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# The birth of a forearc: The basal Great Valley Group, California, USA

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## ABSTRACT

**The Great Valley basin of California (USA) is an archetypal forearc basin, yet the timing, structural style, and location of basin development remain controversial. Eighteen of 20 detrital zircon samples (3711 new U-Pb ages) from basal strata of the Great Valley forearc basin contain Cretaceous grains, with nine samples yielding statistically robust Cretaceous maximum depositional ages (MDAs), two with MDAs that overlap the Jurassic-Cretaceous boundary, suggesting earliest Cretaceous deposition, and nine with Jurassic MDAs consistent with latest Jurassic deposition. In addition, the pre-Mesozoic age populations of our samples are consistent with central North America sources and do not require a southern provenance. We interpret that diachronous initiation of sedimentation reflects the growth of isolated depocenters, consistent with an extensional model for the early stages of forearc basin development.**

## INTRODUCTION

Forearc basins occupy a critical tectonic zone above subducting plates, and their strata contain a record of subduction-related orogenesis (e.g., Dickinson, 1995; Hessler and Sharman, 2018). However, these basins have low preservation potential due to active-margin shortening and/or destructive phases (e.g., Fildani et al., 2008), and therefore, the mechanisms of initial basin formation are not well understood. The Great Valley basin of California (USA) has been the focus of more than 100 years of exploration, including detrital zircon (DZ) provenance studies that have revealed sediment dispersal patterns (DeGraaff-Surpless et al., 2002; Dumitru et al., 2012; Sharman et al., 2015), but also called into question stratigraphic age constraints on the timing of initial basin sedimentation (Surpless et al., 2006). Uncertainty regarding the age of the basal Great Valley Group (GVG) impedes our understanding of how the incipient forearc basin developed as the west coast of North America became a consolidated, two-plate subduction system (e.g., Ernst, 1970; Dickinson, 1995). Here we provide a record of the initiation and provenance of sedimentation within this archetypal forearc basin.

We revisit the timing of the earliest GVG sedimentation using U-Pb geochronology of 20 new DZ samples collected from basal GVG strata (Fig. 1). All samples were collected from strata mapped as Upper Jurassic based on biostratigraphy (Jones et al., 1969; Imlay and Jones, 1970). Eighteen (18) of our 20 samples contain Cretaceous zircons, with nine samples yielding statistically robust Cretaceous maximum depositional ages (MDAs). As first noted by Surpless et al. (2006), a Cretaceous age revision for the basal GVG: (1) lengthens the time interval between initiation of subduction and onset of forearc basin sedimentation; (2) lengthens the duration of the unconformity between the GVG and its underlying basement; and (3) doubles the thickness of Lower Cretaceous GVG strata.

Our results document diachronous accumulation in the earliest Great Valley forearc region, with sedimentation beginning in either Late Jurassic or Early Cretaceous time along the length of the Sacramento Valley forearc basin. We suggest that initial Great Valley forearc sedimentation occurred in isolated latest Jurassic–earliest Cretaceous sub-basins that overfilled to form a larger, single forearc basin during Early Cretaceous time (DeGraaff-Surpless et al., 2002). Documenting the birth of this ancient forearc basin permits improved understanding of the early stages of forearc basin development as well as the Mesozoic development of the central-western margin of North America.

## GEOLOGIC SETTING

The Great Valley forearc basin developed between the Franciscan subduction complex to the west and the Sierra Nevada magmatic arc to the east (Fig. 1; Dickinson, 1995). Sediment initially accumulated unconformably on ophiolitic basement, broadly termed the Coast Range ophiolite (CRO), which lies structurally above the Franciscan complex (Bailey et al., 1970). The timing of the onset of Farallon subduction beneath western North America and the tectonic origin of the CRO are controversial (e.g., Dickinson et al., 1996). In one model, eastward subduction of the Farallon plate beneath North America within a two-plate system was active by 180–165 Ma (Wakabayashi, 1992; Mulcahy et al., 2018), and the CRO formed during extension in the forearc region of an east-dipping Franciscan subduction zone 172–164 Ma (Saleeby, 1996; Shervais, 2001). This subduction margin remained primarily non-accretionary for its first ~50 m.y. and became strongly accretionary at ca. 123 Ma (Dumitru et al., 2010; Wakabayashi, 2015).

In an arc-arc collisional model, the Smartville and Great Valley ophiolite segments of the CRO formed as backarc ophiolites atop a west-dipping subduction zone offshore western North America (Schweickert and Cowan, 1975; Ingersoll, 2000, 2019; Schweickert, 2015). These ophiolites and island arcs accreted onto the California margin during the Sierran phase of the Nevadan orogeny ca. 162–155 Ma (e.g., Ingersoll, 2008). By 150 Ma, the margin was a consolidated two-plate system with eastward subduction generating arc magmatism and initiation of sedimentation of the GVG atop the Great Valley ophiolite.

In both models, the provenance of the GVG is constrained to the Klamath-Sierran magmatic arc by sandstone petrography (e.g., Ingersoll, 1983), DZ geochronology (e.g., DeGraaff-Surpless et al., 2002), isotopic analysis (e.g., Linn et al., 1992), paleocurrent analysis (e.g., Ingersoll, 1979), and mudstone geochemistry (Surpless, 2014). In contrast, a translational model places basal GVG deposition south of the Sierra Nevada, with postulated northward translation to its current position west of the Sierran arc complete by ca. 120 Ma (Wright and Wyld, 2007).

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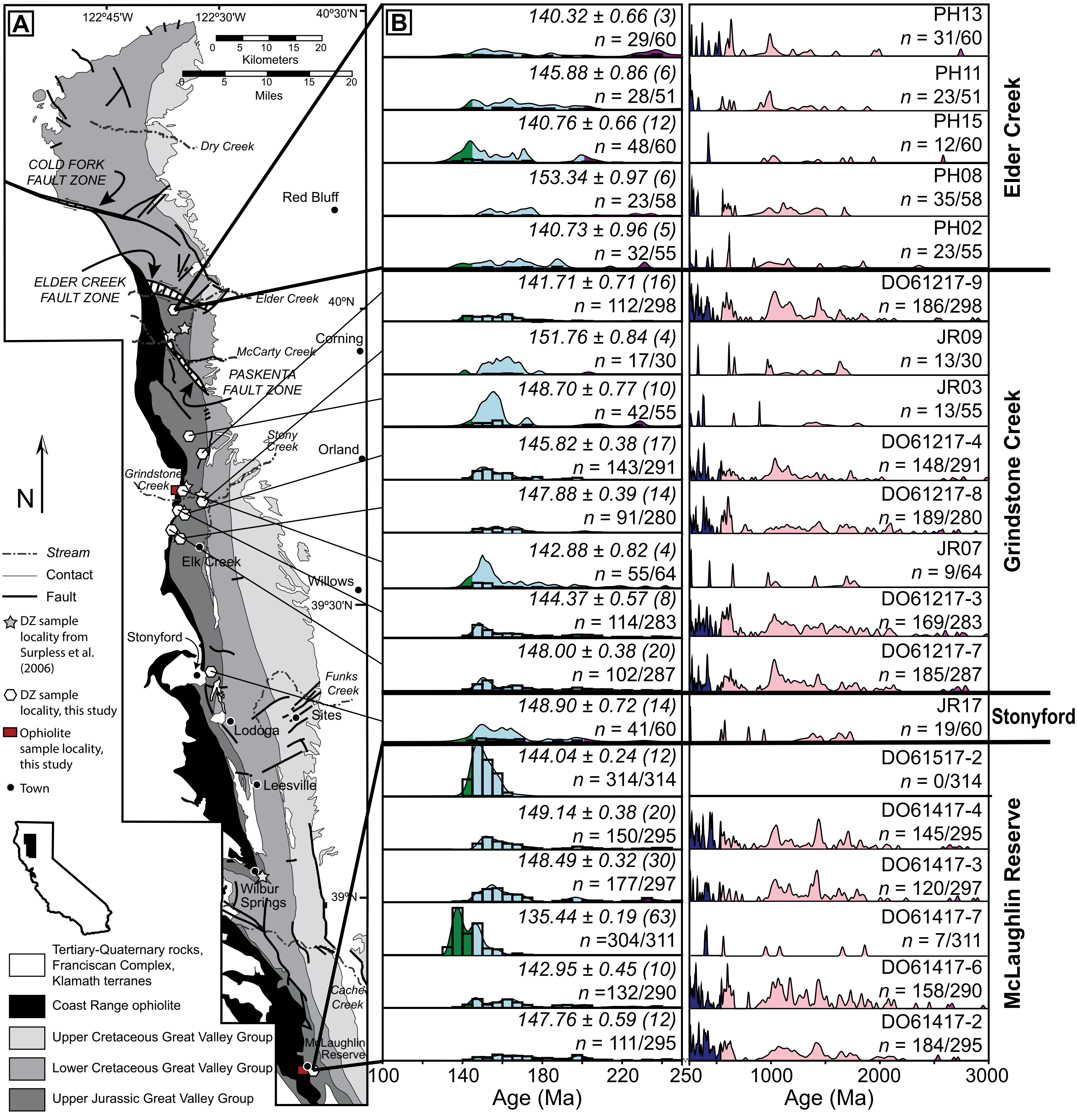


**Figure 1. A: Geologic map showing sample locations within mapped "Jurassic" Great Valley Group strata, California, USA (modified from Surpless et al., 2006). DZ—detrital zircon. B: Probability distribution plots (PDPs) with YC2σ(3+) (youngest cluster of three or more grains that overlap within 2σ uncertainty) maximum depositional ages (MDAs); number of grains used to calculate MDAs is given in parentheses. See text for discussion of MDA calculation. *n* is the subset of U-Pb ages in each plot shown as a function of the total number of U-Pb ages in the sample. Samples are arranged in stratigraphic order within each region, with oldest sample on bottom. Colors on PDPs correspond to geologic periods: green—Cretaceous; light blue—Jurassic; magenta—Triassic; dark purple—Paleozoic; pink—Precambrian.**

## BASAL STRATIGRAPHIC AGE

The Late Jurassic age assignment of the basal GVG is based on two Tithonian zones of the pelecypod *Buchia* (*B. piochii* and *B.* aff. *B. okensis*) and association with ammonites (Jones et al., 1969; Pessagno, 1977). However, calibration of the ammonite stratigraphy with Lower Cretaceous calcareous nannofossils and interbedded radiometrically dated tuff horizons indicated that the *B.* aff. *B. okensis* zone is Berriasian (Bralower, 1990). Rare Late Jurassic to Early Cretaceous *Buchia* fossils within the Franciscan Complex were interpreted as reworked deposits within Cretaceous strata, based on abundant Cretaceous DZs (Dumitru et al., 2015, 2018). Thus, the presence of *Buchia*, in the absence of other age-diagnostic fossils, may not be a reliable age constraint.

Surpless et al. (2006) collected seven samples from documented *Buchia* localities of Jones et al. (1969) within basal GVG strata. Although each sample included only 17–45 Mesozoic zircon grains, Cretaceous zircon composed >5% in each. Another sample from GVG strata mapped as Tithonian also contained ~5% Cretaceous zircon (Surpless, 2014). These ages suggest Early Cretaceous rather than Late Jurassic initiation of basal GVG sedimentation. Given contradictory DZ and biostratigraphic age constraints, we seek to clarify the timing of deposition of the basal GVG.

## METHODS AND RESULTS

We collected 20 medium-grained sandstone samples from strata in four study regions mapped as "Jurassic marine" (Fig. 1; Jennings et al., 1977), including known *Buchia* localities identified by Jones et al. (1969). All samples are within mapped "Jurassic" strata, <1–4.3 km from the CRO contact. We analyzed 11 samples using laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) following the methods of Gehrels et al. (2008) and Gehrels and Pecha (2014), and nine samples using sensitive high-resolution ion microprobe–reverse geometry (SHRIMP-RG) following the methods of DeGraaff-Surpless et al. (2002) (see Tables DR1 and DR2 in the GSA Data Repository[1]).

We used the detritalPy software toolset (Sharman et al., 2018) to calculate the MDA for each sample (File DR3). Dickinson and Gehrels (2009) demonstrated the utility of DZs for calculating MDAs in retroarc samples, noting that the youngest single grain corresponded to the true depositional age (TDA) 90% of the time. Coutts et al. (2019) found that the method of using the youngest cluster of three or more grains that overlap within 2σ uncertainty [YC2σ(3+)], which we apply here, is the most conservative in that it produces ages that are equal to or older than TDAs, but not younger than TDAs. Our forearc samples are likely to yield MDAs similar to TDAs, given their proximity to the Sierra Nevada–Klamath magmatic arc and application of $n = 300$ in 11 of 20 samples; however, because we use YC2σ(3+) rather than less-conservative methods (Coutts et al., 2019), our calculated MDAs may be older than TDA. Although 18 of 20 samples contain Cretaceous zircon, only nine samples yield robust Cretaceous MDAs, which range from 135.44 ± 0.19 to 144.37 ± 0.57 Ma (Fig. 1). Eleven samples yield Jurassic MDAs that range from 145.82 ± 0.38 to 153.34 ± 0.97 Ma (Fig. 1). Samples with Cretaceous or Jurassic MDAs are interspersed along strike in the basal GVG (Fig. 1).

We obtained LA-ICP-MS U-Pb ages from two CRO samples adjacent to the stratigraphically deepest forearc strata (Fig. 1; Table DR1 and Fig. DR1). At Grindstone Creek, titanite separated from a gabbro block in serpentinite located at the contact between the CRO and GVG yielded a U-Pb age of 166.6 ± 4.5 Ma. At the McLaughlin Reserve, we obtained a zircon U-Pb age of 163.6 ± 2.0 Ma from a plagiogranite 2 km from the upper contact of the CRO.

## DISCUSSION AND CONCLUSIONS

We interpret the nine samples that yield robust Cretaceous MDAs as Lower Cretaceous, rather than Upper Jurassic. Of the remaining 11 samples, two have robust MDAs that overlap the 145 ± 0.8 Ma (Ogg and Hinnov, 2012) Jurassic-Cretaceous boundary (145.88 ± 0.86 and 145.82 ± 0.38 Ma), suggesting earliest Cretaceous deposition, and nine have robust Late Jurassic MDAs from 147.76 ± 0.59 to 153.34 ± 0.97 Ma. If these MDAs approximate TDAs, our results document diachronous initiation of sedimentation in the Great Valley forearc during Late Jurassic to Early Cretaceous time.

Using published and new ages for the CRO from our four study regions, the duration of the unconformity between CRO formation and GVG deposition varies along strike, from ≤15 m.y. to ≤23 m.y.. The contact between the CRO and GVG is depositional at Elder Creek, but faulted at the other three localities; uncertainty in the estimated unconformity duration results from the potential removal of section by faulting and the location of our lowest GVG samples as much as 1.8 km above the basal contact. Samples in all areas are well within mapped "Jurassic" strata, requiring revision of the age of the GVG strata at these locations. Our titanite U-Pb age of ca. 166 Ma from the uppermost CRO at Grindstone Creek and zircon U-Pb age of ca. 164 Ma near the top of the CRO at the McLaughlin Reserve are consistent with the age for CRO formation in the Sacramento Valley segment of the forearc (e.g., Shervais et al., 2004).

We interpret the estimated duration of the unconformity as resulting from sediment starvation following formation of ophiolitic basement in either a forearc or backarc setting. DZ data from the oldest Franciscan metagreywacke yield MDAs of ca. 144 Ma (Dumitru et al., 2010; Snow et al., 2010), indicating a lack of significant Franciscan trench sedimentation prior to ca. 144 Ma. Many forearc systems switch between non-accretionary and accretionary during their life cycles (e.g., Noda, 2016), and Dumitru et al. (2010) interpreted this margin as predominantly accretionary beginning ca. 123 Ma. The absence of an accretionary outer forearc high prior to ca. 123 Ma suggests that a different mechanism was responsible for trapping the latest Jurassic–earliest Cretaceous sediments.

Extension in the forearc region, combined with thermal relaxation of newly formed oceanic crust and/or subduction erosion processes, can drive development of accommodation space (von Heune and Scholl, 1991; Fildani et al., 2008; Dewey and Casey, 2011). We suggest that latest Jurassic–Early Cretaceous extension of the Great Valley forearc resulted in deep, isolated, fault-bounded depocenters that accumulated sediment at different times, consistent with previous interpretations of extension during the early stages of GVG sedimentation (Constenius et al., 2000; Hitz and Wakabayashi, 2012). Hitz and Wakabayashi (2012) suggested that serpentinite deposits within the Franciscan Complex and basal GVG formed during 150–135 Ma extension and diapirism in the forearc region. Similar deposits are observed along extensional faults in the modern Marianas forearc (Fryer et al., 2000).

GVG samples with Jurassic MDAs have 55% pre-Mesozoic grains, and the oldest Franciscan metagraywackes with 144 Ma MDAs have 42% pre-Mesozoic grains (Dumitru et al., 2010; Snow et al., 2010), suggesting significant input from the continental interior at the onset of sedimentation. A comparison of the pre-Mesozoic DZ signature of our samples with that of a compilation of coeval retroarc strata in the conterminous United States (Laskowski et al., 2013, and references therein; Fig. 2) suggests

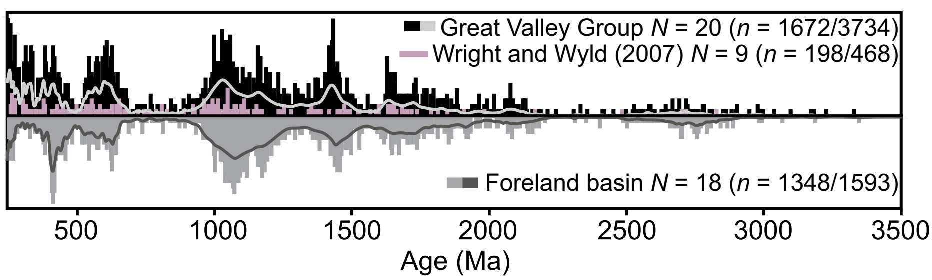


**Figure 2. Histogram and probability distribution plots of Great Valley Group (California, USA) samples from this study (black and light gray, respectively) and Wright and Wyld (2007; pink) mirrored with histogram and probability distribution plots of Kimmeridgian through Hauterivian foreland basin samples compiled by Laskowski et al. (2013; gray and dark gray, respectively); specific foreland data sources are given in the Data Repository (see footnote 1). *N* is the total number of samples, and *n* is the subset of U-Pb ages in each plot shown as a function of the total number of U-Pb ages in each sample.**

[1]GSA Data Repository item 2019269, LA-ICP-MS data, SHRIMP-RG data, table of maximum depositional ages, weighted mean ages of igneous samples, and foreland basin compilation, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

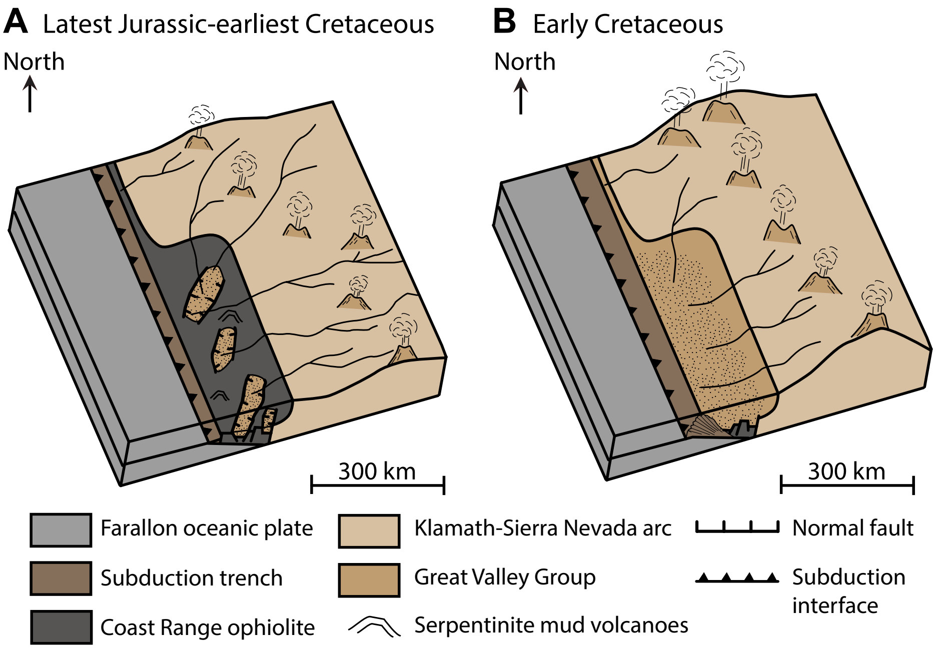


**Figure 3. Simplified tectonic model for early stages of Great Valley forearc basin development (California, USA). A: Latest Jurassic–earliest Cretaceous sedimentation in fault-bounded sub-basins with provenance in both proximal Sierra Nevada–Klamath arc system and interior of North America. B: Early Cretaceous sedimentation in more coherent forearc basin with dominantly proximal arc provenance.**

shared North American sources. Pre-Mesozoic DZs from the oldest Franciscan metagreywackes suggest similar provenance (Dumitru et al., 2010; Snow et al., 2010). Wright and Wyld (2007) inferred that Precambrian DZs from the basal GVG were derived from sources in the southwestern Cordillera and the Oaxaca terrane of Mexico, suggesting that Late Jurassic–earliest Cretaceous deposition occurred in a basin located ~400 km south of the Great Valley basin's current position. Specifically, Wright and Wyld (2007) interpreted the absence of a ca. 1200 Ma DZ component in their compilation as missing a Grenville-age population necessary to tie the GVG to central North America. Our basal GVG zircon data include the 1000–1200 Ma Grenville signature (Fig. 2). Thus, we infer that Wright and Wyld's (2007) analysis was compromised by their relatively small data set ($n = 198$) and that the GVG does not require southern provenance.

Taken together, our age and provenance data from basal GVG strata support a model in which the latest Jurassic to Early Cretaceous forearc system was largely extensional, consistent with previous interpretations of seismic reflection profiles and gravity modeling that indicate that as much as 7 km of Late Jurassic to Early Cretaceous deposition occurred within accommodation space created by synsedimentary normal-fault systems (Constenius et al. 2000). In this setting, preservation of latest Jurassic strata within the underfilled forearc would have occurred only in structurally controlled sub-basins (Fig. 3). DZ ages from the oldest strata would record a mix of Triassic and Jurassic arc magmatism as well as a significant component of pre-Mesozoic basement. With a shift to an accretionary margin in mid–Early Cretaceous time and contemporaneous growth of the magmatic arc (e.g., Paterson and Ducea, 2015), the outer forearc high would have ponded the increased sediment volume within a more coherent forearc system (Fig. 3). GVG DZ signatures from Cretaceous strata would be dominated by Mesozoic arc ages, with relatively fewer pre-Mesozoic grains (e.g., Sharman et al., 2015). Our DZ data document this shift in relative source abundance, as samples with Jurassic MDAs have 55% pre-Mesozoic grains, whereas Cretaceous samples have 37%. Moreover, our depositional age revisions nearly double the thickness of Lower Cretaceous GVG strata, consistent with increased Cretaceous sedimentation rates and arc unroofing.

Our study highlights the utility of large-$n$ DZ analysis to reconstruct the early stages of forearc sedimentation, including the development of isolated depositional centers, and improves our understanding of the Mesozoic development of the central-western margin of North America. Other continental forearc basins, such as the Lancones, Talara, Sechura, and Tumbes basins of Peru, show similar diachroneity and fragmented depositional centers at basin inception, followed by the development of more coherent basin fill (e.g., Fildani et al., 2008; Hessler and Fildani, 2015). Similarly, in island arc–forearc systems such as Sumatra-Java, isolated basins are structurally controlled by basement highs (e.g., Kopp et al. 2002). Thus, this "fill-and-spill" evolution may be more common in forearc systems than has been previously recognized, and the Great Valley forearc provides an excellent ancient onshore example.

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**REFERENCES CITED**

Bailey, E.H., Blake, M.C., Jr., and Jones, D.L., 1970, On-land Mesozoic oceanic crust in California Coast Ranges, *in* Geological Survey Research 1970, Chapter C: U.S. Geological Survey Professional Paper 700-C, p. C70–C81.

Bralower, T.J., 1990, Lower Cretaceous calcareous nannofossil stratigraphy of the Great Valley Sequence, Sacramento Valley, California: Cretaceous Research, v. 11, p. 101–123, https://doi.org/10.1016/S0195-6671(05)80029-1.

Constenius, K.N., Johnson, R.A., Dickinson, W.R., and Williams, T.A., 2000, Tectonic evolution of the Jurassic–Cretaceous Great Valley forearc, California: Implications for the Franciscan thrust-wedge hypothesis: Geological Society of America Bulletin, v. 112, p. 1703–1723, https://doi.org/10.1130/0016-7606(2000)112<1703:TEOTJC>2.0.CO;2.

Coutts, D.S., Matthews, W.A., and Hubbard, S.M., 2019, Assessment of widely used methods to derive depositional ages from detrital zircon populations: Geoscience Frontiers, https://doi.org/10.1016/j.gsf.2018.11.002 (in press).

DeGraaff-Surpless, K., Graham, S.A., Wooden, J.L., and McWilliams, M.O., 2002, Detrital zircon provenance analysis of the Great Valley Group, California: Evolution of an arc-forearc system: Geological Society of America Bulletin, v. 114, p. 1564–1580, https://doi.org/10.1130/0016-7606(2002)114<1564:DZPAOT>2.0.CO;2.

Dewey, J.F., and Casey, J.F., 2011, The origin of obducted large-slab ophiolite complexes, *in* Brown D., and Ryan, P.D., eds., Arc-Continent Collision (Frontiers in Earth Sciences): Berlin, Heidelberg, Springer-Verlag, https://doi.org/10.1007/978-3-540-88558-0_15.

Dickinson, W.R., 1995, Forearc basins, *in* Busby, C.J., and Ingersoll, R.V., eds., Tectonics of Sedimentary Basins: Cambridge, Massachusetts, Blackwell, p. 221–261.

Dickinson, W.R., and Gehrels, G.E., 2009, Use of U-Pb ages of detrital zircons to infer maximum depositional ages of strata: A test against a Colorado Plateau Mesozoic database: Earth and Planetary Science Letters, v. 288, p. 115–125, https://doi.org/10.1016/j.epsl.2009.09.013.

Dickinson, W.R., Hopson, C.A., and Saleeby, J.B., 1996, Alternate origins of the Coast Range Ophiolite (California): Introduction and implications: GSA Today, v. 6, no. 2, p. 1–9.

Dumitru, T.A., Wakabayashi, J., Wright, J.E., and Wooden, J.L., 2010, Early Cretaceous transition from nonaccretionary behavior to strongly accretionary behavior within the Franciscan subduction complex: Tectonics, v. 29, TC5001, https://doi.org/10.1029/2009TC002542.

Dumitru, T.A., Ernst, W.G., Wright, J.E., Wooden, J.L., Wells, R.E., Farmer, L.P., Kent, A.J.R., and

Graham, S.A., 2012, Eocene extension in Idaho generated massive sediment floods into the Franciscan trench and into the Tyee, Great Valley, and Green River basins: Geology, v. 41, p. 187–190, https://doi.org/10.1130/G33746.1.

Dumitru, T.A., Ernst, W.G., Hourigan, J.K., and McLaughlin, R.J., 2015, Detrital zircon U-Pb reconnaissance of the Franciscan subduction complex in northwestern California: International Geology Review, v. 57, p. 767–800, https://doi.org/10.1080/00206814.2015.1008060.

Dumitru, T.A., Hourigan, J.K., Elder, W.P., Ernst, W.G., and Joesten, R., 2018, New, much younger ages for the Yolla Bolly terrane and a revised time line for accretion in the Franciscan subduction complex, California, *in* Ingersoll, R.V., et al., eds., Tectonics, Sedimentary Basins, and Provenance: A Celebration of the Career of William R. Dickinson: Geological Society of America Special Paper 540, p. 339–366, https://doi.org/10.1130/2018.2540(15).

Ernst, W.G., 1970, Tectonic contact between the Franciscan mélange and the Great Valley sequence: Crustal expression of a late Mesozoic Benioff zone: Journal of Geophysical Research, v. 75, p. 886–901, https://doi.org/10.1029/JB075i005p00886.

Fildani, A., Hessler, A.M., and Graham, S.A., 2008, Trench-forearc interactions reflected in the sedimentary fill of Talara basin, northwest Peru: Basin Research, v. 20, p. 305–331, https://doi.org/10.1111/j.1365-2117.2007.00346.x.

Fryer, P., Lockwood, J.P., Becker, N., Phipps, S., and Todd, C.S., 2000, Significance of serpentine mud volcanism in convergent margins, *in* Dilek, Y., et al., eds., Ophiolites and Oceanic Crust: New Insights from Field Studies and the Ocean Drilling Program: Geological Society of America Special Paper 349, p. 35–51, https://doi.org/10.1130/0-8137-2349-3.35.

Gehrels, G.E., and Pecha, M., 2014, Detrital zircon U-Pb geochronology and Hf isotope geochemistry of Paleozoic and Triassic passive margin strata of western North America: Geosphere, v. 10, p. 49–65, https://doi.org/10.1130/GES00889.1.

Gehrels, G.E., Valencia, V.A., and Ruiz, J., 2008, Enhanced precision, accuracy, efficiency, and spatial resolution of U-Pb ages by laser ablation–multicollector–inductively coupled plasma–mass spectrometry: Geochemistry Geophysics Geosystems, v. 9, Q03017, https://doi.org/10.1029/2007GC001805.

Hessler, A.M., and Fildani, A., 2015, Andean forearc dynamics, as recorded by detrital zircon from the Eocene Talara basin, northwest Peru: Journal of Sedimentary Research, v. 85, p. 646–659, https://doi.org/10.2110/jsr.2015.45.

Hessler, A.M., and Sharman, G.R., 2018, Subduction zones and their hydrocarbon systems: Geosphere, v. 14, p. 2044–2067, https://doi.org/10.1130/GES01656.1.

Hitz, B., and Wakabayashi, J., 2012, Unmetamorphosed sedimentary mélange with high-pressure metamorphic blocks in a nascent forearc basin setting: Tectonophysics, v. 568–569, p. 124–134, https://doi.org/10.1016/j.tecto.2011.12.006.

Imlay, R.W., and Jones, D.L., 1970, Ammonites from the *Buchia* zones in northwestern California and southwestern Oregon: U.S. Geological Survey Professional Paper 647-B, 55 p., https://doi.org/10.3133/pp647B.

Ingersoll, R.V., 1979, Evolution of the Late Cretaceous forearc basin, northern and central California: Geological Society of America Bulletin, v. 90, p. 813–826, https://doi.org/10.1130/0016-7606(1979)90<813:EOTLCF>2.0.CO;2.

Ingersoll, R.V., 1983, Petrofacies and provenance of late Mesozoic forearc basin, northern and central California: American Association of Petroleum Geologists Bulletin, v. 67, p. 1125–1142.

Ingersoll, R.V., 2000. Models for origin and emplacement of Jurassic ophiolites of Northern California, *in* Dilek, Y., et al., eds., Ophiolites And Oceanic Crust: New Insights from Field Studies and the Ocean Drilling Program: Geological Society of America Special Paper 349: p. 395–402, https://doi.org/10.1130/0-8137-2349-3.395.

Ingersoll, R.V., 2008, Subduction-related sedimentary basins of the USA Cordillera, *in* Miall, A.D. ed., The Sedimentary Basins of the United States and Canada: Amsterdam, Elsevier, Sedimentary Basins of the World, v. 5, p. 395–428, https://doi.org/10.1016/S1874-5997(08)00011-7.

Ingersoll, R.V., 2019, Forearc strike-slip displacement as an alternative to subduction erosion, with examples from Mexico and California (sinistral Nacimiento fault): Canadian Journal of Earth Sciences (in press).

Jennings, C.W., Strand, R.G., and Rogers, T.H., 1977, Geologic map of California: California Division of Mines and Geology, scale 1:750,000.

Jones, D.L., Bailey, E.H., and Imlay, R.W., 1969, Structural and stratigraphic significance of the *Buchia* zones in the Colyear Springs–Paskenta area, California: U.S. Geological Survey Special Paper 647-A, 21 p.

Kopp, H., Klaeschen, D., Flueh, E.R., Bilas, J., and Reichert, C., 2002, Crustal structure of the Java margin from seismic wide-angle and multichannel reflection data: Journal of Geophysical Research, v. 107, https://doi.org/10.1029/2000JB000095.

Laskowski, A.K., DeCelles, P.G., and Gehrels, G.E., 2013, Detrital zircon geochronology of Cordilleran retroarc foreland basin strata, western North America: Tectonics, v. 32, p. 1027–1048, https://doi.org/10.1002/tect.20065.

Linn, A.M., DePaolo, D.J., and Ingersoll, R.V., 1992, Nd-Sr isotopic, geochemical, and petrographic stratigraphy and paleotectonic analysis: Mesozoic Great Valley forearc sedimentary rocks of California: Geological Society of America Bulletin, v. 104, p. 1264–1279, https://doi.org/10.1130/0016-7606(1992)104<1264:NSIGAP>2.3.CO;2.

Mulcahy, S.R., Starnes, J.K., Day, H.W., Coble, M.A., and Vervoort, J.D., 2018, Early onset of Franciscan subduction: Tectonics, v. 37, p. 1194–1209, https://doi.org/10.1029/2017TC004753.

Noda, A., 2016, Forearc basins: Types, geometries, and relationships to subduction zone dynamics: Geological Society of America Bulletin, v. 128, p. 879–895, https://doi.org/10.1130/B31345.1.

Ogg, J.G., and Hinnov, L.A., 2012, Jurassic, *in* Gradstein, F.M., et al., eds, The Geologic Time Scale 2012, First Edition: Amsterdam, Elsevier, p. 731–791, https://doi.org/10.1016/B978-0-444-59425-9.00026-3.

Paterson, S.R., and Ducea, M.N., 2015, Arc magmatic tempos: Gathering the evidence: Elements, v. 11, p. 91–98, https://doi.org/10.2113/gselements.11.2.91.

Pessagno, E.A., Jr., 1977, Upper Jurassic Radiolaria and radiolarian biostratigraphy of the California Coast Ranges: Micropaleontology, v. 23, p. 56–113, https://doi.org/10.2307/1485310.

Saleeby, J.B., 1996, Coast Range ophiolite as parautochthonous forearc lithosphere: GSA Today, v. 6, no. 2, p. 6–8.

Schweickert, R.A., 2015, Jurassic evolution of the Western Sierra Nevada metamorphic province, *in* Anderson, T.H., et al., eds., Late Jurassic Margin of Laurasia—A Record of Faulting Accommodating Plate Rotation: Geological Society of America Special Paper 513, p. 299–358, https://doi.org/10.1130/2015.2513(08).

Schweickert, R.A., and Cowan, D.S., 1975, Early Mesozoic tectonic evolution of the western Sierra Nevada, California: Geological Society of America Bulletin, v. 86, p. 1329–1336, https://doi.org/10.1130/0016-7606(1975)86<1329:EMTEOT>2.0.CO;2.

Sharman, G.R., Graham, S.A., Grove, M., Kimbrough, D.L., and Wright, J.E., 2015, Detrital zircon provenance of the Late Cretaceous–Eocene California forearc: Influence of Laramide low-angle subduction on sediment dispersal and paleogeography: Geological Society of America Bulletin, v. 127, p. 38–60, https://doi.org/10.1130/B31065.1.

Sharman, G.R., Sharman, J.P., and Sylvester, Z., 2018, detritalPy: A Python-based toolset for visualizing and analysing detrital geo-thermochronologic data: The Depositional Record, v. 4, p. 202–215, https://doi.org/10.1002/dep2.45.

Shervais, J.W., 2001, Birth, death and resurrection: The life cycle of suprasubduction zone ophiolites: Geochemistry, Geophysics, Geosystems, v. 2, 1010, https://doi.org/10.1029/2000GC000080.

Shervais, J.W., Kimbrough, D.L., Renne, P., Hanan, B.B., Murchey, B., Snow, C.A., Zoglman Schuman, M.M., and Beaman, J., 2004, Multistage origin of the Coast Range ophiolite, California: Implications for the life cycle of supra-subduction zone ophiolites: International Geology Review, v. 46, p. 289–315, https://doi.org/10.2747/0020-6814.46.4.289.

Snow, C.A., Wakabayashi, J., Ernst, W.G., and Wooden, J.L., 2010, Detrital zircon evidence for progressive underthrusting in Franciscan metagraywackes, west-central California: Geological Society of America Bulletin, v. 122, p. 282–291, https://doi.org/10.1130/B26399.1.

Surpless, K.D., 2014, Geochemistry of the Great Valley Group: An integrated provenance record: International Geology Review, v. 57, p. 747–766, https://doi.org/10.1080/00206814.2014.923347.

Surpless, K.D., Graham, S.A., Covault, J.A., and Wooden, J.L., 2006, Does the Great Valley Group contain Jurassic strata? Reevaluation of the age and early evolution of a classic forearc basin: Geology, v. 34, p. 21–24, https://doi.org/10.1130/G21940.1.

von Heune, J.C., and Scholl, D.W., 1991, Observations at convergent margins concerning sediment subduction, subduction erosion, and the growth of continental crust: Reviews of Geophysics, v. 29, p. 279–316, https://doi.org/10.1029/91RG00969.

Wakabayashi, J., 1992, Nappes, tectonics of oblique plate convergence, and metamorphic evolution related to 140 million years of continuous subduction, Franciscan Complex, California: The Journal of Geology, v. 100, p. 19–40, https://doi.org/10.1086/629569.

Wakabayashi, J., 2015, Anatomy of a subduction complex: Architecture of the Franciscan Complex, California, at multiple length and time scales: International Geology Review, v. 57, p. 669–746, https://doi.org/10.1080/00206814.2014.998728.

Wright, J.E., and Wyld, S.J., 2007, Alternative tectonic model for Late Jurassic through Early Cretaceous evolution of the Great Valley Group, California, *in* Cloos, M., et al., eds., Convergent Margin Terranes and Associated Regions: A Tribute to W.G. Ernst: Geological Society of America Special Paper 419, p. 81–95, https://doi.org/10.1130/2007.2419(04).

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