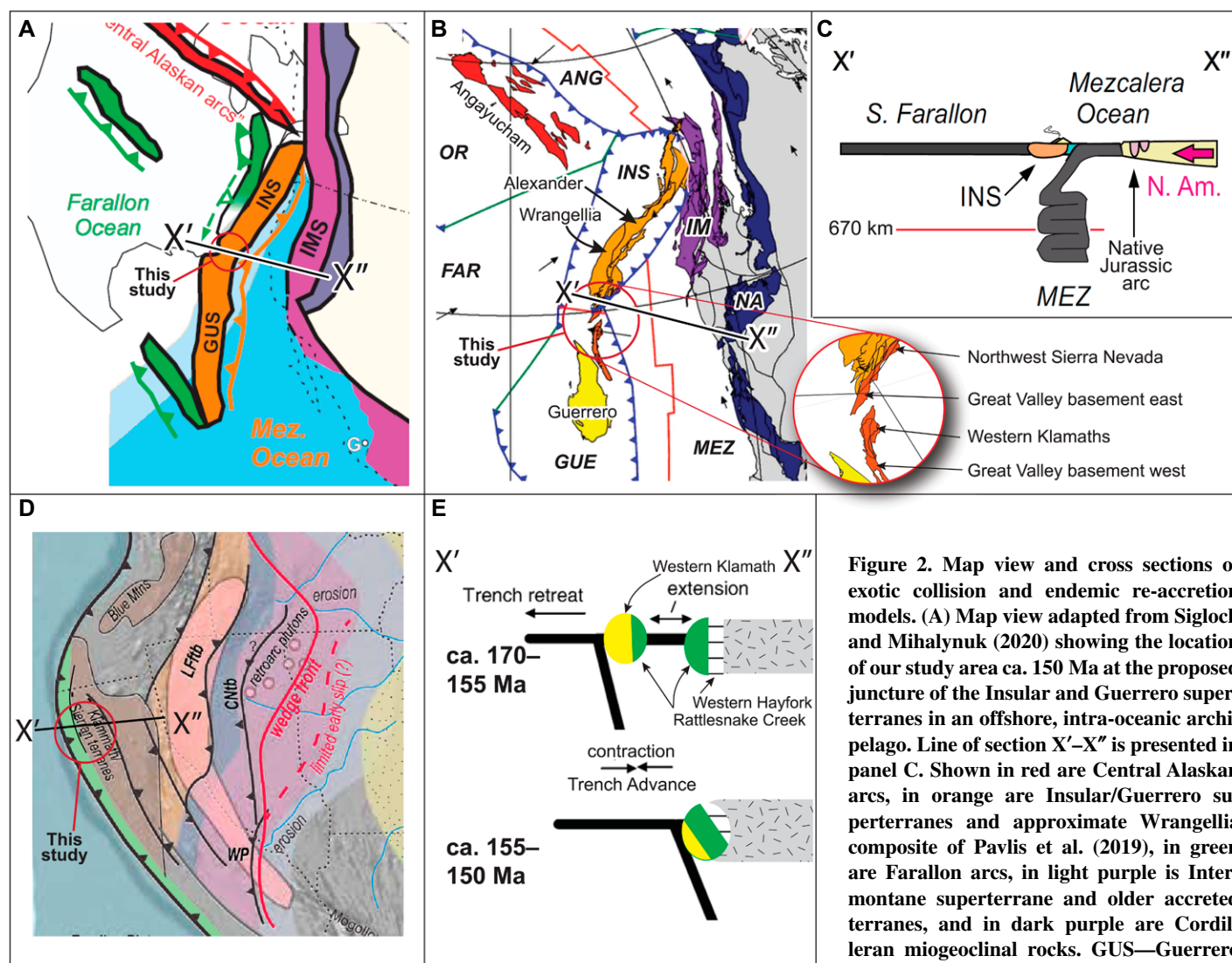
geologic data, leading to paleogeographic reconstructions that are dissimilar for pre-mid-Cretaceous time (see Boschman et al., 2018b; Pavlis et al., 2019). One set of models is based on tomographic images of large, near-vertical features in the mantle that are interpreted as subducted slabs (i.e., tomotectonic models of

Sigloch and Mihalynuk, 2013, 2017; Clennett et al., 2020) and construes them to indicate the collision and accretion of far-traveled “exotic” terranes against the continental subduction margin during west-dipping subduction (Figs. 2A, 2B, and 2C). In contrast, a second set of models invokes east-dipping subduction

under the continental margin and a fringing or “endemic” origin for numerous Mesozoic terranes in the Canadian and Alaskan Cordillera (Figs. 2D and 2E; e.g., Yokelson et al., 2015; Beranek et al., 2017; Gehrels et al., 2017; Boschman et al., 2018a, 2018b; Monger and Gibson, 2019; Pavlis et al., 2019; Fasulo et al., 2020; Manselle et al., 2020; Trop et al., 2020), the western United States (Liu, 2014), and Mexico (Boschman et al., 2018a, 2018b; Cavazos-Tovar et al., 2020). When subjected to geologic tests of their proposed tectonic and paleogeographic reconstructions (i.e., Cowan et al., 1997), exotic models would be supported by histories that are genetically distinct from processes on the continental margin, whereas endemic models would be supported by histories that can be genetically linked with processes on the continental margin.

The Klamath Mountains Province of northern California and southern Oregon is an excellent location in which to assess this problem by applying geologic tests of sedimentary provenance that are explicitly based on the tectonic and paleogeographic reconstructions proposed in the exotic and endemic models (Figs. 1 and 3). A western succession of rocks in the Klamath Mountains Province (Western Hayfork, Rattlesnake Creek, and Western Klamath terranes) is specifically invoked in tomotectonic models and interpreted as a component of an exotic archipelago resulting from west-dipping, intra-oceanic subduction (Sigloch and Mihalynuk, 2013, 2017; Clennett et al., 2020). In this scenario (Figs. 2A–2C), collision of the “exotic” Western Hayfork, Rattlesnake Creek, and Western Klamath terranes against the continental margin was the mechanism responsible for Late Jurassic deformation in the Klamath Mountains.

In contrast, numerous researchers have interpreted an endemic Middle–Late Jurassic setting for rocks of the Western Hayfork, Rattlesnake Creek, and Western Klamath terranes (e.g., Snoke, 1977; Harper, 1980; Saleeby et al., 1982; Harper and Wright, 1984; Wright and Fahan, 1988; Hacker and Ernst, 1993; Harper et al., 1994; Hacker et al., 1995; Frost et al., 2006; Yule et al., 2006; Ernst et al., 2008). In these models (Figs. 2D–2E), slab rollback and associated extension on the continental-plate margin during east-dipping subduction generated a fringing magmatic arc built on older previously accreted terranes (i.e., endemic to the plate margin) and a marginal basin. Subsequent contraction ca. 155–150 Ma led to closure of the marginal basin, deformation, and re-accretion of the endemic arc (e.g., Snoke, 1977; Harper, 1980; Saleeby, 1981, 1983, 1992; Saleeby et al., 1982; Saleeby and Busby-Spera, 1992; Saleeby



**Figure 2.** Map view and cross sections of exotic collision and endemic re-accretion models. (A) Map view adapted from Sigloch and Mihalynuk (2020) showing the location of our study area ca. 150 Ma at the proposed juncture of the Insular and Guerrero superterrane in an offshore, intra-oceanic archipelago. Line of section X'–X" is presented in panel C. Shown in red are Central Alaskan arcs, in orange are Insular/Guerrero superterrane and approximate Wrangellia composite of Pavlis et al. (2019), in green are Farallon arcs, in light purple is Intermontane superterrane and older accreted terranes, and in dark purple are Cordilleran miogeoclinal rocks. GUS—Guerrero superterrane, INS—Insular superterrane, MEZ—Mezcalera. (B) Map view ca. 150 Ma adapted from video screenshot of Clennett et al. (2020; supplemental material) showing the proposed location of our study area between the rifting Guerrero and Insular plates. Line of section X'–X" is presented in panel C. Shown in red are the Angayucham arcs, in purple is the Intermontane superterrane, in blue are North American terranes, in light orange is the Insular superterrane composed of Wrangellia terrane in the south and Alexander terrane in the north, in yellow is the Guerrero superterrane, and in dark orange is the Western Jurassic belt. GUE—Guerrero plate, INS—Insular plate, IM—Intermontane superterrane, MEZ—Mezcalera plate, ANG—Angayucham plate, FAR—Farallon plate, OR—Orcas plate, NA—North American terranes. Blow-up inset shows GPlates screenshot of our study area in greater detail depicting the proposed paleogeographic reconstruction of Clennett et al. (2020) of the northwest Sierra Nevada, the western and eastern segments of the Great Valley basement, and the Western Klamaths. (C) Cross section of “Early Cretaceous” west-dipping subduction adapted from Sigloch and Mihalynuk (2013) showing the Insular superterrane (INS) formed above the westward-subducting Mezcalera oceanic plate (MEZ). At the latitude of the Klamath Mountains Province, the Western Klamath, Rattlesnake Creek, and Western Hayfork terranes comprise their Insular superterrane. (D) Map view adapted from Yonkee et al. (2019, their fig. 16B) showing the location of our study area in Late Jurassic time (ca. 160–150 Ma) on the edge of North America above an east-dipping subducting plate. LFfb—Luning-Fencemaker fold-and-thrust belt; CNtb—Central Nevada thrust belt; WP—Wheeler Pass thrust. (E) Cartoon cross section modified from Lee et al. (2007), depicting east-dipping subduction and Middle and Late Jurassic arc extension followed by re-accretion of the Western Klamath and portions of the Rattlesnake Creek terranes on the plate margin.

IMS—Intermontane superterrane, MEZ—Mezcalera. (B) Map view ca. 150 Ma adapted from video screenshot of Clennett et al. (2020; supplemental material) showing the proposed location of our study area between the rifting Guerrero and Insular plates. Line of section X'–X" is presented in panel C. Shown in red are the Angayucham arcs, in purple is the Intermontane superterrane, in blue are North American terranes, in light orange is the Insular superterrane composed of Wrangellia terrane in the south and Alexander terrane in the north, in yellow is the Guerrero superterrane, and in dark orange is the Western Jurassic belt. GUE—Guerrero plate, INS—Insular plate, IM—Intermontane superterrane, MEZ—Mezcalera plate, ANG—Angayucham plate, FAR—Farallon plate, OR—Orcas plate, NA—North American terranes. Blow-up inset shows GPlates screenshot of our study area in greater detail depicting the proposed paleogeographic reconstruction of Clennett et al. (2020) of the northwest Sierra Nevada, the western and eastern segments of the Great Valley basement, and the Western Klamaths. (C) Cross section of “Early Cretaceous” west-dipping subduction adapted from Sigloch and Mihalynuk (2013) showing the Insular superterrane (INS) formed above the westward-subducting Mezcalera oceanic plate (MEZ). At the latitude of the Klamath Mountains Province, the Western Klamath, Rattlesnake Creek, and Western Hayfork terranes comprise their Insular superterrane. (D) Map view adapted from Yonkee et al. (2019, their fig. 16B) showing the location of our study area in Late Jurassic time (ca. 160–150 Ma) on the edge of North America above an east-dipping subducting plate. LFfb—Luning-Fencemaker fold-and-thrust belt; CNtb—Central Nevada thrust belt; WP—Wheeler Pass thrust. (E) Cartoon cross section modified from Lee et al. (2007), depicting east-dipping subduction and Middle and Late Jurassic arc extension followed by re-accretion of the Western Klamath and portions of the Rattlesnake Creek terranes on the plate margin.

and Harper, 1993; Harper and Wright, 1984; Wright and Fahan, 1988; Hacker and Ernst, 1993). As noted by Snoke and Barnes (2006), assessment of the facing directions and polar-

ity of the arcs that formed the terranes in the Klamath Mountains is one of the most important outstanding questions in early Mesozoic Cordilleran geology.

The goal of this contribution was specifically to test these contrasting Middle–Late Jurassic paleogeographic and paleotectonic models for the Klamath Mountains Province by assessing



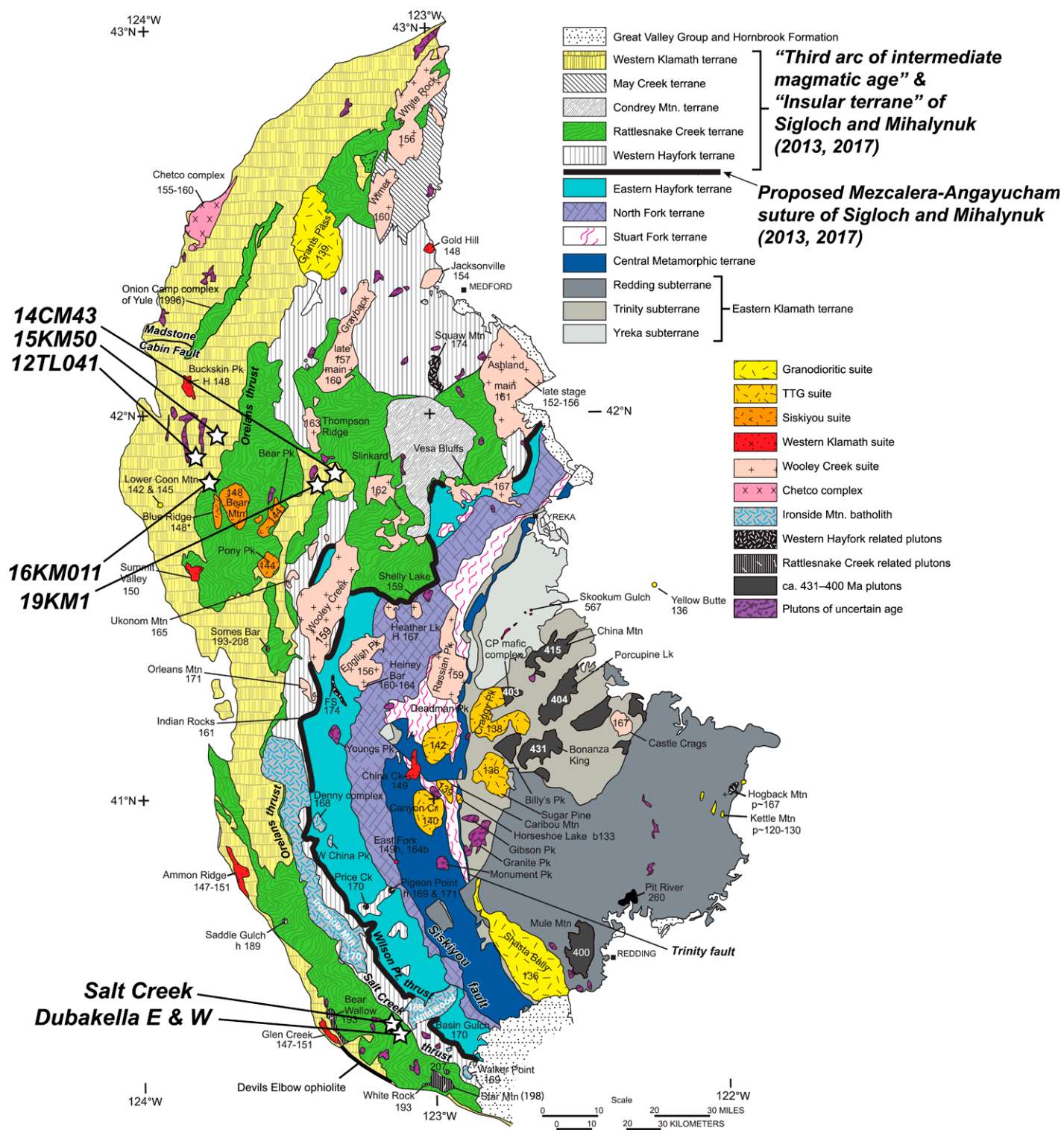


Figure 3. Geologic map of the Klamath Mountains Province after Snoke and Barnes (2006), Irwin and Wooden (1999), and Coint et al. (2013) showing principal tectonostratigraphic terranes and plutons color coded according to age group, as well as sample locations for this study. Numbers associated with each pluton are ages in Ma. Ages were determined by U-Pb (zircon) unless noted: t indicates U-Pb on titanite; h and b indicate K-Ar ages on hornblende and biotite, respectively; and H and p indicate  $^{40}\text{Ar}/^{39}\text{Ar}$  ages on hornblende and plagioclase, respectively. Ck—Creek; CP—Craggy Peak; FS—Forks of Salmon pluton; Lk—Lake; Mtn—Mountain; Pk—Peak; Pt—Point; TTG—tonalite-trondhjemite-granodiorite.



the provenance of Middle and Late Jurassic sedimentary rocks of the Rattlesnake Creek and Western Klamath terranes. We present new detrital zircon U-Pb ages and compare them with published magmatic and detrital ages representing specific provenance scenarios matched to the exotic and endemic models. Our observations add substantial support to endemic models wherein, during east-dipping subduction, the opening and subsequent closing of the Galice/Josephine marginal basin resulted from *in situ* extension and contraction along the continental subduction margin.

## GEOLOGIC BACKGROUND

### Terranes of the Klamath Mountains

The Klamath Mountains Province (Figs. 1 and 3) is a system of fault-bounded and imbricated thrust plates of variably metamorphosed igneous and sedimentary protoliths that shallowly dip eastward in a regional sense and are intruded by numerous early Paleozoic to Early Cretaceous plutons (Irwin, 1972; Hacker et al., 1995; Irwin, 2003; Snoke and Barnes, 2006; Dickinson, 2008). Tectonostratigraphic units in the Klamath Mountains range from Neoproterozoic to Late Jurassic, with ages generally decreasing to the west and structurally downward (Snoke and Barnes, 2006).

The easternmost terrane, the Eastern Klamath terrane, consists of the Trinity, Yreka, and Redding subterrane (Fig. 3; Metcalf et al., 2000; Grove et al., 2008; Lindsley-Griffin et al., 2008). The Trinity subterrane is composed of the Neoproterozoic Trinity ophiolite (ca. 579–556 Ma; Wallin et al., 1988; Metcalf et al., 2000), Ordovician Trinity peridotite (ca.  $472 \pm 32$  Ma, Sm-Nd mineral isochron; Jacobsen et al., 1984), and a Silurian–Devonian succession of ophiolitic plutons (ca. 435–404 Ma; Wallin et al., 1995; Wallin and Metcalf, 1998). Apatite fission-track ages indicate at least two episodes of exhumation of the Trinity subterrane in mid- to Late Cretaceous and early Miocene time (Batt et al., 2010), suggesting that the Trinity ophiolite, Trinity peridotite, and Silurian–Devonian ophiolitic plutons were not exposed at the surface until mid-Cretaceous time at the earliest.

The Yreka subterrane (Fig. 3) structurally overlies the Trinity subterrane and consists mostly of Silurian–Devonian metapelites deposited ca. 450–400 Ma with detrital zircon ages of 381–476 Ma, 2.0–1.0 Ga, and 2.7 Ga (Wallin et al., 1995, 2000; Grove et al., 2008). In addition, the Antelope Mountain Quartzite occupies a thrust sheet at the northeast edge of the Yreka terrane and bears ca. 2.5–1.7 Ga detrital zircon grains (Wallin et al., 2000; Lindsley-Griffin et al., 2008). The Redding subterrane also

structurally overlies the Trinity subterrane and consists of mid-Paleozoic volcanic rocks overlain by Mississippian to Jurassic volcanic and marine sedimentary rocks (Wallin and Metcalf, 1998; Barrow and Metcalf, 2006).

West of the Eastern Klamath terrane, the Central Metamorphic terrane (Fig. 3) has been interpreted to represent oceanic lithosphere that was accreted to the Eastern Klamath terrane during east-dipping Devonian subduction (Barrow and Metcalf, 2006; Dickinson, 2008). Devonian (ca. 380 Ma) Rb-Sr radiometric ages from the Central Metamorphic terrane (Lanphere et al., 1968) are commonly interpreted as dating the emplacement of the structurally overlying Trinity peridotite (see Snoke and Barnes, 2006).

To the west, the Siskiyou thrust fault separates the Central Metamorphic terrane from the underlying Stuart Fork–North Fork terranes (Fig. 3). The Stuart Fork terrane includes shale, chert, and volcanic rocks metamorphosed to blueschist facies in Late Triassic time and is generally interpreted as a subduction complex or accretionary prism (Hotz, 1977; Goodge, 1989; Hacker et al., 1995). The North Fork terrane (Fig. 3) is Triassic to Early Jurassic in age (ca. 200–188 Ma) and includes serpentinitized ultramafic, metasedimentary, metabasaltic, volcanoclastic metasedimentary, and metagabbroic rocks (Ando et al., 1983; Ernst, 1991; Hacker et al., 1993; Ernst et al., 2008; Scherer and Ernst, 2008). Ion microprobe detrital zircon U-Pb ages from the North Fork terrane include abundant Paleozoic to early Proterozoic grains with youngest age modes ca. 189 and 162 Ma, indicating an Early to Middle(?) Jurassic maximum depositional age (Scherer and Ernst, 2008).

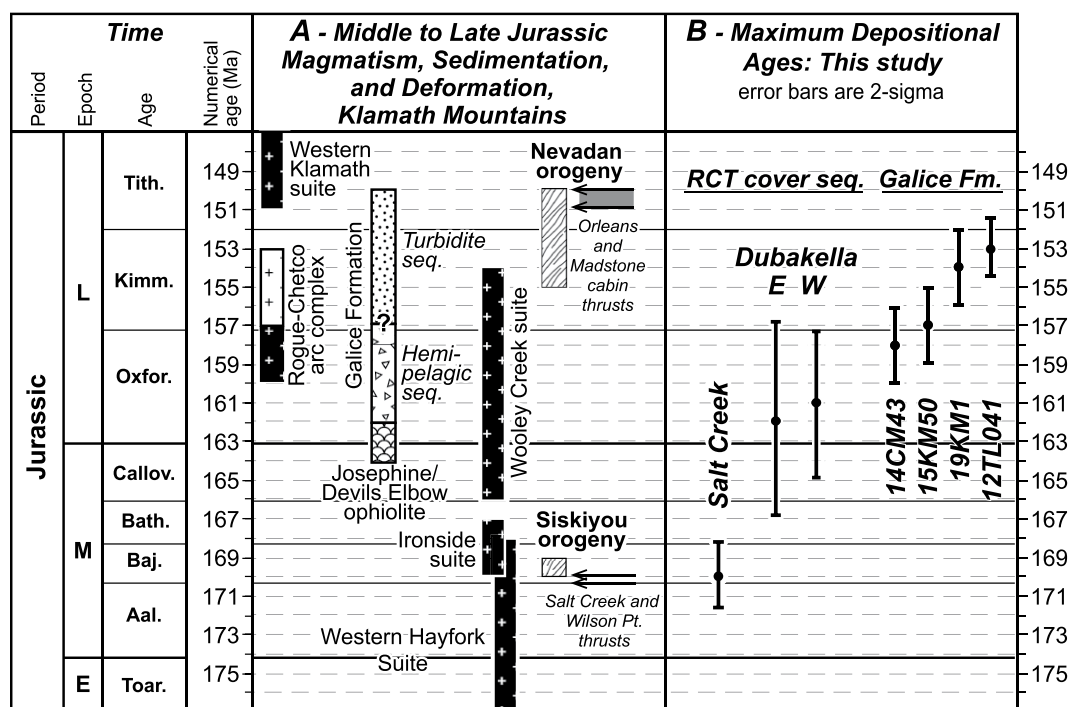
The Eastern Hayfork terrane (Fig. 3) lies structurally beneath the Stuart Fork–North Fork terranes and consists of disrupted and weakly metamorphosed sedimentary rocks, *mélange*, and broken formation of Middle Triassic to Early Jurassic age (Irwin, 1972; Wright, 1982; Hacker and Ernst, 1993). Sandstone blocks in the Eastern Hayfork terrane yield detrital zircon U-Pb ages of 2600–2500, 2350–2250, 1900–2020, and 1890–1725 Ma (Scherer et al., 2010), interpreted as olistoliths of Antelope Mountain Quartzite derived from the Yreka terrane. Chert-argillite matrix *mélange* yields detrital zircon age modes of 1870, 1620, 1285, 966, 792, 628, 539, 417, 298, and 245 Ma (Ernst et al., 2017).

The three most western terranes of the Klamath Mountains, located to the west of the Eastern Hayfork terrane, are the Western Hayfork, Rattlesnake Creek, and Western Klamath terranes (Figs. 3). The exotic versus endemic nature of these three outboard terranes bears directly on the problem of plate configuration and the associated mechanism responsible for

orogeny and westward expansion of the Cordilleran plate margin during Late Jurassic time. Evidence that indicates the Rattlesnake Creek terrane formed the basement to both the Western Klamath terrane and the Western Hayfork terrane includes (1) late Middle Jurassic intrusions into the Rattlesnake Creek terrane (i.e., the  $164 \pm 4$  Ma Preston Peak ophiolite; Snoke, 1977; Saleeby and Harper, 1993), (2) the occurrence of rocks similar to the Rattlesnake Creek terrane in the Western Klamath terrane (i.e., the Onion Camp complex and Fiddler Mountain olistostrome; Yule et al., 2006), and (3) placement of Middle Jurassic plutons requiring that the Rattlesnake Creek terrane was juxtaposed with the Western Hayfork terrane (Wright and Fahan, 1988). These observations have been interpreted to represent the presence of “rift-edge facies,” linking the three terranes during Middle–Late Jurassic time (Snoke, 1977; Wright and Fahan, 1988; Saleeby and Harper, 1993; Yule et al., 2006).

The Early to Middle Jurassic Western Hayfork terrane (Fig. 3) consists of a suite of ca. 177–168 Ma metamorphosed sedimentary and volcanic rocks intruded by ca. 170 Ma calc-alkaline plutons (Fig. 4A; Wright, 1982; Gray, 1986; Wright and Fahan, 1988; Hacker and Ernst, 1993; Barnes and Barnes, 2020). The Western Hayfork terrane lies structurally beneath the Eastern Hayfork terrane along the Wilson Point thrust and is thrust over the Rattlesnake Creek terrane along the Salt Creek thrust (Figs. 3 and 4A; Wright, 1982; Wright and Fahan, 1988; Wright and Wyld, 1994; Barnes et al., 2006).

The Rattlesnake Creek terrane includes a basement of late Paleozoic to Triassic serpentinite-matrix *mélange* and peridotite massifs and a cover sequence of clastic sedimentary and volcanic rocks known as the Salt Creek and Dubakella Mountains assemblages in the southern Klamath Mountains (Wright and Wyld, 1994). Based on radiolaria in *mélange* chert blocks and crosscutting relationships with a ca. 207–193 Ma early Mesozoic intrusive suite, Wright and Wyld (1994) assigned an age of Late Triassic–Early Jurassic to the Rattlesnake Creek terrane cover sequence. In contrast, Irwin and Blome (2004) reported multiple locations of Early to Middle Jurassic (Bathonian) radiolaria in the Rattlesnake Creek terrane, and Irwin (2010) and Irwin et al. (2011) suggested that detrital sedimentary rocks in the Rattlesnake Creek terrane may be more analogous to the Galice(?) Formation. In the west-central Klamath Mountains, Snoke (1977) mapped a conglomerate-grit unit in a coherent metavolcanic and metasedimentary sequence (his Bear Basin Road sequence), which represents the Rattlesnake Creek terrane cover sequence



**Figure 4.** Summary of regional ages and events as well as maximum depositional ages from this study. (A) Compilation of data from the Klamath Mountains region depicting the timing of magmatism, sedimentation, and deformation; data sources are given in the text. (B) Maximum depositional ages from this study. E—Early; M—Middle; L—Late; RCT—Rattlesnake Creek terrane. Tith.—Tithonian, Toar.—Toarcian, Aal.—Aalenian, Baj.—Bajocian, Bath.—Bathonian, Callov.—Callovian, Oxf.—Oxfordian, Kimm.—Kimmeridgian.

(Bushey et al., 2006; Frost et al., 2006). Wright and Wyld (1994) noted the presence of volcanic as well as quartzose metamorphic detritus in the Rattlesnake Creek terrane cover sequence and suggested that the depositional basin was situated near an active volcanic system with sediment input from the western North American Cordillera (Wright and Wyld, 1994). Subsequent analysis of meta-argillite from the Rattlesnake Creek terrane cover sequence yielded initial  $^{87}\text{Sr}/^{86}\text{Sr}$  of 0.7063–0.7114, initial  $\epsilon\text{Nd}$  from  $-4.5$  to  $-8.3$ , and depleted mantle model ages ca. 1.67–1.34 Ga, leading Frost et al. (2006) to suggest that the isotopic composition of the cover sequence was comparable to major river systems in North America and supporting a link between the Rattlesnake Creek terrane and the western North American Cordillera.

The Western Klamath terrane is the youngest and most outboard terrane in the Klamath Mountains and was emplaced structurally beneath the Rattlesnake Creek terrane along the Orleans thrust before ca. 150 Ma (Figs. 3 and 4A; Saleeby et al., 1982; Harper and Wright, 1984; Harper et al., 1994). The Western Klamath terrane consists of three key units (Fig. 4A): (1) the ca. 160–153 Ma Rogue-Chetco arc complex (Harper et al., 1994; Harper, 2006; Yule et al., 2006), (2) the ca. 164–162 Ma Josephine and Devils Elbow ophiolite (Harper, 1984; Wyld and Wright, 1988; Harper et al., 1994), and (3) a ca. 157–150 Ma sedimentary basin nonconformably overlying the above basement units (Galice Formation; Pessagno and Blome, 1990; Harper

et al., 1994; Pessagno, 2006). The Galice Formation *sensu lato* includes a basal hemipelagic sequence ranging from 162 Ma (late Callovian; the youngest age of the underlying Josephine ophiolite) to 157 Ma (middle Oxfordian), based on correlation of the top of the hemipelagic sequence to 157  $\pm$  2 Ma radiolarian tuff at the top of the Rogue Formation (Saleeby, 1984; MacDonald et al., 2006). A turbiditic sequence, the Galice Formation *sensu stricto*, overlies the hemipelagic sequence and is interpreted to range in age from ca. 157 to 150 Ma (Harper et al., 1994; Harper, 2006; Pessagno, 2006).

Various provenance techniques suggest that the source area for the Galice Formation represents a mix of young volcanic arc and older accreted terrane sources (MacDonald et al., 2006). Miller and Saleeby (1995) presented detrital zircon U-Pb ages of multigrain fractions from the Galice Formation and observed two distinct age distributions that they expressed as average intercept ages, including a Mesoproterozoic average ca. 1583 Ma and an early Mesozoic average ca. 215 Ma. Subsequently, Miller et al. (2003) reported ion-microprobe single-crystal detrital zircon U-Pb ages that included age modes ca. 227 and 153 Ma, as well as lesser quantities of Paleozoic and Proterozoic ages. Finally, MacDonald et al. (2006) showed that the source area for rocks of the Galice Formation represents a mix of arc and accreted terranes that was established by ca. 162 Ma. In addition to these Galice Formation studies, Wright and Wyld (1986) reported xenocrystic Paleoproterozoic (ca. 1.7 Ga)

zircon grains from the Devils Elbow ophiolite in the southern Klamath Mountains (Fig. 3), equivalent to the Josephine ophiolite, supporting the input of Precambrian sources into the Western Klamath terrane.

#### Jurassic Deformation in the Klamath Mountains and Sierra Nevada

The timing and nature of Jurassic deformation in the Klamath Mountains and along-strike equivalents in the Sierra Nevada terranes have been the subject of great interest and debate (e.g., Schweickert and Cowan, 1975; Saleeby et al., 1982; Harper and Wright, 1984; Moores and Day, 1984; Ingersoll and Schweickert, 1986; Wright and Fahan, 1988; Coleman et al., 1988; Wyld and Wright, 1988; Hacker and Ernst, 1993; Hacker et al., 1995; Snoke and Barnes, 2006; Dickinson, 2008). Accreted terranes of the Klamath Mountains were contiguous along strike with accreted terranes of the Sierra Nevada prior to ca. 140 Ma, when the Klamath block separated from the Sierra Nevada block and moved trenchward (Constenius et al., 2000; Snow and Scherer, 2006; Ernst, 2013).

A single Late Jurassic Nevadan orogeny was originally conceived to be responsible for the majority of deformation in the Klamath Mountains and Sierra Nevada regions (e.g., Taliaferro, 1942; Schweickert and Cowan, 1975; Schweickert, 1978, 1981; Schweickert et al., 1984; Day et al., 1985); however, subsequent work indicated the presence of older, Middle

Jurassic deformation (e.g., Wright and Fahan, 1988; Coleman et al., 1988). Thus, Jurassic deformation in the Klamath Mountains has been considered both as a Middle–Late Jurassic continuum of deformation, and as two distinct periods of deformation, including a Middle Jurassic Siskiyou orogeny and a Late Jurassic Nevadan orogeny (Fig. 4A). Evidence for Middle Jurassic Siskiyou orogenesis includes emplacement of the Rattlesnake Creek terrane beneath the Western Hayfork terrane along the Salt Creek thrust and emplacement of the Western Hayfork terrane beneath the Eastern Hayfork terrane along the Wilson Point thrust, as constrained by ca. 170–169 Ma multigrain thermal ionization mass spectrometry (TIMS) zircon U–Pb ages on the Ironside Mountain batholith, which intrudes the Wilson Point thrust (Figs. 3 and 4A; Wright and Fahan, 1988; Barnes and Barnes, 2020).

The Siskiyou orogeny was immediately followed by oblique rifting of the Rattlesnake Creek terrane, forming the Josephine ophiolite–floored basin, while arc activity broadened to span both sides of the rift zone, represented by the Wooley Creek plutonic belt to the east and the Rogue–Chetco arc to the west (Figs. 3 and 4A; Saleeby et al., 1982; Harper, 1984; Wright and Wyld, 1986; Wright and Fahan, 1988; Hacker and Ernst, 1993; Harper et al., 1994; Harper, 2003; Snoke and Barnes, 2006; Yule et al., 2006). Several plutons of the Wooley Creek suite also stitch the Eastern and Western Hayfork terranes together along the Wilson Point thrust (Fig. 3), including the Vesa Bluffs pluton ( $167.1 \pm 1.8$  Ma; single-crystal laser-ablation–inductively coupled plasma–mass spectrometry [LA–ICP–MS]; Allen and Barnes, 2006) and the Wooley Creek batholith (as old as  $159.22 \pm 0.10$  Ma, single-crystal chemical-abrasion–isotope-dilution–thermal ionization mass spectrometry [CA–ID–TIMS]; Coint et al., 2013). Deposition of the Galice Formation ensued in the submarine Josephine basin as regional extensional stresses turned to contractional deformation associated with the Nevadan orogeny ca. 155–150 Ma (Saleeby and Harper, 1993; Harper et al., 1994; Hacker et al., 1995; Miller and Saleeby, 1995; Shervais et al., 2005; MacDonald et al., 2006).

Evidence for Late Jurassic Nevadan orogenesis in the Klamath Mountains includes emplacement of the Rogue–Chetco arc complex beneath the Josephine ophiolite along the Madstone Cabin thrust ca. 152–150 Ma (Figs. 3 and 4A; Dick, 1976; Harper and Wright, 1984; Blake et al., 1985; Harper et al., 1994; Hacker et al., 1995; Yule, 1996) and thrusting of the Rattlesnake Creek terrane over the Western Klamath terrane along the Orleans thrust (Figs. 3 and 4A; Saleeby et al., 1982; Harper and Wright, 1984; Harper et al., 1994; Garlick et al., 2009). In ad-

dition, numerous workers have observed that the Galice Formation (Western Klamath terrane) was subject to syndepositional structural contraction ca. 155–150 Ma and was intruded by calc-alkaline magmas starting ca. 153–151 Ma (Figs. 3 and 4A; Western Klamath suite). Additionally, the Galice Formation is overlain by undeformed rocks of the Great Valley Group, interpreted to indicate that the Nevadan event concluded no later than 140 Ma (Saleeby et al., 1982; Wright and Fahan, 1988; Harper and Wright, 1984; Harper et al., 1994; Irwin, 1997; Chamberlain et al., 2006; Garlick et al., 2009). Finally, other workers have suggested that local deformation persisted in the Klamath Mountains until ca. 135 Ma (Harper et al., 1994; Hacker et al., 1995).

### Exotic Models for Late Jurassic Deformation in the Klamath Mountains

Arguments that favor the collision of an exotic, intra-oceanic arc as the mechanism responsible for Late Jurassic deformation in the Klamath Mountains (e.g., Davis, 1968; Hamilton, 1969, 1978; Burchfiel and Davis, 1972; Irwin, 1972, 1985; Coney et al., 1980; Moores et al., 2002) largely derive from geologic relationships of the terranes of the Sierra Nevada and California Coast Ranges (Fig. 1; e.g., Moores, 1970, 1998; Schweickert and Cowan, 1975; Moores and Day, 1984; Schweickert et al., 1984; Dickinson et al., 1996; Schweickert, 2015). In the Sierra Nevada, many workers have adopted a double-subduction model of facing magmatic arcs to explain the more outboard location of Middle Jurassic ophiolitic rocks in the California Coast Ranges (i.e., Coast Range ophiolite) with respect to the Western Jurassic belt, a Middle–Late Jurassic arc-basin complex in the foothills of the Sierra Nevada. These observations are used to suggest that together the Coast Range ophiolite and Western Jurassic belt represent an east-facing arc generated above a west-dipping subduction zone (e.g., Ingersoll and Schweickert, 1986; Moores et al., 2002; Godfrey and Dilek, 2000; Schweickert, 2015). These models suggest that the mechanism responsible for Late Jurassic deformation in the Sierra Nevada is the collision and accretion of the exotic, intra-oceanic Western Jurassic belt and Coast Range ophiolite.

Application of a double-subduction model is less tenable for rocks of the Klamath Mountains because the Late Jurassic (ca. 160–153 Ma) Rogue–Chetco arc complex is located west of ophiolitic material (Figs. 3 and 4A; see Saleeby, 1996; Dickinson, 2008), prompting some authors to present models invoking coeval but dissimilar along-strike subduction configurations for the contiguous along-strike Klamath

Mountains and Sierra Nevada foothills (e.g., Ingersoll and Schweickert, 1986; Godfrey and Dilek, 2000). We also note, however, that the presence of inherited Precambrian zircon grains in igneous rocks (Day and Bickford, 2004) and Precambrian detrital zircon grains in sedimentary rocks (Snow and Ernst, 2008) has led workers to consider the Western Jurassic belt of the Sierra Nevada to represent a single, east-dipping subduction zone beneath North America (Day and Bickford, 2004; Snow and Scherer, 2006; Snow and Ernst, 2008; LaMaskin, 2012).

One particular set of models by Sigloch and Mihalynuk (2013, 2017) argues for an exotic, archipelago origin for numerous western North American terranes, including the Western Klamath, Rattlesnake Creek, and Western Hayfork terranes (Figs. 2A–2C). These models are based on seismic images of the mantle derived from USArray and global network data as analyzed with multiple-frequency P-wave tomography. These images show massive, almost vertical features with faster-than-average seismic wave velocities beneath North America and the Atlantic Ocean from 800 to 2000 km in depth, which were interpreted by Sigloch and Mihalynuk (2013, 2017) as cold, relict slab walls formed by vertical slab sinking. These relict slab walls were then mapped directly to paleotrench positions by moving the plates back over the mantle, which was assumed to be stationary, using plate motion models. Volcanic arc terranes can then be interpreted to have formed above stationary subduction zones feeding the slab walls. The largest of these imaged slab walls has previously been interpreted as the Farallon slab (e.g., Li et al., 2008; van der Meer et al., 2010, 2012), a remnant of east-dipping subduction; however, Sigloch and Mihalynuk (2013, 2017) argued that most of this slab wall is not Farallon slab. They instead subdivided it into Angayucham, Mezcalera, and Southern Farallon slab wall components, interpreted as having formed by vertical sinking during west-dipping subduction. Sigloch and Mihalynuk (2017) identified a north-south tract of at least 11 collapsed Jurassic–Cretaceous basins (in the Klamath Mountains, the Galice–Josephine basin), about half of which contain mantle rocks, and they proposed that these mark the locations of an oceanic suture that runs along the entire western margin of North America. They termed this feature the Mezcalera–Angayucham suture, named after the now totally subducted Mezcalera and Angayucham Oceans and plates, and they argued that the suture formed diachronously between ca. 155 Ma and ca. 50 Ma during closure of those oceans.

The geology of the Klamath Mountains is explicitly tied to the exotic tomotectonic model of Sigloch and Mihalynuk (2017), who defined



a Western Jurassic–Foothills composite terrane as part of their Insular superterrane (Figs. 2A and 2C). The authors specifically noted that in the Klamath Mountains, rocks of the Western Jurassic (here termed the Western Klamath), Rattlesnake Creek, and Western Hayfork terranes comprise a “third arc of intermediate magmatic ages” (Sigloch and Mihalynuk, 2017, p. 1510) interpreted to have formed above the westward-subducting Mezcalera Ocean (Figs. 2A and 2C), an interpretation that they suggested agrees with that of Dickinson (2008). Sigloch and Mihalynuk (2017) specifically attributed the “initial pulse of Nevadan deformation [Harper et al., 1994] to first impingement of the Insular superterrane into North America” (Sigloch and Mihalynuk, 2017, p. 1509; their event A1 ca.  $146 \pm 24$  Ma). In this scenario, the Late Jurassic Nevadan orogeny in the Klamath Mountains occurred offshore in an archipelago setting and was driven by far-field stresses associated with the collision of the northernmost portions of the Insular superterrane against Canada. The Nevadan orogeny was presumably followed by continued westward subduction into a stationary, intra-oceanic trench beneath the composite Western Klamath–Rattlesnake Creek–Western Hayfork terranes until collision with the previously accreted Eastern Klamath through Eastern Hayfork terranes produced the Mezcalera–Angayucham suture ca. 135–110 Ma at the latitude of California (Sigloch and Mihalynuk, 2017).

The specific geological arguments presented by Sigloch and Mihalynuk (2017) require that their Mezcalera–Angayucham suture in the Klamath Mountains is the Wilson Point thrust and its along-strike counterparts (Fig. 3), located between the Western Hayfork (Insular) and Eastern Hayfork (Intermontane) terranes. Sigloch and Mihalynuk (2017) stated that the decisive test between west-dipping versus east-dipping subduction history is the timing of Intermontane–Insular superterrane suturing, which should be post-ca. 155 Ma, and they stated that current arguments for or against pluton stitching of this suture lack credence until plutons have been subjected to “robust isotopic studies” (Sigloch and Mihalynuk, 2017, p. 1507).

In a GPlates model (Müller et al., 2018) derived largely from inferences made in the tomo-tectonic model (Fig. 2B), Clennett et al. (2020) defined a Western Jurassic belt (their Fig. 3) composed of the (1) Western Klamaths, (2) basement of the Great Valley, and (3) northwest Sierra Nevada. This Western Jurassic belt was considered to be an Insular-associated terrane situated between the Insular and Guerrero superterrane beginning ca. 170 Ma. In this scenario, Middle–Late Jurassic rifting occurred between

the southern portion of the Insular superterrane (Wrangellia terrane) and Guerrero superterrane, resulting in formation of the Josephine ophiolite and associated Galice basin in the Klamath Mountains, and closure of the rift (Clennett et al., 2020) resulted in Late Jurassic (Nevadan) orogenesis (Fig. 2B). This contractional event is depicted to have occurred in an offshore archipelago setting, between the Great Valley basement and the Western Klamaths, and driven by ca. 150 Ma first impingement of the Insular superterrane into North America, occurring between their northernmost Insular superterrane and North American rocks in Canada (Clennett et al., 2020). Finally, Clennett et al. (2020) portrayed the Western Klamaths and portions of the Great Valley basement colliding with the previously accreted Intermontane terranes ca. 80 Ma at the latitude of southern California and arriving at their present positions ca. 50 Ma, following dextral translation.

### Endemic Models for Late Jurassic Deformation in the Klamath Mountains

In contrast to exotic models, numerous workers have interpreted an endemic Middle–Late Jurassic setting for the Western Klamath, Rattlesnake Creek, and Western Hayfork terranes (e.g., Snoke, 1977; Davis et al., 1978; Harper, 1980; Saleeby et al., 1982; Harper and Wright, 1984; Wright and Wyld, 1986; Wright and Fahan, 1988; Wyld and Wright, 1988; Hacker and Ernst, 1993; McClelland et al., 1992; Harper et al., 1994; Hacker et al., 1995; Barnes et al., 2006; Frost et al., 2006; Yule et al., 2006; Harper, 2006; MacDonald et al., 2006). In this scenario (Figs. 2D–2E and 4A), late Middle Jurassic intra-arc/backarc rifting (i.e., Josephine–Devils Elbow ophiolite) occurred in the previously accreted Rattlesnake Creek terrane, producing a new west-facing arc (Rogue–Chetco arc complex) and leaving behind a remnant arc, the Western Hayfork terrane, and generating marginal-basin fill (Galice Formation). Subsequently, the Western Klamath terrane and its Rattlesnake Creek terrane basement were then re-accreted to the plate margin during Late Jurassic time (i.e., Nevadan orogeny) and stitched by postthrust plutons of the Western Klamath and Siskiyou suites (Figs. 3 and 4A; Wright and Fahan, 1988; Harper et al., 1990; Barnes et al., 2006). The reason for the change from extension to contraction is vigorously debated and variously attributed to subduction of a seafloor spreading center (e.g., Shervais et al., 2005) or changes in convergence rate, coupling, and direction of subducting lithosphere (e.g., Wright and Fahan, 1988; Ernst, 1990; Saleeby et al., 1992; Hacker et al., 1993, 1995; Harper et al., 1994).

## METHODS

### Detrital Zircon U–Pb Geochronology

#### Sample Preparation and Analysis

To test the exotic versus endemic models, we targeted clastic rocks of the Rattlesnake Creek terrane cover sequence and Galice Formation in the Western Klamath terrane (Fig. 3; Table 1). We prepared detrital zircon samples following standard methods of crushing, pulverizing, magnetic separation, and density separation. We placed zircons grains onto double-sided tape, mounted them in epoxy, and ground them to expose grain interiors, and then we conducted cathodoluminescence imaging at California State University, Northridge, the Southeastern North Carolina Regional Microanalytical and Imaging Consortium at Fayetteville State University, and the Arizona LaserChron Center. U and Pb isotopic data were collected by LA-ICP-MS at three different laboratories (Table 1; Supplemental Information<sup>1</sup>).

We report  $^{206}\text{Pb}/^{238}\text{U}$  ages for grains younger than 900 Ma and  $^{207}\text{Pb}/^{206}\text{Pb}$  ages for grains older than 900 Ma. Analyses with >5% uncertainty ( $1\sigma$ ) in  $^{206}\text{Pb}/^{238}\text{U}$  age are not included, and analyses with >10% uncertainty ( $1\sigma$ ) in  $^{206}\text{Pb}/^{207}\text{Pb}$  age are not included, unless the  $^{206}\text{Pb}/^{238}\text{U}$  age is younger than 900 Ma. For grains older than 600 Ma, we report analyses within the concordance range 80% to 105% ( $^{206}\text{Pb}/^{238}\text{U}$  vs.  $^{207}\text{Pb}/^{206}\text{Pb}$ ), whereas for grains younger than 600 Ma, we did not filter for discordance because of imprecision of the  $^{207}\text{Pb}$  measurement and large uncertainty in  $^{207}\text{Pb}/^{206}\text{Pb}$  ages for Phanerozoic grains (Bowring and Schmitz, 2003; Ireland and Williams, 2003; Bowring et al., 2006; Gehrels et al., 2008; Spencer et al., 2016; Gehrels et al., 2020). We plotted kernel density estimates (KDEs; Vermeesch, 2018a) of the full range of ages in each sample at 30 m.y. bandwidth, which is the average adaptive, automatic, kernel-density bandwidth of our samples. To assess Mesozoic ages in greater detail and to detect potential subdistributions at the <10 Ma level, we plotted KDEs at 5 m.y. bandwidth. Method details and complete data are provided in the Supplementary Material (see footnote 1).

### Maximum Depositional Age Estimates and Provenance Analysis

We calculated maximum depositional ages (MDAs) using IsoplotR (Vermeesch, 2018a) as

<sup>1</sup>Supplemental Material. Analytical methods, sample collection locations in the southern Klamath Mountains, and Data tables. Please visit <https://doi.org/10.1130/GSAB.S.14721087> to access the supplemental material, and contact editing@geosociety.org with any questions.

TABLE 1. SAMPLE LOCATIONS, ALIQUOTS, AND LOCATIONS ANALYZED, KLAMATH MOUNTAINS PROVINCE

Sample location description	Samples	Location (WGS84)		Aliquots	Laboratory*
		Latitude (°N)	Longitude (°W)		
<u>Rattlesnake Creek terrane cover sequence</u>					
In the area of Hayfork and Wildwood, California. Map units variably defined as undivided sedimentary and volcanic rocks of the Salt Creek assemblage (Wright and Wyld, 1994) and clastic sedimentary rock, which may be correlative with the Galice(?) Formation (Irwin et al., 2011).	Salt Creek ( <i>n</i> = 152)	40°23.845'	123°07.364'	TLKM003 ( <i>n</i> = 102)	USC
	Dubakella E ( <i>n</i> = 202)	40°21.448'	123°06.021'	16KM001 ( <i>n</i> = 50)	CSUN
	Dubakella W ( <i>n</i> = 108)	40°21.294'	123°06.329'	TLKM001 ( <i>n</i> = 84)	USC
				16KM003 ( <i>n</i> = 118)	USC
In the area of the Bear Mountain intrusive complex, along Bear Basin Road. Map units variably defined as Bear Basin Road sequence (Snoke, 1977) and Rattlesnake Creek terrane (Frost et al., 2006).	16KM011 ( <i>n</i> = 64)	41°48.804'	123°45.04'	TLKM002	USC
				n/a	CSUN
<u>Galice Formation</u>					
Along the South Fork of the Smith River, 1.6 km upstream from Patrick Creek. Stop 5 in Harper et al. (2002). Basal-most thick-bedded unit of the Galice Formation above the Volcano-Pelagic unit (Wagner and Saucedo, 1987).	12TL041 ( <i>n</i> = 115)	41°52.158'	123°49.839'	n/a	USC
In the area of the Bear Mountain intrusive complex. Mapped as Galice Formation, Western Klamath terrane (Snoke, 1977; Frost et al., 2006).	15KM50 ( <i>n</i> = 91)	41°55.783'	123°44.394'	n/a	ALC
In the area mapped as Galice Formation in the Klamath River appendage of Saleeby and Harper (1993).	19KM1 ( <i>n</i> = 39)	41°49.601'	123°22.900'	n/a	ALC
	14CM43 ( <i>n</i> = 96)	41°43.715'	123°26.705'	n/a	ALC

Note: WGS84—World Geodetic System 1984.

\*USC—University of South Carolina; CSUN—California State University, Northridge; ALC—Arizona LaserChron Center.

the weighted mean average of the youngest cluster of grains overlapping at  $2\sigma$  with individual  $2\sigma$  grain errors that overlap the weighted mean age (Dickinson and Gehrels, 2009b; Spencer et al., 2016; Dumitru et al., 2018; Andersen et al., 2019; Coutts et al., 2019; Herriott et al., 2019; Gehrels et al., 2020). Advantages of this approach include calculation of a statistical point estimate that can be objectively compared to other geological ages calculated as point estimates (Schmitz, 2012) and demonstration of the best overall coincidence with MDAs calculated by chemical abrasion–thermal ionization mass spectrometry (Coutts et al., 2019; Herriott et al., 2019).

To assess provenance, we compared the age distributions in our samples to previously published ages representing geologically plausible Middle–Late Jurassic sediment sources (Fig. 5; Table 2) by combining available U–Pb zircon data (detrital and primary igneous) for rocks older than 150 Ma within the proposed source areas. To avoid *a priori* biasing of the predicted sediment source area age distributions, we did not preferentially weight those distributions. Where available, we used all of the  $^{206}\text{Pb}/^{238}\text{U}$  ages reported from individual intrusive bodies to render an age distribution that was representative of that which might be expected were they measured in a detrital sample eroded from the intrusive body. While the proportions of zircon grains representing age modes in the unweighted, composite age distributions constructed for each predicted sediment source area may ultimately be equivocal, the age modes themselves are an accurate representation of the ages in each predicted source area and are therefore useful for provenance analysis. We then used visual and multidimensional scaling techniques (MDS) to assess our results as compared to these scenarios. MDS is

a means of assessing the dissimilarity between samples as distance in Cartesian coordinates (Saylor et al., 2018) based on a statistical distance between age distributions, here assessed in two dimensions using the Kolmogorov–Smirnov distance statistic (Vermeesch, 2018a). On MDS plots, more similar samples cluster together, and more dissimilar samples plot farther apart (Vermeesch, 2018a). Although the Kolmogorov–Smirnov dissimilarity is sample-size dependent, differing sample sizes are not considered to be a major problem for MDS analysis (Vermeesch, 2018b).

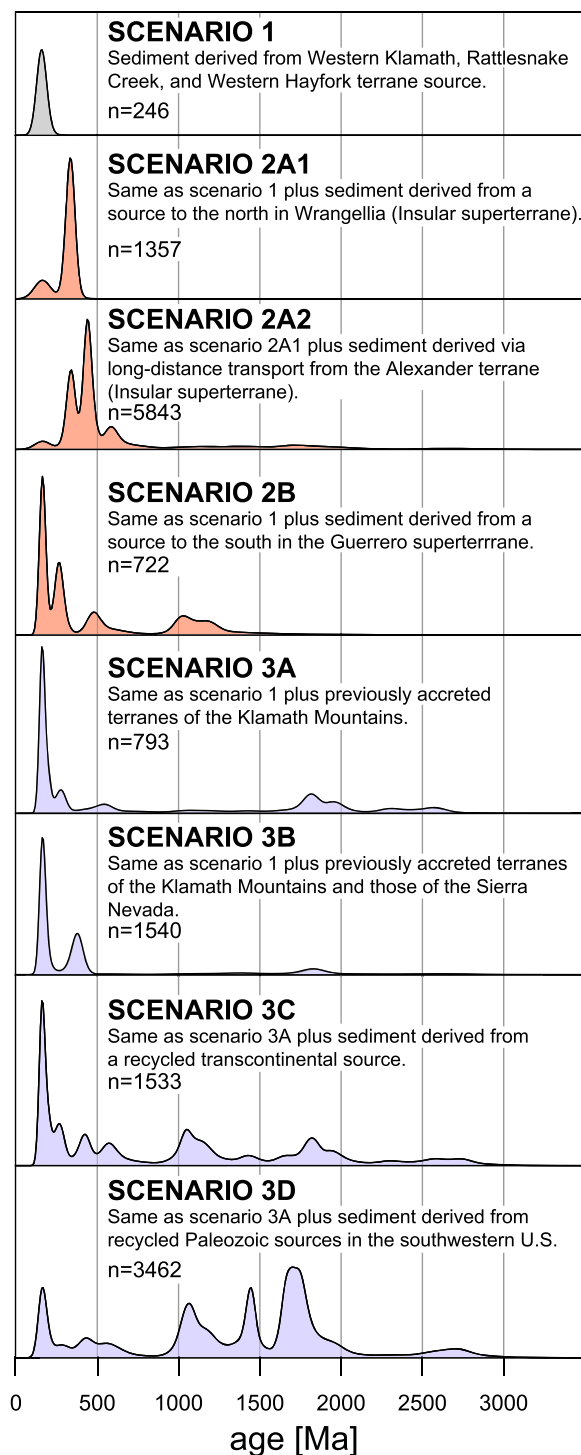
Scenario 1 (Figs. 2A, 2C, and 5; Table 2) is consistent with the model of Sigloch and Mihalynuk (2013, 2017), which invokes west-dipping subduction beneath an exotic, intra-oceanic arc. In scenario 1, sediment is assumed to have been derived from local sources restricted to the Western Klamath, Rattlesnake Creek, and Western Hayfork terranes (Table 2).

Scenario 2 (Figs. 2B, 3C, and 5; Table 2) is also consistent with models involving west-dipping subduction beneath an exotic, east-facing, intra-oceanic arc, but it incorporates the paleogeographic reconstructions of Clennett et al. (2020) and Sigloch and Mihalynuk (2020). Scenario 2A (Table 2) is consistent with sediment sourced from the Insular superterrane to the north of the study area via southward longshore transport and/or funneling of sediment through the proposed trench to the east of the Insular superterrane (Figs. 2B and 2C) and includes two scenarios. Scenario 2A1 (Fig. 5; Table 2) includes a local Western Klamath, Rattlesnake Creek, and Western Hayfork source (i.e., scenario 1) plus primary and recycled sources from the Wrangellia terrane (Insular superterrane) to the north of the study area, whereas, scenario 2A2 includes all sources of scenario 2A1, but it also

accounts for potential long-distance transport of sediment from the north by adding additional primary and recycled sources in the Alexander terrane (Insular superterrane). Scenario 2B is consistent with sourcing of sediment from the Guerrero superterrane to the south of the study area via northward longshore transport and/or funneling of sediment through the proposed trench to the east of the Guerrero superterrane and includes a local Western Klamath, Rattlesnake Creek, and Western Hayfork source (i.e., scenario 1) plus a source of recycled detritus from the Guerrero superterrane.

Scenario 3 (Figs. 2D, 2E, and 5; Table 2) is consistent with endemic models invoking east-dipping subduction beneath the continent and includes tests for four geologically plausible sediment sources. Scenario 3A (Fig. 5; Table 2) represents a sediment source that includes rocks of the Western Klamath, Rattlesnake Creek, and Western Hayfork terranes (i.e., scenario 1) and sourcing of recycled sediment from previously accreted terranes of the greater Klamath Mountains Province excluding ages from the Eastern Klamath terrane not exposed at the surface in Middle Jurassic time (i.e., Batt et al., 2010). Scenario 3B (Fig. 5; Table 2) includes sourcing from rocks of the Western Klamath, Rattlesnake Creek, and Western Hayfork terranes (i.e., scenario 1) and models primary and recycled sediment derivation from the previously accreted terranes of both the Klamath Mountains and Sierra Nevada foothills using U–Pb ages from modern streams draining both provinces, consistent with the accreted terranes being contiguous along strike prior to ca. 140 Ma (Constenius et al., 2000; Ernst, 2013). Scenarios 3C and 3D expand the possible sediment source areas to include plausible sources of recycled sediment from the continental interior. Scenario 3C (Fig. 5;

## Sediment Provenance Scenarios



**Figure 5. Kernel density estimate plots (30 m.y. bandwidth) of sediment provenance scenarios (see Table 2).**

Table 2) represents sediment derived from the Western Klamath, Rattlesnake Creek, and Western Hayfork terranes plus recycled sediment from previously accreted terranes of the greater Klamath Mountains Province (i.e., scenario 3A) and adds a source of recycled transcontinental sand enriched by southwestern Laurentian sources (Fig. 3D). Recycled transcontinental

sand enriched by southwestern Laurentian sources is represented by Middle and Late Jurassic ages from rocks of the Colorado Plateau inferred to have been delivered to the study area via a river system that flowed north along the axis of the Cordilleran arc, or by erosion and recycling of backarc basin deposits from collisional orogenic highlands in western and central

Nevada (Fig. 3D; Luning-Fencemaker fold-and-thrust system; Wyld, 2002; Wyld et al., 2003; LaMaskin et al., 2011). Scenario 3D (Fig. 5; Table 2) represents sediment derived from the Western Klamath, Rattlesnake Creek, and Western Hayfork terranes plus recycled sediment from previously accreted terranes of the greater Klamath Mountains Province (i.e., scenario 3A) and adds a source of recycled sediment represented by U-Pb ages from Paleozoic rocks in the Grand Canyon delivered to the study area via a river system that flowed north along the axis of the Cordilleran arc (Fig. 3D).

## RESULTS

All samples of clastic rocks in the Rattlesnake Creek terrane cover sequence and Galice Formation in the Western Klamath terrane contain a range of Precambrian, Paleozoic, and Mesozoic ages (Figs. 6, 7, and 8; Table 3). Rattlesnake Creek terrane cover sequence samples (Fig. 6; Table 3) all contain prominent Precambrian age distributions ca. 2.7–2.5, 1.8–1.7, and 1.5–1.0 Ga, dominated by ca. 1.8–1.7 Ga ages. Each of our Rattlesnake Creek terrane cover sequence samples, except 16KM011 ( $n = 64$ ), contain Neoproterozoic ages ca. 630–560 Ma (Fig. 6). Paleozoic ages centered on 370–360 Ma are present in all samples and were represented by proportionally large numbers of grains in our samples Dubakella E and W (Figs. 6 and 8). Mesozoic ages vary in our samples (Fig. 8; Table 3), with dominant age distributions ca. 300–250 Ma and 197–160 Ma. The MDA for Rattlesnake Creek terrane cover sequence sample Salt Creek is Middle Jurassic (Bajocian, ca.  $170 \pm 1.7$  Ma; Fig. 9A; Table 3). MDAs are early Late Jurassic (Oxfordian) for samples Dubakella E (ca.  $162 \pm 5.0$  Ma) and Dubakella W (ca.  $161 \pm 3.8$  Ma; Figs. 9B and 9C; Table 3). In MDS space (Fig. 10A), our Rattlesnake Creek terrane cover sequence samples are well clustered in both dimensions. The samples plot near scenarios 3A, 3C, and 3D (Figs. 5 and 10A; Table 2).

Precambrian detrital zircon age distributions are present in all Galice Formation samples (Fig. 7; Table 3). Samples 14CM43 and 19KM1 from the Klamath River appendage of Saleeby and Harper (1993) contain Precambrian ages ca. 2.6–2.3, 1.8–1.7, 1.4, and 1.0 Ga (Fig. 7). Samples 12TL041 and 15KM50, both from the area of the Bear Mountain intrusive complex, contain lower proportions of ca. 2.0–1.6 Ga grains and greater proportions of ca. 1.4–1.0 Ga ages as compared to the other Galice Formation samples (Fig. 7). Neoproterozoic ages ca. 690–545 Ma are present in three of our Galice Formation samples (Fig. 7). Mesozoic ages vary



TABLE 2. MIDDLE–LATE JURASSIC SEDIMENT PROVENANCE SCENARIO INFORMATION AND DATA SOURCES

Paleotectonic/ paleogeographic setting	Predicted sediment sources	Previously published ages representing predicted sediment sources
<b>Scenario 1</b> An intra-oceanic arc exotic to western Laurentia generated by west-dipping subduction.	Sediment derived from Western Klamath, Rattlesnake Creek, and Western Hayfork terrane source.	Individual ages (>ca. 150 Ma) derived from igneous bodies in the Klamath Mountains (Irwin and Wooden, 1999; Irwin, 2003; Allen and Barnes, 2006) with approximate ages 208–193 Ma (Rattlesnake Creek plutons), 177–168 Ma (Western Hayfork and Ironside Mountain suites), 166–154 Ma (Wooley Creek suite), and 160–153 Ma (Rogue-Chetco complex).
<b>Scenario 2</b> An intra-oceanic arc exotic to western Laurentia generated by west-dipping subduction and experiencing Middle–Late Jurassic rifting between southern Wrangellia (Insular superterrane) and the Guerrero superterrane.	Scenario 2A1: Same as scenario 1 plus sediment derived from a source to the north in Wrangellia (Insular superterrane). Scenario 2A2: Same as scenario 2A1 plus sediment derived via long-distance transport from the Alexander terrane (Insular superterrane). Scenario 2B: Same as scenario 1 plus sediment derived from a source to the south in the Guerrero superterrane.	Same as scenario 1 plus known primary and detrital ages from southern Wrangellia (Alberts, 2019, Paleozoic samples; Ruks, 2015). Same as scenario 2A1 plus the data of White et al. (2016) representing all Alexander terrane ages. Same as scenario 1 plus known ages from the Guerrero superterrane (Ortega-Flores et al., 2016, Arteaga complex, sample Placeres 23; Martini et al., 2009, Arteaga complex, samples TJP, TZT; Ortega-Flores et al., 2021, Charcas Formation sample CH14-1, Esperanza Formation sample GTO14-1).
<b>Scenario 3</b> East-dipping subduction beneath the continent. A period of extension and slab rollback on the continental-plate margin generated a fringing magmatic arc built on older previously accreted terranes.	Scenario 3A: Same as scenario 1 plus previously accreted terranes of the Klamath Mountains. Scenario 3B: Same as scenario 1 plus previously accreted terranes of the Klamath Mountains and those of the Sierra Nevada. Scenario 3C: Same as scenario 3A plus sediment derived from a recycled transcontinental source. Scenario 3D: Same as scenario 3A plus sediment derived from recycled sources in the southwestern U.S.	Same as scenario 1 plus detrital zircon data from the Klamath Mountains (Scherer and Ernst, 2008; Scherer et al., 2010; Ernst et al., 2017). Data published by Cecil et al. (2010), Cassel et al. (2012), and Malkowski et al. (2019) from modern streams draining both the Klamath Mountains and Sierra Nevada foothills terranes, an actualistic estimator of the age distributions present in regional accreted terrane sources. Same as scenario 3A plus data from samples of Middle and Late Jurassic age from the Colorado Plateau (Dickinson and Gehrels, 2009a, samples CP-12, 15, 16, 21, 24, 43, 45, and 54). Same as scenario 3A plus all data from samples of Paleozoic strata in Grand Canyon (Gehrels et al., 2011).

in our samples (Fig. 8), with age distributions ca. 420, 305–281 Ma, 230, 195, 180–165 Ma, and a dominant age mode in each sample of 158 or 157 Ma. The MDA for sample 14CM43 (Fig. 9D; Table 3) is early Late Jurassic (Oxfordian, ca.  $158 \pm 1.7$ ), and the remaining samples (Figs. 9E–9G; Table 3) are middle Late Jurassic (Kimmeridgian) with MDAs of  $157 \pm 2.4$  Ma (15KM50),  $154 \pm 1.6$  Ma (19KM1), and  $153 \pm 1.4$  Ma (12TL041). In MDS space, Galice Formation sequence samples are distinct from Rattlesnake Creek terrane cover sequence samples (Fig. 10A). Three Galice Formation samples plot in a group around scenario 3B, and sample 15KM50 plots nearest to scenario 3C.

## DISCUSSION

### Maximum Depositional Ages

Samples from the Rattlesnake Creek terrane cover sequence do not contain a high proportion of young ages (e.g., as low as 7% total Mesozoic ages; Table 3), making MDA assessment nonideal (Dickinson and Gehrels, 2009b; Spencer et al., 2016; Andersen et al., 2019; Coutts et al., 2019; Herriott et al., 2019; Gehrels et al., 2020; Sharman and Malkowski, 2020). Nonetheless, our samples do include 38 grains younger than the previously assigned minimum age of 193 Ma (Wright and Wyld, 1994) and thus provide new constraints on the timing of deposition for por-

tions of the Rattlesnake Creek terrane cover sequence. Samples yield MDAs (Figs. 4B and 9A–9C) ranging from 170 Ma (Middle Jurassic; Bajocian) to 161 Ma (early Late Jurassic; Oxfordian), a span of 9 m.y., and suggesting that deposition of the Rattlesnake Creek terrane cover sequence occurred during the interval of extension and seafloor spreading in numerous locations in the Klamath Mountains (e.g., Devils Elbow, Preston Peak, and Josephine ophiolites), as well as deposition of the hemipelagic sequence of the Galice Formation (Figs. 4A and 4B; ca. 162–157 Ma) and the early period of Wooley Creek suite magmatism (Allen and Barnes, 2006).

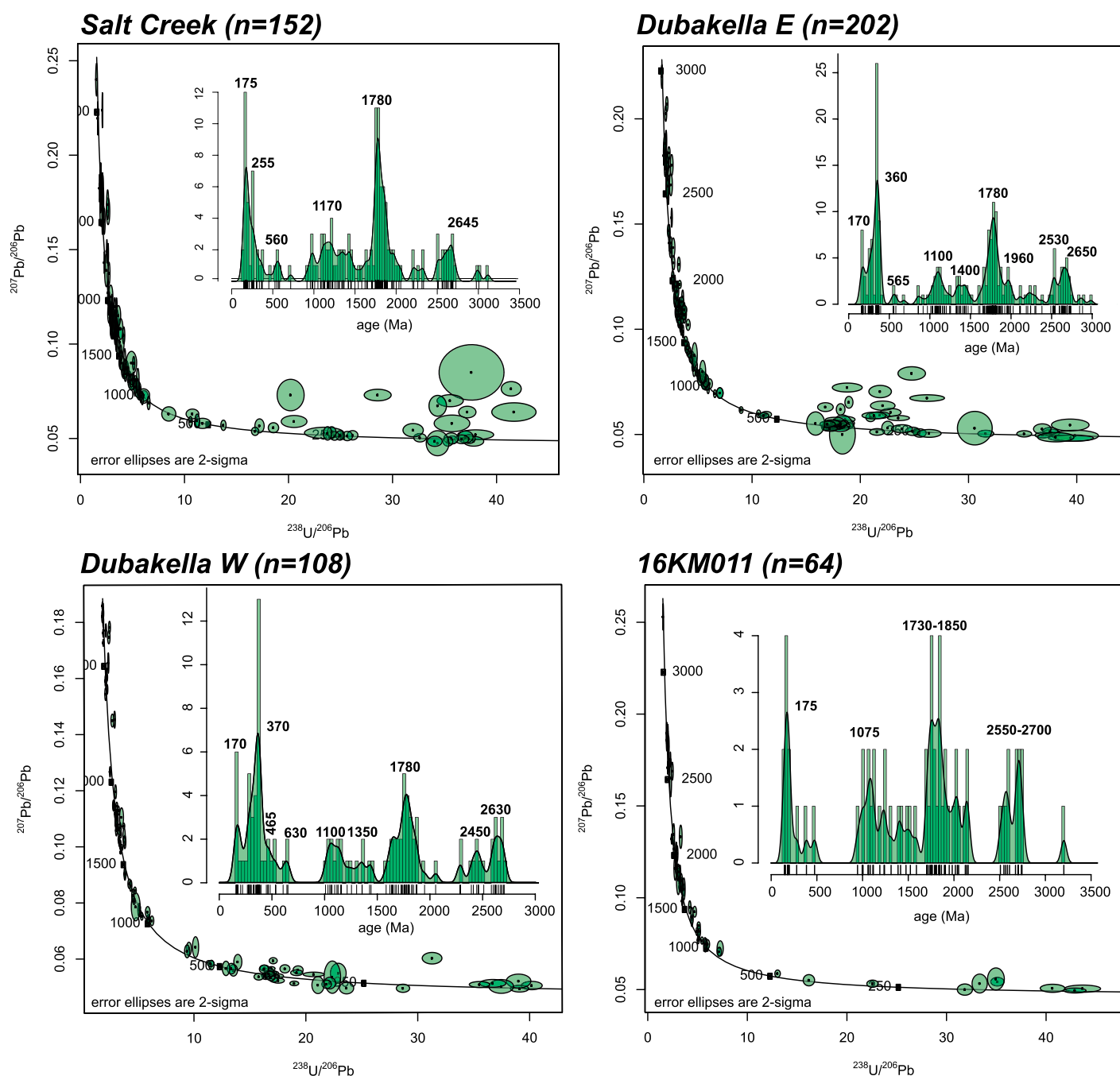
Early Late Jurassic MDAs of 158–153 Ma (Oxfordian–Kimmeridgian) for the Galice Formation (Figs. 4B and 9D–9G) are in excellent agreement with existing faunal estimates of ca. 157 Ma for initiation of Galice Formation turbidite deposition (Pessagno and Blome, 1990; Pessagno, 2006) and the  $157 \pm 2$  Ma radiolarian tuff age from the top of the underlying Rogue Formation (Saleeby, 1984), as well as regional estimates of ca. 155–150 Ma for thrusting and subsequent deformation of the Galice Formation in the Klamath Mountains (Harper et al., 1994; MacDonald et al., 2006). Based on the degree of concurrence with paleontologic ages and the high proportion of young zircon in the Galice Formation samples (i.e., Cawood, 2012; Dickinson and Gehrels, 2009b; Spencer et al., 2016; Herriott et al., 2019; Sharman and Malkowski,

2020), we suggest that our MDAs are reasonable estimates for turbidite deposition in the Galice Formation.

Additional observations suggesting that the majority of our samples were deposited close to the calculated MDAs include a lack of post-Nevadan ages in our samples, despite the fact that magmatism in the Klamath Mountains was nearly continuous from ca. 150 to 136 Ma (Allen and Barnes, 2006; Barnes et al., 2006). In particular, we note a general lack of ages in our Rattlesnake Creek terrane cover sequence samples representing magmatism in the late period of the Wooley Creek suite, which was nearly continuous from 166 to 152 Ma.

Taken together, our data corroborate a period of late Middle to early Late Jurassic regional basin formation and sedimentation in the Rattlesnake Creek and Western Klamath terranes (Figs. 2D, 2E, 4A, and 4B). Regional crosscutting relationships suggest that basin formation began as early as ca. 170 Ma (inferred age of the Preston Peak and China Peak precursors to the Josephine ophiolite; Saleeby and Harper, 1993) and no later than ca. 164 Ma (Josephine and Devils Elbow ophiolites) and that sedimentation of the Galice Formation was syncontractional, ending ca. 150 Ma (Harper et al., 1994; Hacker et al., 1995). Thus, our data fall exceptionally well within these temporal estimates of basin formation and sedimentation based on paleontologic and geochronological estimates

# RATTLESNAKE CREEK TERRANE - COVER SEQUENCE



**Figure 6.** Tera-Wasserburg plots and kernel density estimate plots (30 m.y. bandwidth) as insets for detrital zircon U-Pb data from the Rattlesnake Creek terrane cover sequence.

independent of our data (Figs. 4A and 4B; Saleeby, 1984; Pessagno and Blome, 1990; Saleeby and Harper, 1993; Pessagno, 2006).

Our radioisotopic data corroborate field structural and intrusive observations showing that our samples were deposited prior to the postulated ca. 150 Ma collision of the Mezcalera arc and

the “initial pulse of Nevadan deformation” (Siegloch and Mihalynuk, 2017, p. 1509). Our new MDAs confirm that the provenance of sedimentary rocks in the Rattlesnake Creek and Western Klamath terranes bears directly on the question of contrasting exotic versus endemic Late Jurassic paleogeographic and paleotectonic models

for the Klamath Mountains and the western U.S. Cordillera.

## Provenance Analysis

The age distributions present in our samples and our provenance analysis of geologically

## WESTERN KLAMATH TERRANE - GALICE FORMATION

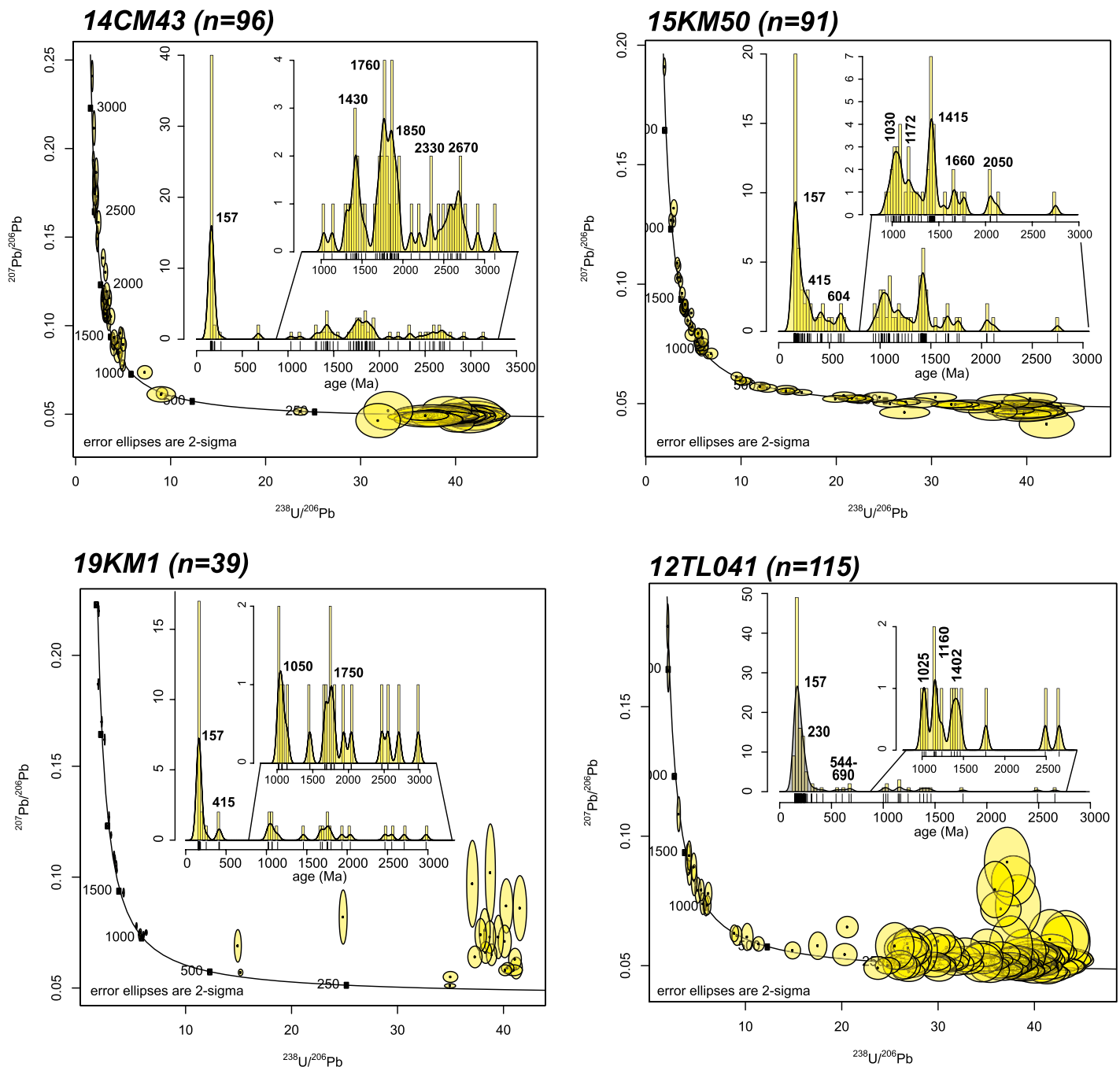


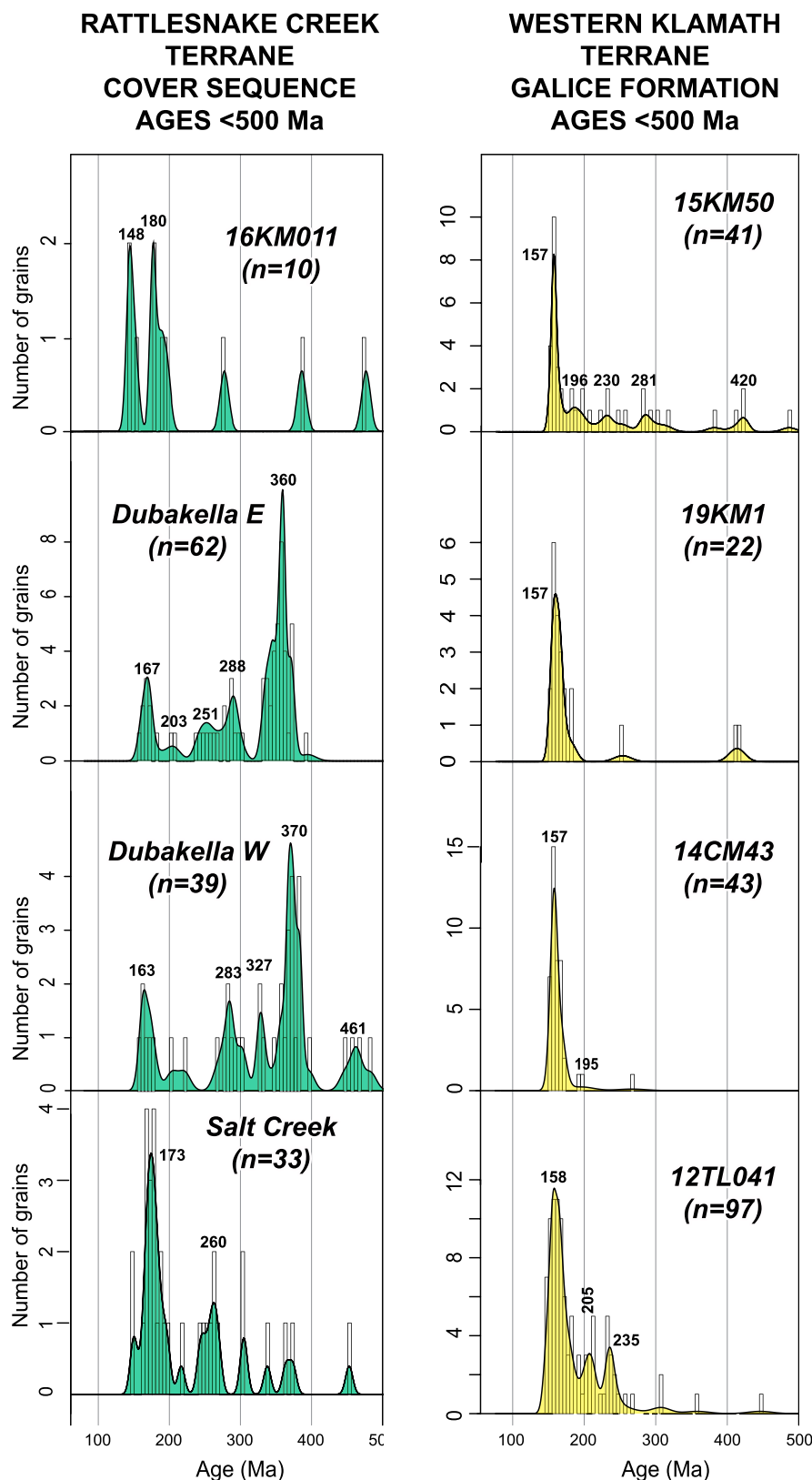
Figure 7. Tera-Wasserburg plots and kernel density estimate plots (30 m.y. bandwidth) as insets for U-Pb detrital zircon data from the Galice Formation of the Western Klamath terrane.

plausible Middle–Late Jurassic sediment sources are not consistent with exotic models for the origin of the Western Klamath or Rattlesnake Creek terranes. Exotic scenario 1 lacks the appropriate distribution of Precambrian ages observed in our samples (Figs. 5–7 and 10B) and plots far from samples of the Rattlesnake

Creek terrane cover sequence and Galice Formation in MDS space (Fig. 10A). All of our samples do bear ages ca. 205–160 Ma, which are broadly consistent with the local sources that comprise the predicted sediment source of scenario 1 (Sigloch and Mihalynuk, 2013, 2017); however, our samples also contain up to

~83% Precambrian and Paleozoic zircon grains (Figs. 6, 7, and 10B; Table 3). There is simply no known primary or recycled source of Precambrian grains in the Western Jurassic, Rattlesnake Creek, or Western Hayfork terranes that could comprise the predicted sediment source in scenario 1.





**Figure 8.** Kernel density estimate plots (5 m.y. bandwidth) for detrital zircon ages younger than 500 Ma from our samples. Note that many of these plots show more age modes than the plots in Figures 6 and 7 due to the differences in bandwidth used.

Scenarios 2A1 and 2A2, after Sigloch and Mihalynuk (2020) and Clennett et al. (2020), do contain Precambrian zircon; however, the age distributions in these potential sources do not match the ages in our samples, and they plot far from samples of Rattlesnake Creek terrane cover sequence and the Galice Formation in MDS space (Figs. 10A and 10B). Scenarios 2A and 2B predict that there should be few ages older than 600 Ma and very few ages older than 1.3 Ga; however, our samples bear abundant ages in these ranges (Figs. 6, 7, and 10B). Scenario 2B, after Sigloch and Mihalynuk (2020) and Clennett et al. (2020), plots closer to samples from our study area, reflecting age modes at 1.2–1.0 Ga, 470, 335, 254, and 171 Ma, which are broadly similar to our data; however, scenario 2B contains only a very small proportion of ages older than 1.2 Ga (Figs. 5 and 10B), which are present in great abundance in our samples (Figs. 6, 7, and 10B).

In contrast, our results are broadly consistent with all four predicted sediment sources representing endemic models (scenarios 3A, 3B, 3C, and 3D; Figs. 5 and 10B). Each predicted source includes detrital zircon grains of the appropriate ages and proportions as those observed in samples from the Rattlesnake Creek and Western Klamath terranes (Figs. 5, 6, 7, and 10B). To address potential bias in our provenance comparisons resulting from overrepresentation of ages younger than 250 Ma in modern sediment from the Klamath Mountains and Sierra Nevada (i.e., swamping-out by younger plutonic ages; Cecil et al., 2010; Cassel et al., 2012; Malkowski et al., 2019), we removed ages younger than 250 Ma and reanalyzed the data using MDS and visual analysis (Figs. 11A and 11B).

Our Rattlesnake Creek terrane cover sequence samples and two Galice Formation samples (19KM1 and 14CM43; Figs. 11A and 11B) plot near or between Klamath–Sierra Nevada sources (scenario 3A and 3B) and recycled transcontinental sand enriched by southeastern U.S. sources (scenario 3C), as well as sources in the southwestern United States (scenario 3D). Galice Formation samples 15KM50 and 12TL041 bear a low to moderate proportion of post–250 Ma grains, but those present are a close match to recycled transcontinental sand enriched by southeastern U.S. sources (scenario 3C).

Samples Dubakella E and W contain abundant ages ca. 370 and 360 Ma, as well as ca. 1.8–1.7 Ga, which, along with other ages present, provide a close match to ages from modern streams draining the Klamath Mountains and Sierra Nevada (Figs. 11A and 11B; scenario 3B). Ages ca. 380 Ma in modern sediment likely represent the full age range of grains present in

TABLE 3. RESULTS OF U-PB GEOCHRONOLOGY, KLAMATH MOUNTAINS PROVINCE

Sample name	Percent of ages by era	Age modes and distributions at 30 m.y. kernel bandwidth	Age modes and distributions for grains younger than 500 Ma at 5 m.y. kernel bandwidth	Maximum depositional age
<b>Rattlesnake Creek terrane cover sequence</b>				
Salt Creek ( <i>n</i> = 152)	78% Precambrian 8% Paleozoic 14% Mesozoic	ca. 2645, 1780, 1185, 560, 255, and 175 Ma	ca. 260 and 173 Ma	170 ± 1.7 Ma, MSWD = 1.36, <i>n</i> = 6; Middle Jurassic, Bajocian
Dubakella E ( <i>n</i> = 202)	69% Precambrian 24% Paleozoic 7% Mesozoic	ca. 2650, 2530, 1960, 1780, 1400, 1100, 565, 360, and 167 Ma	ca. 360, 288, 251, 203, and 167 Ma	162 ± 5.0 Ma, MSWD = 1.27, <i>n</i> = 4; early Late Jurassic, Oxfordian
Dubakella W ( <i>n</i> = 108)	62% Precambrian 31% Paleozoic 7% Mesozoic	ca. 2630, 2450, 1780, 1350, 1100, 630, 465, 370, and 163 Ma	ca. 461, 370, 327, 283, and 163 Ma	161 ± 3.8 Ma, MSWD = 2.99, <i>n</i> = 3; early Late Jurassic, Oxfordian
16KM011 ( <i>n</i> = 64)	83% Precambrian 5% Paleozoic 12% Mesozoic	ca. 2700–2550, 1850–1730, 1075, and 175 Ma	ca. 180 and 148 Ma	n/a
<b>Western Klamath terrane, Galice Formation</b>				
14CM43 ( <i>n</i> = 96)	55% Precambrian 1% Paleozoic 44% Mesozoic	ca. 2670, 2330, 1850, 1760, 1430, and 157 Ma	ca. 157 Ma	158 ± 1.7 Ma, MSWD = 0.48, <i>n</i> = 30; early Late Jurassic, Oxfordian
15KM50 ( <i>n</i> = 91)	54% Precambrian 13% Paleozoic 33% Mesozoic	ca. 2050, 1660, 1415, 1172, 1030, 604, 415, 157 Ma	ca. 420, 281, 230, 196, and 157 Ma	157 ± 2.4 Ma, MSWD = 0.49, <i>n</i> = 17; middle Late Jurassic, Kimmeridgian
19KM1 ( <i>n</i> = 39)	44% Precambrian 7% Paleozoic 49% Mesozoic	ca. 1750, 1050, 415, and 157 Ma	ca. 195 and 157 Ma	154 ± 1.6 Ma, MSWD = 0.92, <i>n</i> = 4; middle Late Jurassic, Kimmeridgian
12TL041 ( <i>n</i> = 115)	15% Precambrian 6% Paleozoic 79% Mesozoic	ca. 1042, 1160, 1025, 690–544, 230, and 157 Ma	ca. 235, 205, and 158 Ma	153 ± 1.4 Ma, MSWD = 1.50, <i>n</i> = 23; middle Late Jurassic, Kimmeridgian

\*MSWD—mean square of weighted deviates.

rocks of the Bowman Lake batholith and associated plutons in the Northern Sierra terrane, which range from 371 to 353 Ma (Powerman et al., 2020). The presence of prominent age modes ca. 370 and 360 Ma in our samples is further confirmation that accreted terranes of the Klamath Mountains were contiguous along strike with the Sierra Nevada foothills prior to ca. 140 Ma, when the Klamath block separated from the Sierra Nevada block and moved trenchward (Constenius et al., 2000; Snow and Scherer, 2006; Ernst, 2013).

Our results suggest that sediment sources to the Klamath Mountains during Middle and Late Jurassic time were largely mixtures generated from recycling through previously accreted terranes of the Klamath Mountains and Sierra Nevada, recycled transcontinental sand either input directly to the basin or recycled through Middle and Late Jurassic, “pre-Nevadan” orogenic sources (e.g., through the Luning-Fence-maker fold-and-thrust belt; Wyld, 2002; Wyld et al., 2003; LaMaskin et al., 2011; LaMaskin, 2012), and primary and/or recycled sources in the southwestern United States. Variations within our samples and as compared to the predicted sediment sources analyzed here likely represent a combination of sampling bias due to the low number of pre-Mesozoic analyses per sample, hydrodynamic sorting of ages during transport and deposition (Lawrence et al., 2011), and variations in the evolution of drainage basins and sediment routing systems over time (e.g., DeGraaff-Surpless et al., 2002; see Caracciolo, 2020).

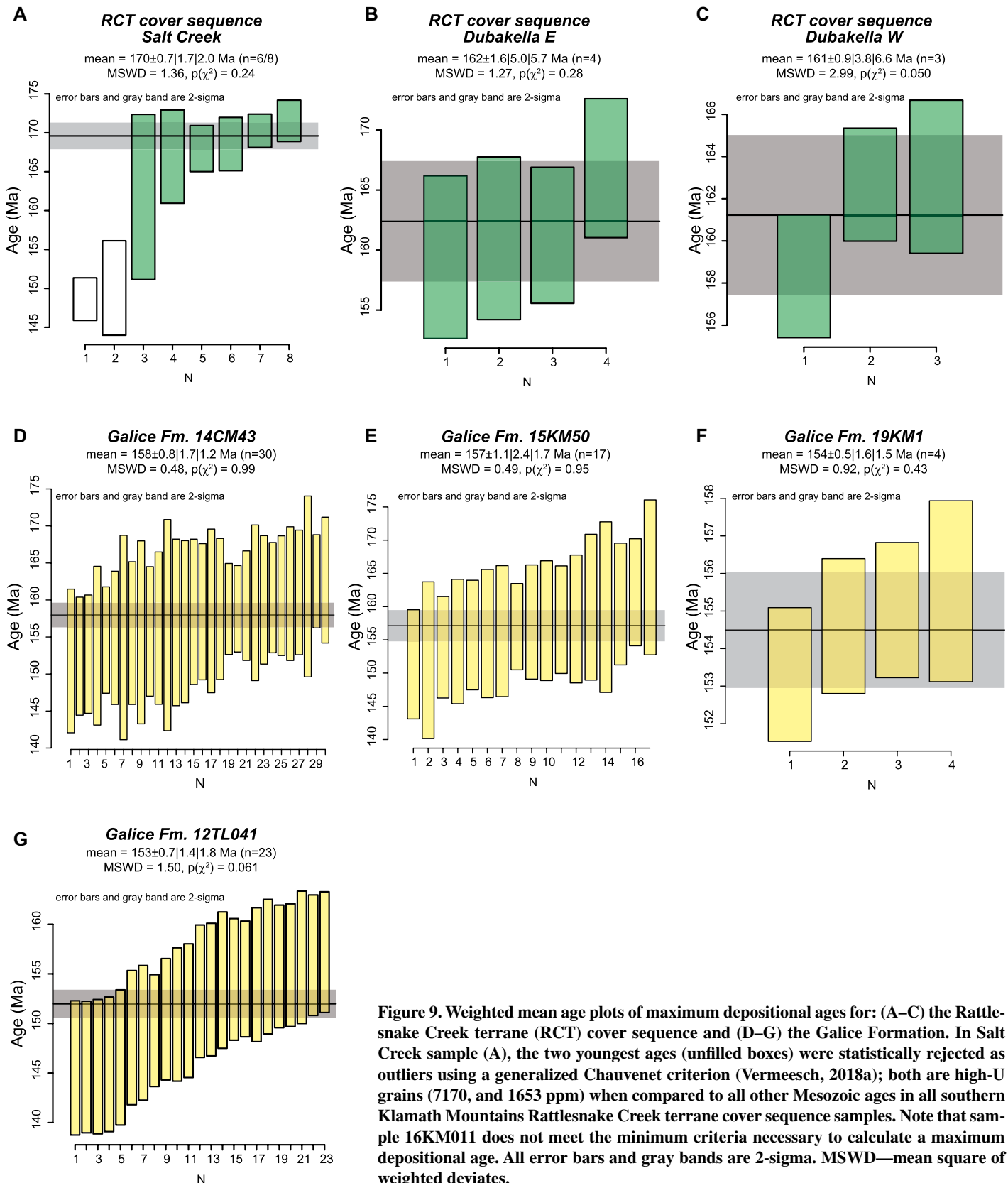
### Implications for the History of the Klamath Mountains Province

Middle Jurassic and early Late Jurassic MDAs for the Rattlesnake Creek terrane cover sequence (Salt Creek assemblage) are at least 23 m.y. younger than the age of the Late Triassic to Early Jurassic intrusive suite (207–193 Ma) that was interpreted by Wright and Wyld (1994) to crosscut the cover sequence. We suggest that multiple bodies of sedimentary rock of varying ages—some cut by the Mesozoic intrusive suite (Wright and Wyld, 1994) and some not—may be present in the Rattlesnake Creek terrane, and we note that these MDAs are consistent with Middle Jurassic radiolaria ages in Irwin and Blome (2004) and the interpretations of Irwin (2010) and Irwin et al. (2011), who suggested that some clastic portions of the Rattlesnake Creek terrane cover sequence may be more analogous to the Galice Formation. Deformation of the cover sequence corresponds to a period of serpentinite remobilization, causing fragments of the cover sequence to be incorporated into the basement mélange (Wright and Wyld, 1994). Traditionally, this deformation of the cover sequence has been attributed to Middle Jurassic Siskiyou deformation; however, ca. 170–161 Ma MDAs for the cover sequence require that these rocks were deformed after the Siskiyou event by Late Jurassic (Nevadan) orogenesis (Figs. 4A and 4B). More detailed U-Pb geochronology is necessary to decipher these details; however, the detrital zircon U-Pb ages presented here suggest that sampled rocks of the Rattlesnake Creek terrane

cover sequence were deposited no earlier than early Middle to early Late Jurassic time.

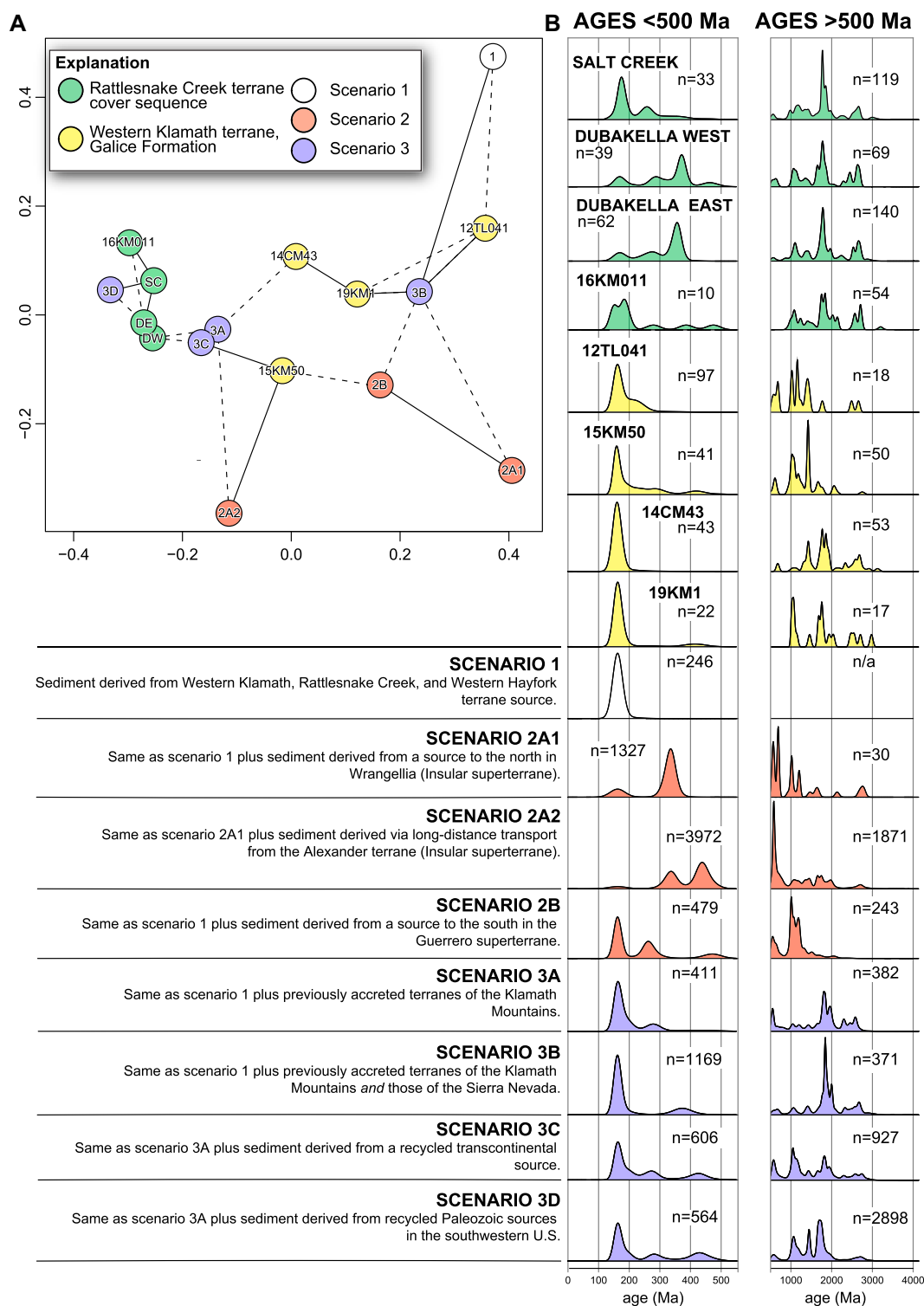
Our data are consistent with endemic models of the Middle–Late Jurassic tectonic evolution of the Klamath Mountain Province (Fig. 12), where Middle–Late Jurassic extension in the Rattlesnake Creek terrane generated a new continent-fringing arc-basin complex, the Western Klamath terrane. Deposition of the Rattlesnake Creek terrane cover sequence took place 170–161 Ma during extension and seafloor spreading in numerous locations in the Klamath Mountains (Fig. 12A; e.g., Devils Elbow, Preston Peak, and Josephine ophiolites). Although the timing of sedimentation of the Rattlesnake Creek terrane cover sequence is revised here, the conclusion that previously accreted terranes of the Klamath Mountains and the Sierra Nevada provided an uplifted orogenic source of sediment to depocenters on the basement assemblage of the Rattlesnake Creek terrane is consistent with the petrographic and isotopic observations and interpretations of Wright and Wyld (1994) and Frost et al. (2006).

Subsequent early and middle Late Jurassic filling of the marginal ocean basin is represented by turbidite sandstone deposits of the Galice Formation (Fig. 12A). Our results suggest that the sources of sediment to the Galice Formation turbidite sandstone are dominated by local syndepositional magmatic sources likely derived from volcanic equivalents of the Wooley Creek suite and Rogue-Chetco arc complex, but they also contain detritus eroded from previously accreted terranes of



**Figure 9.** Weighted mean age plots of maximum depositional ages for: (A–C) the Rattlesnake Creek terrane (RCT) cover sequence and (D–G) the Galice Formation. In Salt Creek sample (A), the two youngest ages (unfilled boxes) were statistically rejected as outliers using a generalized Chauvenet criterion (Vermeesch, 2018a); both are high-U grains (7170, and 1653 ppm) when compared to all other Mesozoic ages in all southern Klamath Mountains Rattlesnake Creek terrane cover sequence samples. Note that sample 16KM011 does not meet the minimum criteria necessary to calculate a maximum depositional age. All error bars and gray bands are 2-sigma. MSWD—mean square of weighted deviates.



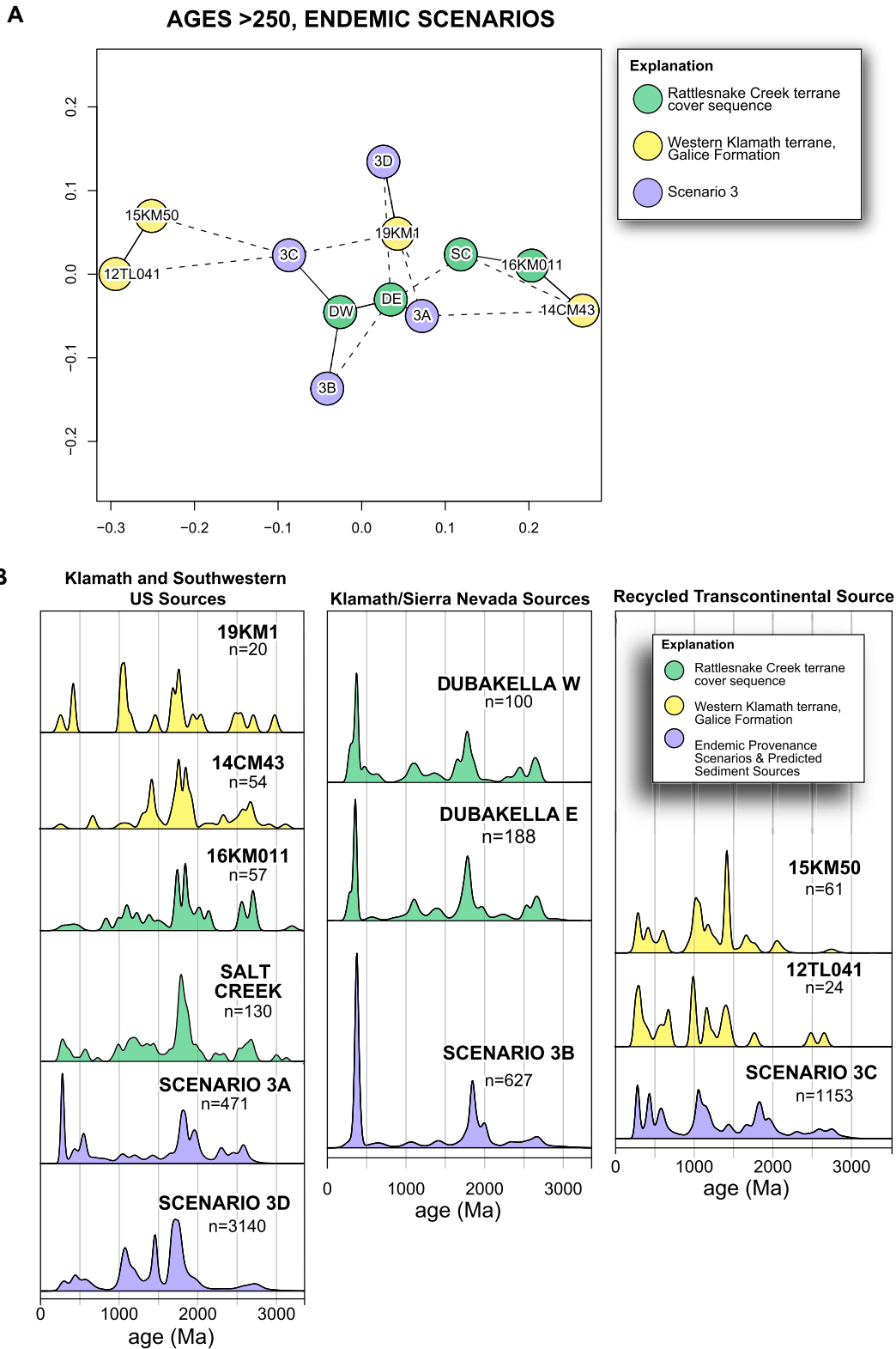


**Figure 10. Provenance analysis results for all ages in all samples (this study) and provenance scenarios (see Table 1). (A) Multidimensional scaling plot of Rattlesnake Creek terrane cover sequence and Galice Formation samples, as well as provenance scenarios. Each sample is connected to its closest neighbor with a solid line and to its second-closest neighbor with a dashed line. (B) Stacked kernel density estimate plots for ages younger than 500 Ma at 15 m.y. bandwidth and for ages older than 500 Ma at 30 m.y. bandwidth for Rattlesnake Creek terrane cover sequence and Galice Formation samples, as well as provenance scenarios (Vermeesch, 2018a). DW—Dubakella West sample, DE—Dubakella East sample, SC—Salt Creek sample.**

the Klamath Mountains and the Sierra Nevada, and a likely additional source of recycled transcontinental sand. Finally, in Late Jurassic time ca. 155–150 Ma, the arc-basin complex closed, the Western Klamath and Rattlesnake Creek terranes were re-accreted to the North American plate margin, and the Rattlesnake

Creek terrane cover sequence was deformed and incorporated into the Rattlesnake Creek terrane basement assemblage (Fig. 12B). Our interpretation of the presence of Middle and Late Jurassic rift-related sedimentary deposits in the Rattlesnake Creek terrane is analogous to other interpretations of rift-edge facies

(Snoke, 1977; Saleeby and Harper, 1993; Yule et al., 2006; MacDonald et al., 2008) that tie rocks of the Western Klamath terrane and Rattlesnake Creek terrane together during the evolution of *in situ* extension of the North American plate margin in Middle and Late Jurassic time.



**Figure 11. Provenance analysis results for ages older than 250 Ma in endemic scenarios (i.e., scenario 3; see Table 1). (A) Multidimensional scaling plot showing Rattlesnake Creek terrane cover sequence and Galice Formation samples, as well as scenarios 3A, 3B, 3C, and 3D. DW—Dubakella West sample, DE—Dubakella East sample, SC—Salt Creek sample. (B) Kernel density estimate plots (30 m.y. bandwidth) comparing ages older than 250 Ma. See Figure 10 for sample name abbreviations.**

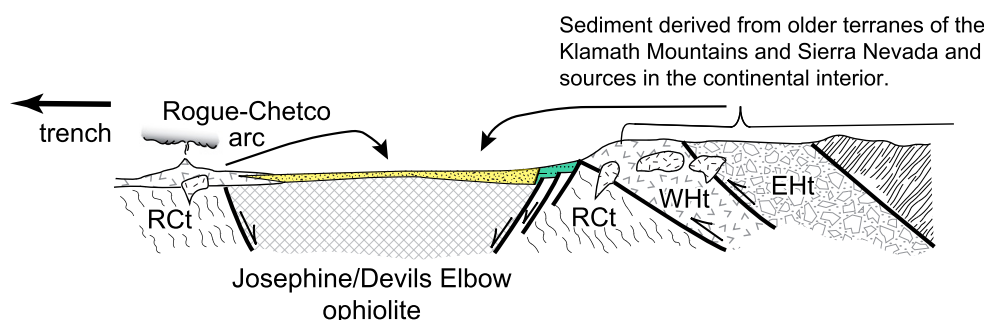
### Implications for the Assembly of Western North America

Exotic, intra-oceanic models for the origin of Insular-associated terranes above a west-dipping

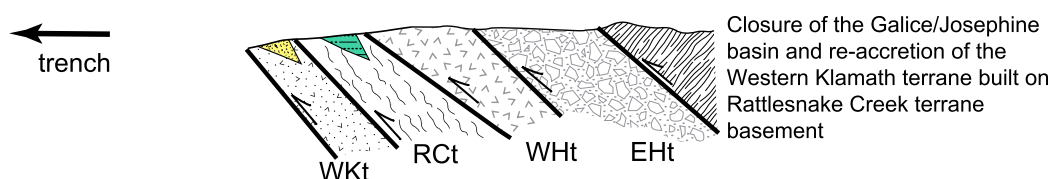
subduction zone fail several geologic tests in the Klamath Mountains. First, as shown here, there are no known primary or recycled sources of the detrital zircon reported here for rocks of the Western Klamath and Rattlesnake Creek terrane

in the sediment sources predicted by the tomotectonic models or Sigloch and Mihalynuk (2013, 2017) or Clennett et al. (2020). Second, we note that the boundary between the Eastern and Western Hayfork terranes, which is proposed to be the

## A late Middle to middle Late Jurassic



## B middle Late to late Late Jurassic



terrane. (B) Late Jurassic closure of the basin and re-accretion of the endemic Western Klamath terrane against North America.

Mezcalera-Angayucham suture of Sigloch and Mihalynuk (2017), is stitched by the ca. 170–169 Ironside Mountain batholith and by the Wooley Creek batholith with robust isotopic ages as old as ca.  $159.22 \pm 0.10$  Ma (Fig. 3; Coint et al., 2013). Thus, the “suture” developed prior to ca. 155 Ma, in contrast to Sigloch and Mihalynuk’s (2017) requirement that the “suture” must everywhere be younger than ca. 155 Ma, and well prior to either the 135–110 Ma age suggested by Sigloch and Mihalynuk (2017) at the latitude of California, or the 80 Ma age depicted by Clennett et al. (2020). Finally, we note that the interpretations of Dickinson (2008) are in fact not consistent with the interpretation of Sigloch and Mihalynuk (2017), i.e., that the Western Klamath, Rattlesnake Creek, and Western Hayfork terranes formed above the westward-subducting Mezcalera Ocean. While Dickinson (2008) does suggest that the Rattlesnake Creek terrane may have formed above a west-dipping subduction zone, he honors geologic constraints that require its accretion to the plate margin to have occurred by Middle Jurassic time. Dickinson (2008) then suggests that accretion of the Rattlesnake Creek terrane was followed by a flip in subduction polarity and that magmatism in the Western Hayfork terrane “can be taken to mark initiation of a west-facing magmatic arc built on the newly expanded continental margin” (p. 337). In this manner, Dickinson (2008) accepts the endemic model argued for here, wherein the Western

Klamath terrane and associated Josephine/Galice basin formed during slab rollback and extension on the plate margin during east-dipping subduction, followed by contraction and basin closure.

These fundamental geologic observations in the Klamath Mountains add to arguments against west-sipping subduction presented for portions of the Canadian and Alaskan Cordillera (e.g., Monger, 2014; Pavlis et al., 2019, 2020) and further call into question essential elements of the exotic tometectonic models. Our results are consistent with geologic observations presented in numerous other studies suggesting that tectonic models invoking exotic, intra-oceanic archipelagos composed of Cordilleran arc terranes formed above a west-dipping subduction zone are not supported by geologic data (e.g., Trop and Ridgway, 2007; Hampton et al., 2010; Monger, 2014; Surpless et al., 2014; Yokelson et al., 2015; Box et al., 2019; Pavlis et al., 2019, 2020; Manselle et al., 2020; Trop et al., 2020). Detailed geologic observations in these regions, and in the Klamath Mountains, suggest that collisions and sutures that match tometectonic predictions are not observed. As a result, the interpretation of a continent-scale suture representing Late Jurassic and Cretaceous consumption of an oceanic Mezcalera plate is not supported. Instead, numerous observations in western North America lend support to models incorporating east-dipping Mesozoic subduction beneath the North American continental margin.

**Figure 12.** Simplified model depicting the western Klamath Mountains from ca. 170 to 150 Ma, modified from Frost et al. (2006). Green represents sediment of the Rattlesnake Creek terrane cover sequence, and yellow represents sediment of the Galice Formation in the Western Klamath terrane. (A) Intra-arc rifting of the Rattlesnake creek terrane away from the Western Hayfork terrane and associated generation of Middle–Late Jurassic ophiolites and sedimentation sourced from older, previously accreted terranes and dominantly recycled sources on the continental interior. RCt—Rattlesnake Creek terrane, WHt—Western Hayfork terrane, Eht—Eastern Hayfork terrane, WKt—Western Klamath terrane.

## CONCLUSIONS

New detrital zircon U–Pb ages from clastic rocks of the Rattlesnake Creek and Western Klamath terranes in the Klamath Mountains are consistent with derivation from a combination of the older terranes of the Klamath Mountains and Sierra Nevada, active-arc sources, and recycled sources in the continental interior. Our observations are consistent with, and lend additional support to, an endemic Middle–Late Jurassic setting for the Western Klamath, Rattlesnake Creek, and Western Hayfork terranes (e.g., Snoke, 1977; Harper, 1980; Saleeby, 1981, 1983, 1992; Saleeby et al., 1982; Saleeby and Busby-Spera, 1992; Saleeby and Harper, 1993; Harper and Wright, 1984; Wright and Fahan, 1988; Hacker and Ernst, 1993), where during east-dipping subduction, the opening (Galice/Josephine basin) and subsequent closing (local Nevadan orogeny) of a marginal ocean basin occurred as a result of *in situ* extension and contraction, respectively, along the continental subduction margin (Fig. 12). Middle and Late Jurassic incorporation of sediment derived from previously accreted material of the Klamath Mountains and Sierra Nevada, plus sand from the interior of North America, into the Rattlesnake Creek and Western Klamath terranes requires that these terranes were endemic to the North American plate margin in Middle–Late Jurassic time and indicates that re-accretion of these endemic terranes was the driver of subsequent Late

Jurassic deformation in the Klamath Mountains. Models of exotic, intra-oceanic archipelagos composed of Cordilleran arc terranes formed above a west-dipping subduction zone and accreted to the plate margin after ca. 150 Ma are not consistent with multiple lines of geologic evidence.

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