Research Article

Cordilleran Subduction Initiation: Retroarc Timing and Basinal Response in the Inyo Mountains, Eastern California

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1. Introduction

Sedimentary records of subduction initiation are generally poorly preserved because of erosion, deformation, and overprinting by later magmatism, but preserved records can provide valuable insight into the timing and mechanisms of the transition from a previous tectonic regime to subduction [1–4]. The western margin of Laurentia transitioned from a transform to a convergent boundary with an offshore subduction zone in the early Permian time (e.g., [5, 6]; Figure 1). Arc magmatism was previously thought to have begun in the early Triassic time at ca. 250 Ma, due to exposure of arc plutons of that age in eastern California [7–9], and at ca. 255 Ma Sm/Nd age from the Kings Kaweah ophiolite that is interpreted to represent metamorphism along the subduction interface during early subduction [6]. More recent ages from plutons in Sonora, Mexico, and the El Paso terrane in southeastern California record local earliest arc magmatism at ca. 275 Ma ([10–13]; Figure 1). The precise timing of subduction initiation, however, is uncertain, and the structural and sedimentological responses to the change in tectonic regime remain incompletely understood.

The Inyo Mountains in eastern California are a rare location in which Permian strata contain detrital zircon that crystallized in the early Cordilleran arc ([14]; Figure 1). Permian rocks in the Inyo Mountains have been biostratigraphically dated as Asselian (lowest Permian) through Wuchiapingian (late Permian) (ca. 299-254 Ma; Figure 2). Stratigraphic and structural mapping suggests that Permian strata were deposited in the framework of contractional tectonism that was...
California-Coahuila transform system

Major faults

Permian plutons

30° 32° 34° 36° 38° 40°
−122° −120° −118° −116° −114° −112°

Mojave desert

LA

AZ

SAF

Craton hinge line

CCT

CA

BC

SO

500 km

Inyo Mountains:
Lone Pine Basin

Inyo Mountains:
Darwin Basin

Permian plutons

Paleozoic facies belts

Island arc
Slope-abyssal
Shelf-terrestrial

Figure 1: Location and tectonic setting of the Inyo Mountains showing major tectonic elements and Paleozoic facies belts. Most features are shown in their present location; the California-Coahuila transform (CCT) is shown in its reconstructed Pennsylvanian-Permian position with two parallel strands. Inset: map of the Inyo Mountains showing the Lone Pine Basin and Darwin Basin field areas with locations of measured sections and detrital zircon samples, the approximate extent of strands of the Last Chance thrust system (LCT) east and west of the field area, and the approximate location of the Conglomerate Mesa Uplift (CMU) that separated the Lone Pine and Darwin Basins. SAF = San Andreas Fault; CA = California; AZ = Arizona; BC = Baja California, Mexico; SO = Sonora, Mexico; LA = Los Angeles. Adapted from Dickinson [8], Dickinson and Lawton [36], Stevens and Stone [42], Arvizu et al. [10], Chapman et al. [82], and Cecil et al. [12].
likely related to subduction initiation [15–17] and during the earliest arc magmatism [14], in the location of the future back-arc, or “proto-back-arc.” As such, Inyo Mountain strata contain unique information on the proto-back-arc basinal response to the transition to subduction and earliest magmatism. Here, we employ detrital zircon geochronology and geochemistry, stratigraphy, lithostratigraphy, and sandstone petrography to decipher the depositional setting and provenance of the late Artinskian and younger Permian sedimentary rocks, the timing of initial Cordilleran arc magmatism, and the tectonic history and the architecture of Permian basins in the Inyo Mountains. These data enhance understanding of the timing of subduction initiation, earliest magmatism, and basin development in response to early subduction-related contraction.

1.1. The Inyo Mountains. The Inyo Mountains are a narrow, northwest-trending fault block roughly 20 km east of the Sierra Nevada, at the western edge of the Basin and Range physiographic province in eastern California (Figure 1). Early Cretaceous dextral displacements (up to 400 km) within the current Sierra Nevada likely translated western terranes to the north, placing the Permo-Triassic Inyo Mountains basin several hundred kilometers closer to the Klamath Mountains and western Sierra Nevada terranes [18–22]. The Inyo Mountains contain extensive outcrops of locally metamorphosed and structurally complex sedimentary rocks that range from Neoproterozoic to early Triassic in age [16, 23]. Late Precambrian to early-middle Paleozoic Inyo Mountain strata represent the southwesternmost preserved portion of the northeast-trending Cordilleran passive margin ([15, 24, 25]; Figure 1).

Permain marine strata accumulated in the Lone Pine and Darwin Basins of the northwestern and southeastern Inyo Mountains, respectively, which were separated by a paleotopographic ridge termed the Conglomerate Mesa Uplift by Stevens et al. ([15, 26]; Figures 1 and 3). Strata in the Lone Pine Basin consist of Lone Pine Formation members A, B, C, and D [16]. Approximately coeval strata in the Darwin Basin consist of the sedimentary rocks of Santa Rosa Flat units 1–12 [17]. Both sequences are overlain by the late Permian to early Triassic (?) Conglomerate Mesa Formation. The Reward Conglomerate, interpreted to be the uppermost member of the Lone Pine Formation by Stone et al. [16], is here reinterpreted as likely correlative with the Conglomerate Mesa Formation, based on Late Permian detrital zircon ages from both units reported here and by Riggs et al. [14] that differ from new, exclusively pre-Permian detrital zircon ages from the underlying strata. The Conglomerate Mesa Formation is overlain by the regionally widespread, early to middle (?) Triassic Union Wash Formation [16, 27].

Strata in the Lone Pine and Darwin Basins pinch out against the flanks of the Conglomerate Mesa Uplift, which experienced deformation and uplift throughout the early and middle Permian time ([16, 23]; Figure 3). This deformation is inferred from folds at several stratigraphic levels in the Darwin Basin section [17]. The Pennsylvanian to Early Permian Keeler Canyon Formation [28, 29] underlies both basins and is exposed at the crest of the uplift, where it is unconformably overlain by the Union Wash Formation [17]. Sakmarian fusulinids in the basal strata of both basins constrain the timing of uplift initiation to ca. 295–290 Ma ([16, 17, 23]; Figure 2).
1.2. Tectonic Regime Change. During the Neoproterozoic to Late Devonian time, the west coast of Laurentia was a northeast-trending passive margin that is represented by thick sequences of marine sedimentary rocks [8, 30, 31]. Passive margin sedimentation was interrupted by a series of tectonic and magmatic events in western Laurentia, including the Late Devonian to Mississippian Antler orogeny in present-day Nevada, which resulted in an uplifted marginal thrust complex and a deep foreland basin to the east, and the offshore McCloud arc system in present-day northern California [6, 8, 9, 32–35]. In the Pennsylvanian to early Permian time, a northwest-striking, left-lateral transform fault, called the California-Coahuila transform by Dickinson [8], is hypothesized to have truncated the passive margin, cutting across earlier Paleozoic depositional and structural trends ([9, 25, 30, 36–38]; Figure 1). Strike-slip truncation is also recorded by metamorphic strike-slip ribbons that were transpressively accreted along the truncation zone in the Pennsylvanian-Permian time, inboard (east) of the Foothills ophiolite belt [6].

Between early Permian and Triassic times, the strike-slip boundary transitioned into a northwest-trending subduction zone with an active magmatic arc [6, 7, 9, 12, 39, 40]. Initial convergence involved several thrusting events along the western margin of the continent, including the Last Chance thrust (Figure 1), which developed as a northeast-trending ramp-flat thrust with a regional decollement that extended southeastward beneath the Lone Pine Basin to the edge of the Mississippian platform [41, 42]. Alternatively, if the California-Coahuila transform was transpressional [43], the Last Chance thrust may have been caused by the contractional component of strain partitioning in the California-Coahuila transform [44, 45]. The Last Chance thrust has been interpreted to have potentially formed the boundary of the northeast-trending Conglomerate Mesa Uplift [17, 42]. Continental strike-slip truncation, convergence, and early magmatism set the tectonic framework for the development of the Lone Pine and Darwin Basins throughout Permian time.

2. Methods

2.1. Stratigraphy and Lithofacies Analysis. Eight stratigraphic sections (Figures 4(a)–(h)) were measured in the Lone Pine and Darwin Basins at locations where the strata are well exposed, upright, and structurally simple (Figure 1). The Lone Pine Basin composite section begins in the upper part of Lone Pine Formation member A/B combined; the Darwin Basin composite section begins at the base of Santa Rosa Flat unit 7 (Figure 5). Units were characterized and distinguished by grain size, lithology, sedimentary structures and textures, inferred depositional process, and interpreted depositional environment. Detailed stratigraphic and lithofacies analysis can be found in Lodes [46].

2.2. Detrital Zircon U-Pb Geochronology and Geochemistry. Twelve 10 kg samples of sandy lithofacies were collected in Inyo Mountain strata for detrital zircon analysis (Table 1). Samples were crushed and zircon crystals extracted using standard heavy mineral and magnetic separation methods (e.g., [47]). Detrital zircon grains (150-200 per sample) were analyzed for U-Th-Pb and trace element concentrations at the University of California Santa Barbara (UCSB) laser-ablation split-stream petrochronology lab using a Photon Machines 193 nm excimer laser with a HeLex sample cell with a 20-25-micrometer beam, coupled to either a Nu Instruments Plasma high-resolution multicollector inductively coupled mass spectrometer or a Nu Instruments AttoM high-resolution single-collector ICPMS for U and Pb isotope analysis and an Agilent 7700x quadrupole ICPMS for measurement of trace element concentrations.
U-Pb and trace element analyses in June 2017 were calibrated using the 91500 zircon standard (1062.4 ± 0.4 Ma; [48]) placed every 10 grains, the Plesovice zircon standard (337.71 ± 0.37 Ma; [49]) for the first three grains and then every 40 grains, and the GJ-1 zircon standard (601.9 ± 0.7 Ma; [50]) placed every 20 grains, with an analysis run always ending with 91500 and GJ-1. Samples analyzed in October 2017 were calibrated using 91500 every 10 grains, the glass standard BHVO as the first four analyses, GJ-1 every 20 grains, Plesovice every 60 grains, the Piexe zircon standard (564 Ma; [51]) every 60 grains, and the Mud Tank zircon standard (730 ± 12 Ma; [52]) every 60 grains. Our values for
Figure 5: Summary stratigraphic sections of the Lone Pine and Darwin Basins. Black vertical lines indicate detailed sections (see Figure 4). The x-axis denotes grain size subdivisions. Plba was not measured in its entirety, as the base was covered.
Table 1: Sample names, formations, units, and locations (latitude, longitude). R = Reward Conglomerate. Coordinate system is WGS 84, except for samples 7-30-14-2 and 7-30-14-3, which use NAD 27. *Sample is from Leary et al. [57].

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Unit</th>
<th>Lat (‘N)</th>
<th>Location (‘W)</th>
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<tr>
<td>Lone Pine Formation</td>
<td>A/B</td>
<td>36.78583</td>
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<tr>
<td>12-02-16-1*</td>
<td>C</td>
<td>36.80974</td>
<td>-118.1102’</td>
</tr>
<tr>
<td>10-11-15-1*</td>
<td>C</td>
<td>36.72577</td>
<td>-118.0385’</td>
</tr>
<tr>
<td>12-03-16-1*</td>
<td>C</td>
<td>36.72251</td>
<td>-118.0359’</td>
</tr>
<tr>
<td>12-03-16-2*</td>
<td>D</td>
<td>36.7259’</td>
<td>-118.0398’</td>
</tr>
<tr>
<td>12-03-16-4*</td>
<td>D</td>
<td>36.77753</td>
<td>-118.0691’</td>
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Sedimentary rocks of Santa Rosa Flat

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Unit</th>
<th>Lat (‘N)</th>
<th>Location (‘W)</th>
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<tbody>
<tr>
<td>6-23-17-1</td>
<td>9</td>
<td>36.48858</td>
<td>-117.7331’</td>
</tr>
<tr>
<td>6-28-17-2</td>
<td>10</td>
<td>36.4886’</td>
<td>-117.7324’</td>
</tr>
<tr>
<td>10-12-15-3*</td>
<td>11</td>
<td>36.48521</td>
<td>-117.7355’</td>
</tr>
<tr>
<td>6-28-17-1</td>
<td>11</td>
<td>36.48890</td>
<td>-117.7323’</td>
</tr>
<tr>
<td>6-20-17-3*</td>
<td>12a</td>
<td>36.51592</td>
<td>-117.7334’</td>
</tr>
<tr>
<td>6-20-17-4*</td>
<td>12a</td>
<td>36.51611</td>
<td>-117.7332’</td>
</tr>
</tbody>
</table>

Conglomerate Mesa Fm. and Reward Conglomerate

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Unit</th>
<th>Lat (‘N)</th>
<th>Location (‘W)</th>
</tr>
</thead>
<tbody>
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<td>10-12-15-1</td>
<td>C</td>
<td>36.48797</td>
<td>-117.7406’</td>
</tr>
<tr>
<td>7-30-14-2</td>
<td>C</td>
<td>36.72827</td>
<td>-118.0477’</td>
</tr>
<tr>
<td>7-30-14-3</td>
<td>R</td>
<td>36.73842</td>
<td>-118.0551’</td>
</tr>
<tr>
<td>Tr_Reward</td>
<td>R</td>
<td>36.73836</td>
<td>-118.0553’</td>
</tr>
</tbody>
</table>

3. Results

3.1. Stratigraphy and Lithofacies. The Lone Pine Formation (members A-D) and the Reward Conglomerate in the Lone Pine Basin and units 7-12 of the sedimentary rocks of Santa Rosa Flat in the Darwin Basin are ~1 km and ~2 km thick, respectively (Figures 4 and 5). Members A and B of the Lone Pine Formation are difficult to separate in the sections studied so are here combined into a single unit termed member A/B. Units 1–6 of the sedimentary rocks of Santa Rosa Flat were not investigated; they are calcareous siltstones, sandstones, and conglomerates containing Wolfcampian fusulinids, interpreted to have been deposited mostly in a deep marine setting by turbidity currents [17]. Details of each stratigraphic member or unit are provided in Table 2. Units in the Lone Pine and Darwin Basins are here broken into “slope/basinal,” “shelf,” and “fluvial” lithofacies associations. The slope/basinal lithofacies association includes Lone Pine Formation member A/B and sedimentary rocks of Santa Rosa Flat units 9, 11, and 12. The shelf lithofacies association includes Lone Pine Formation members C and D and sedimentary rocks of Santa Rosa Flat units 7, 8, and 10. The fluvial lithofacies association includes the Reward Conglomerate.

Lone Pine Formation member A/B (Figure 6(a); Table 2) is composed of planar-laminated mudstone and siltstone, indicating deposition on the continental rise as fining-upwards packages of silt and mud settled out of the distal lobes of turbidity currents. Planar-laminated and minor crossbedded mud and sand, with interspersed soft-sediment deformation structures and rip-up clasts in member C and lower member D, indicate deposition on the continental shelf punctuated by higher-energy depositional events (Figure 6(b)). Coarser grains, sandstone and micrite clasts, and crossbedding in upper member D and the Reward conesperiences were within 1–2% of the published values. Error assessment follows Kylander-Clark et al. [53].

U-Pb and trace element analyses were obtained together to ensure that the same growth zones were sampled within each crystal. Data were reduced using the software package Iolite 2.5 in WaveMetrics IgorPro 6.37. Grain ages that were discordant by >10% or reversely discordant by >5% are not reported, nor are grains with an uncertainty > 10% of the age. For grains older than ca. 1.0 Ga (or after a break in age groupings), the $^{207}$Pb/$^{206}$Pb age is reported, and for grains younger than ca. 1.0 Ga, the $^{206}$Pb/$^{238}$U age is reported. Graphical representations of the data were created using Iso-Plot 4.15 software in Excel [54], and DensityPlotter 8.4 [55], and statistical analyses used DZStats 2.2 [56]. All analytical data are provided in Supplemental Table 1. All age errors reported are $2\sigma$, and the average $2\sigma$ uncertainty for the ages is ~0.1-3% of the age. Data from eight samples are provided in Leary et al. [57].

2.3. Petrography. Ten thin sections of very fine to coarse sandstone were point counted (Supplemental Table 2) and plotted on ternary diagrams. For each sample, at least 300 grains were counted using the Gazzi-Dickinson method [58]. Matrix composition was noted but not counted in the point counts. Calcite and micrite grains were counted separately and were not considered sedimentary-lithic grains for the Qm-F-Lt (monocrystalline quartz-feldspar-lithic) ternary diagram because they cannot be confidently allocated to one of the three categories [59, 60]. They are considered here to likely be intrabasinal clasts that either crystallized in place, were precipitated, or were deposited via turbidity currents derived from a nearby carbonate shelf and are less likely to have come from extrabasinal tectonic uplifts.

Rocks of the Lone Pine Basin commonly contain metamorphic minerals (mostly tremolite) that crystallized during subsequent tectonic burial; these are interpreted to have been contact metamorphosed to quartz-calcite-tremolite rocks, likely by nearby Jurassic plutons. In order to reconstruct the original proportion of deposited detrital minerals prior to metamorphism, point counted proportions of total quartz, calcite, and tremolite were converted to monocrystalline quartz, calcite, and polycrystalline quartz (chert) using elemental abundances of each mineral, assuming no net change to composition. The proportion of monocrystalline quartz was estimated by multiplying the point counted proportion of monocrystalline quartz by the reconstructed total quartz proportion.
Table 2: Stratigraphy and lithofacies of measured sedimentary units in the Lone Pine and Darwin Basins. SRF = sedimentary rocks of Santa Rosa Flat.

<table>
<thead>
<tr>
<th>Formation, member or unit</th>
<th>Color</th>
<th>Grain size</th>
<th>Sorting, rounding</th>
<th>Sedimentary structures</th>
<th>Bed thickness (cm)</th>
<th>Clast composition/fossils</th>
<th>Lithology</th>
<th>Lithofacies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lone Pine, A/B</td>
<td>Gray, white</td>
<td>Mud, silt</td>
<td>Poor, rounded</td>
<td>Planar lamination</td>
<td>~0.5</td>
<td>Fusulinids</td>
<td>Marl</td>
<td>Slope/basinal</td>
</tr>
<tr>
<td>undifferentiated</td>
<td></td>
<td></td>
<td>Moderate-poor, subrounded</td>
<td>Planar lamination, crossbedding, ripples, slumping, normal grading, rip-up clasts</td>
<td>~1-6</td>
<td>Bryozoans, brachiopods, gastropods, ooids, trace fossils</td>
<td>Carbonate-siliciclastic sandstone, marl</td>
<td>Shelf</td>
</tr>
<tr>
<td>Lone Pine, C</td>
<td>Gray</td>
<td>Mud, sand</td>
<td>Moderate-poor, subrounded</td>
<td>Planar lamination, crossbedding, ripples, flame structures, slumping, normal grading</td>
<td>~1-100</td>
<td>Bryozoans, trace fossils, burrows</td>
<td>Carbonate-siliciclastic sandstone, marl</td>
<td>Shelf</td>
</tr>
<tr>
<td>Lone Pine, lower D</td>
<td>Gray, colorful clasts</td>
<td>Sand, pebble conglomerate</td>
<td>Poor, subrounded</td>
<td>Crossbedding, ripples, imbricated clasts, planar lamination</td>
<td>~10-100</td>
<td>Chert, sandstone, micrite, quartzite, limestone</td>
<td>Sandstone, conglomerate</td>
<td>Shelf</td>
</tr>
<tr>
<td>rewarding</td>
<td>Dark brown-gray, colorful clasts</td>
<td>Cobble conglomerate, minor sand</td>
<td>Poor, subrounded</td>
<td>Crossbedding, planar lamination, imbricated clasts</td>
<td>~10-100</td>
<td>Chert, sandstone, micrite, gastropods, crinoid stems, brachiopods</td>
<td>Conglomerate, sandstone</td>
<td>Fluvial</td>
</tr>
<tr>
<td>Conglomerate</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>SRF, 7</td>
<td>Dark gray</td>
<td>Mud, minor pebble conglomerate</td>
<td>Poor, subrounded</td>
<td>Rip-up clasts</td>
<td>Massive-meter-scale</td>
<td>Fusulinids, corals, brachiopods, articulated bivalves, bryozoans, crinoids</td>
<td>Fossiliferous grainstone with intraclasts of underlying Keeler Canyon Fm.</td>
<td>Shelf</td>
</tr>
<tr>
<td>SRF, 8</td>
<td>Gray, tan</td>
<td>Silt, minor pebble conglomerate</td>
<td>Moderate-poor, subangular</td>
<td>Planar bedding</td>
<td>~5-30</td>
<td>Crinoids, fusulinids</td>
<td>Interbedded siltstone and wackestone</td>
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</tr>
<tr>
<td>SRF, g3/9s</td>
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<td>Mud, silt, minor pebble conglomerate</td>
<td>Poor, subrounded</td>
<td>Normal grading, ripples, planar beddng</td>
<td>~10</td>
<td>Chert, crinoids, fusulinids, trace fossils</td>
<td>Calcareous siltstone</td>
<td>Shelf</td>
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<tr>
<td>SRF, 9</td>
<td>Dark gray</td>
<td>Mud, silt, minor pebble conglomerate</td>
<td>Moderate-poor, subrounded</td>
<td>Normal grading, planar lamination, rip-up clasts</td>
<td>~10-100</td>
<td>Chert, brachiopods, gastropods, crinoids</td>
<td>Calcareous siltstone</td>
<td>Shelf</td>
</tr>
<tr>
<td>SRF, 10</td>
<td>Dark gray</td>
<td>Mud with bioclasts</td>
<td>Poor, angular</td>
<td>Massive</td>
<td>Massi</td>
<td>Bryozoans, corals, brachiopods, fusulinids, crinoids</td>
<td>Fossiliferous wackestone</td>
<td>Shelf</td>
</tr>
<tr>
<td>SRF, 11</td>
<td>Medium gray</td>
<td>Silt, sand, minor pebble conglomerate</td>
<td>Moderate-well, subrounded</td>
<td>Crossbedding, ripples, normal grading, planar lamination</td>
<td>~10</td>
<td>Crinoids*</td>
<td>Sandstone</td>
<td>Slope/basinal</td>
</tr>
<tr>
<td>Formation, member or unit</td>
<td>Color</td>
<td>Grain size</td>
<td>Sorting, rounding</td>
<td>Stratigraphy and lithofacies</td>
<td>Bed thickness (cm)</td>
<td>Clast composition/fossils</td>
<td>Lithology</td>
<td>Lithofacies</td>
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</tr>
<tr>
<td>SRF, 12a Maroon, green</td>
<td>Mud</td>
<td>Moderate, subrounded</td>
<td>Planar lamination</td>
<td>cm scale</td>
<td>N.A.</td>
<td>Carbonate-siliciclastic sandstone</td>
<td>Slope/basinal*</td>
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<tr>
<td>SRF, 12a (channels) Light tan Sand, minor pebble conglomerate</td>
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<td>Normal grading</td>
<td>~10-30</td>
<td>Limestone, chert</td>
<td></td>
<td></td>
<td>Slope/basinal</td>
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</tr>
</tbody>
</table>

Note: samples are stored in the collections of Northern Arizona University Division of Geoscience, Flagstaff, Arizona 86001. *Fossils in this unit were transported.
Figure 6: Lone Pine Formation (Lone Pine Basin; a–d) and the sedimentary rocks of Santa Rosa Flat (Darwin Basin; e–i) and sedimentary petrology results. The pencil is 15 cm long. (a) Thin-bedded strata of members A and B, undifferentiated. (b) Member C with planar bedding and ripples. (c) Member D; conglomerate grades into sandstone. (d) Reward Conglomerate; crossbedded sandstone is interbedded with conglomerate. (e) Unit 7 contains bivalve shells aligned along bedding planes. (f) Unit 9; Bouma sequence layers a, b, and c (Bouma, 1962). (g) Intact gastropod shell in Unit 10. (h) Unit 11; high-angle crossbeds in the lower half of the photograph. (i) Unit 12a; sandstone from one of many calcareous sandstone channels in the unit. (j) Photomicrograph from Santa Rosa Flat unit 11 (Darwin Basin), with extensive calcite mineralization along with monocrystalline and polycrystalline quartz (cross-polarized view). (k) Photomicrograph from Lone Pine Formation member D (Lone Pine Basin), with monocrystalline and polycrystalline quartz, secondary tremolite mineralization (outlined in pink), and a lack of calcite grains (cross-polarized view). (l) QmFLt diagram of all point counted samples; modified after Dickinson et al. [59]. (m) Qm-calcite-Chert diagram of point counted samples and reconstructed Lone Pine Basin compositions. Qm = monocrystalline quartz; Ca = calcite; Ch = chert; F = feldspar; Lt = lithic grains, including polycrystalline quartz and chert but not calcite.
Conglomerate suggest further shallowing with a proximal source for grains, and a major influx of subrounded cobbles in the Reward Conglomerate suggests deposition in a fluvial setting (Figures 6(c) and 6(d)).

Unit 7 of the sedimentary rocks of Santa Rosa Flat (Table 2; Figure 6(e)) is composed of limestone with intact fossils. The intact nature of the fossils suggests that they were not transported far or exposed to breaking waves. This unit, for which the name Upland Valley Limestone has been proposed [26], was thus likely deposited partially within the photic zone and on the outer shelf or upper slope. Interbedded layers of crinoidal limestone and siltstone in unit 8 suggest deposition on the continental shelf. Fine-grained turbidites indicated by Bouma sequences in unit 9 suggest that this unit was deposited near the bottom of the continental slope or on the continental rise, and local fusulinid-rich beds in unit 9 were likely deposited by sediment gravity flows (Figure 6(f)). Unit 10 contains limestone with intact fossils that indicate shallow-marine deposition in the photic zone (Figure 6(g)). Fine-grained turbidites in unit 11 indicate deposition on the continental slope or in a basal environment (Figure 6(h)). The mud component of unit 12 was likely a swept off continental shelf during storms to accumulate as hemipelagic muds at the margins of a submarine fan complex, and the interbedded sandstone layers (Figure 6(i)) are interpreted as submarine channels filled with carbonate material from nearby carbonate shelves.

Rocks of the Lone Pine Formation and the sedimentary rocks of Santa Rosa Flat were mostly deposited in a marine environment. The depositional settings of strata in the Lone Pine Basin exhibit a shoaling-upwards pattern, from a deep marine to continental shelf to fluvial environment. The depositional settings of strata in the Darwin Basin exhibit a shoaling and then deepening pattern: the oldest units are interpreted to have been deposited in a deep marine environment, middle units in a continental shelf environment, and upper units in a submarine fan environment on the continental slope.

3.2. Sandstone Petrography. Point count data (Supplemental Table 2) from thin sections (Figures 6(j) and 6(k)) from the two basins plot separately on ternary diagrams (Figures 6(l) and 6(m)). Figure 6(l) shows the monocrystalline quartz, feldspar, and lithic-grain content of samples from the Lone Pine and Darwin Basins; Lone Pine samples are richer in monocrystalline quartz. Samples from the Darwin Basin plot in the recycled orogen and continental-block fields [59]. Lone Pine Basin sandstones contain a metamorphic-grain assemblage of quartz (SiO₂), tremolite, and calcite (CaO); Figure 6(m) shows reconstructed values that represent the calculated proportions of Qm, calcite, and chert in the protholith. Samples from the basins plot separately even after this reconstruction, with Darwin Basin samples containing a higher proportion of carbonate grains relative to the Lone Pine Basin.

3.3. Detrital Zircon U-Pb Geochronology and Geochemistry. Twelve samples yielded detrital zircons for U-Pb analysis (Table 1), including five from the Lone Pine Formation of the Lone Pine Basin (one from member A/B, three from member C, and one from member D), three from the sedimentary rocks of Santa Rosa Flat of the Darwin Basin (one from unit 11 and two from unit 12), two from the Reward Conglomerate, and two from member C of the Conglomerate Mesa Formation (Table 1) that were analyzed for comparison. In total, 1712 concordant grains were analyzed, 635 from the Darwin Basin and 1077 from the Lone Pine Basin. Most grains are rounded and abraded. Detrital zircon spectra are similar among all samples, with most samples showing prominent spikes centered around 400 Ma, 1100 Ma, and to a lesser extent ca. 1900 Ma, along with several Archean grains (Figure 7). Both basins have ~10% 300-800 Ma grains, ~30% 800-1300 Ma grains, ~10% 1300-1600 Ma grains, ~10% 1600-1800 Ma grains, and ~20% grains over 1800 Ma. The Reward Conglomerate and the Conglomerate Mesa Formation contain rare Permian and early Triassic grains (~1%) that have similar age distributions and are the only two units for which maximum depositional ages were calculated. Maximum depositional ages were calculated using the weighted-mean-age method described in Dickinson and Gehrels [61], modified to use the maximum number of youngest grains that provide the lowest MSWD (mean square of weighted deviates). The maximum depositional ages of the Reward Conglomerate (ca. 255 Ma) and the Conglomerate Mesa Formation (ca. 254 Ma) are similar. All other Permian Inyo Mountain samples contain exclusively 300 Ma or older detrital zircon, because zircon ages in those samples are significantly older than the sediment depositional age; maximum depositional ages were not calculated for those samples.

Trace element ratios were calculated from 69 Permian-Triassic detrital zircon grains likely derived from the Cordilleran arc (ca. 268-248 Ma; Figure 8), and 59 grains in the age range 300-400 Ma. Trace element concentrations and ratios, such as U/Yb, reflect the composition of the host magma in which the zircon grain crystallized and can be used to distinguish between magma emplaced into continental versus oceanic crust [62–66]. For example, higher U/Yb values measured in zircon that crystallized in the continental crust are presumed to reflect the influence of large-ion-lithophile-enriched continental crust during partial melting [64]. Th/U ratios can be used as an additional provenance method to identify a potential genetic link between zircons and a crustal province or terrane in which a zircon may have crystallized [14, 66, 67].

U/Yb ratios of Permian-Triassic grains (~0.1-2.2) are consistent with ratios of magma that was emplaced into the continental crust ([62–64, 66], Figure 8(a)), and Th/U ratios (~0.2-0.9) are similar to Th/U ratios from zircons in plutons emplaced into the El Paso Terrane ([12, 14]; Figure 8(b)). Carboniferous grains have Th/U ratios of 0.09-2.24 and U/Yb ratios of 0.1 to 5.34, also indicating crystallization in the continental crust; therefore, these grains likely were not derived from the McCloud Island arc that was active offshore of Laurentia during the Carboniferous time [6, 9, 34].

3.4. Interpretation of Zircon Data. Detrital zircon spectra of middle to late Permian samples are similar to those of
samples from Colorado Plateau Permian sandstones ([51, 68]; Figure 9). The Appalachian orogenies of northeastern Laurentia were likely the source for detrital zircon in the 280-500 Ma age group ([59, 69, 70]; Figure 7). The Llano-Grenville province, which was added to eastern Laurentia during the 1300-950 Ma broader Grenville orogeny, is interpreted to be the source for zircon in the age group ca. 1300-1000 Ma; these grains could also have been recycled from the Appalachian foreland basin ([69, 71]; Figure 7). The Granite-Rhyolite province, which was accreted to Laurentia during a tectonic event associated with A-type intracratonic magmatism [71, 72], probably sourced detrital zircon in the age group 1450-1300 Ma (Figure 7). The Yavapai (1.8-1.7 Ma) and Mazatzal (1.7-1.6 Ma) provinces likely supplied zircon grains in the ca. 1800-1600 Ma age group ([51, 71]; Figure 7). Older Paleoproterozoic grains (2500-1800 Ma) and Archaean grains (3015-2500 Ma) were presumably eroded from the basement of the Laurentian shield or recycled from its sedimentary cover ([51]; Figure 7). Transport of detrital zircon across the Laurentian craton agrees with interpretations by Dickinson and Gehrels [51].
4. Discussion

4.1. Conglomerate Mesa Uplift. The Conglomerate Mesa Uplift, which separated the Lone Pine and Darwin Basins, is hypothesized to have formed at ca. 295–290 Ma as a fault-propagation fold associated with the Last Chance thrust, at the toe of the coeval Last Chance allochthon, and continued to develop until ca. 270 Ma ([15–17, 23, 42]; Figure 3). Several lines of evidence developed in this study support the Conglomerate Mesa Uplift as a distinct topographic feature. Strata in the Lone Pine and Darwin Basins are distinct lithologically and mineralogically, which indicates partitioning of the basins during deposition. Darwin Basin samples contain higher proportions of calcite, which likely reflects proximity to the Bird Spring carbonate shelf to the east ([16, 17, 23, 24]; Figure 6(m)). The relative lack of carbonate grains in the Lone Pine Basin supports a topographic divide between the basins. Monocrystalline quartz is dominant in Lone Pine Basin sandstones (Figures 6(l) and 6(m)); these grains were likely either recycled from the Keeler Canyon Formation sediment in the Conglomerate Mesa Uplift or sourced by ocean longshore currents that transported eolian siliciclastic sediment from continental Laurentia.

In contrast to lithologic differences, detrital zircon age populations between the Lone Pine and Darwin Basins are indistinguishable. As the Reward Conglomerate and Conglomerate Mesa Formation are here interpreted to be correlative and overlie the Conglomerate Mesa Uplift, the influx of Permo-Triassic detrital zircon grains in those units is not attributed here to differences between basins. However, the Reward Conglomerate yielded more Permo-Triassic zircons than the Conglomerate Mesa Formation; this difference could reflect the Reward Conglomerate sampling locations being on the west side of the Inyo Mountains, closer to the early Cordilleran arc. This higher abundance of arc-derived zircon grains also suggests transport of zircon grains by erosion and fluvial processes rather than by eruptions and atmospheric transport, as the latter process would likely deposit grains in a more spatially uniform way.

![U vs. Yb](image1.png)

![Th/U vs. age](image2.png)

**Figure 8:** Detrital zircon trace element geochemistry results for Permian, Cordilleran arc-derived grains in Inyo Mountain sandstones. (a) Uranium/ytterbium ratios. Continental and Oceanic refer to the type of crust in which the magma that hosted analyzed zircons was emplaced; plots adapted from Grimes et al. [63]. (b) Thorium/uranium ratios plotted against age; Th/U ratios from Permian intrusive rocks in the El Paso terrane from Cecil et al. [12] are included for comparison. IM = Inyo Mountains; EPM = El Paso Mountains.
The Conglomerate Mesa Uplift and the Last Chance thrust have roughly northeast-southwest orientations that parallel stratigraphic and structural trends of the Devonian-Mississippian Antler orogenic belt ([8, 32, 33]; Figure 1). Thus, the deformation observed could have resulted from the propagation of a southeast-directed wedge top at the southern end of the Antler orogenic belt [42]. Here, we agree with interpretations of Stevens and Stone [42] and argue that the Conglomerate Mesa Uplift and the Last Chance thrust are too young to be directly associated with Antler tectonism. We propose that these features were formed during the transition from transpression to subduction initiation or during the earliest subduction, by folding induced by sinistral-oblique, southwest-directed convergence.

4.2. Subduction Initiation. Deformation that produced the Conglomerate Mesa Uplift and the Lone Pine and Darwin Basins has been hypothesized to have resulted from the earliest Permian contractual tectonism during the transition from a strike-slip tectonic regime to subduction (e.g., [15]). We argue that the initiation of the Conglomerate Mesa Uplift was likely related to the Last Chance thrust and that the Last Chance thrust could represent either the earliest subduction or part of the contractual element of strain partitioning during the transpressional tectonic regime. In the latter scenario, continued deformation of the Conglomerate Mesa Uplift after 285 Ma would have resulted from subduction-related contraction. We suggest that these scenarios are both possible and that regardless, Permian deformational and depositional events occurred during the transition from transpressional tectonism to subduction and during the earliest subduction stage.

Strike-slip faulting along the California-Coahuila transform is thought to have been active by ca. 300 Ma [6, 8, 36], and the earliest known Cordilleran arc magmatism is recorded by ca. 275 Ma plutos [10–12, 73]. Therefore, if the initiation of the Last Chance thrust at ca. 295 was caused by subduction initiation, the transition time between subduction initiation and initial magmatism would have been ~20 Myr.

Rains et al. [40] and Saleeby and Dunne [9] cited tectonic and chronologic similarities between Cordilleran subduction initiation and a modern example of induced subduction initiation in the Puysegur subduction zone south of New Zealand, where changes in plate motion have been converting a transpressional boundary (the Alpine Fault) into a convergent plate boundary and subduction zone over the past ~20 million years [3, 74–76]. In both the Cordilleran and Puysegur cases, subduction initiation was preceded by strike-slip faulting and the translation of terranes [9, 30, 36, 76, 77]. Additionally, in both cases, a relatively thick and strong continental crust was ruptured, and thus, presubduction weakening and sufficient time were necessary to allow for subduction initiation [12, 76, 77].

The transition between the development of the Alpine Fault and initiation of the Puysegur subduction zone lasted roughly 3 Myr [76], and the transition between subduction initiation and initial magmatism lasted nearly 20 Myr [78]. Although the transitions from a strike-slip tectonic regime to subduction and from subduction to initial arc magmatism do not have necessarily have characteristic transition times, the two settings are broadly analogous. Considering similar transition times between strike-slip faulting and subduction initiation, and between subduction initiation and initial magmatism, Cordilleran subduction could have initiated as early as 295 Ma, coeval with the development of the Last Chance thrust and the Conglomerate Mesa Uplift.

The alternative scenario is that the Last Chance thrust represented the contractual element of strain partitioning during a transpressional tectonic regime prior to continental rupture and subduction initiation. Thrust faults associated with strain-partitioned systems are often oriented ~30-45 degrees from the strike of the transform fault (e.g., the San Andreas Fault; [79]), an angle compatible with the relationship between the strike of California-Coahuila transform and folding within the Last Chance thrust [45]. In this scenario, lithospheric rupture along the California-Coahuila transform would have evolved from a partitioned system of shortening structures and strike-slip faults to a continuous subduction zone by ca. 285 Ma [45], and continued deformation of the Conglomerate Mesa Uplift after 285 Ma would have occurred in response to subduction-related contraction. In light of these possibilities, we suggest that the deformation that caused the Last Chance thrust and Conglomerate Mesa Uplift was related to the transition from strike-slip faulting to subduction or during the earliest subduction and that subduction initiated sometime between 295 and 285 Ma.

4.3. Sedimentary Response to Local Transpressional or Subduction-Related Tectonism. The mechanism of subduction initiation, whether spontaneous or induced [3], should control shoaling and deepening patterns of sedimentary strata deposited on the upper plate. The sea level in the Permian time was relatively uniform, apart from a regression of ~70 m that occurred from ca. 270 to ca. 260 Ma ([80]; Figure 10). A change from basinal to shelf deposition (or vice
versa), however, would amount to several hundreds of meters or kilometers of shoaling or deepening. Therefore, shoaling and deepening patterns seen in Permian strata off the west coast of Laurentia can be dominantly attributed to subsidence and uplift mechanisms associated with transpressional and contractional tectonism.

Geodynamical modelling suggests that induced subduction initiation should leave a sequential record of rapid uplift, rapid subsidence, and then gradual uplift in the upper plate, as seen in both the Puyssegur subduction zone and in Permian strata of the El Paso terrane [1–3, 40]. The coeval sedimentary responses to subduction initiation in the Lone Pine and Darwin Basins of the Inyo Mountains, however, differ from those of the El Paso terrane strata (Figure 10). This difference may be due to the inferred position of the Inyo Mountains east of the protoarc, in contrast to the arc-proximal position of the El Paso terrane strata, which contain abundant volcaniclastic sediment [40]. In a subduction setting produced by induced nucleation, upper plate thrusting is a key characteristic early in the subduction initiation process [3]. Thrusting in the proto-back-arc could have prompted complex and episodic shoaling and deepening patterns in basins as faults and associated folds formed and moved and could explain the contrasting depositional environments in the Lone Pine and Darwin Basins.

Strata in the Lone Pine Basin show a gradual shoaling-upwards pattern throughout the Permian time, whereas strata in the Darwin Basin show a shoaling trend from the Sakmarian to late Artinskian stages (from ca. 295 to 283 Ma), a deepening trend until the Roadian stage (from ca. 283 to 275 Ma), and finally a shoaling trend until the Changhsingian stage (from ca. 275 to 255 Ma) (Figures 2 and 10). In addition, the stratigraphic section in the Darwin Basin is much thicker (Figure 5), implying more structural relief on the southeastern side of the Conglomerate Mesa Uplift. The differing patterns between the Lone Pine and Darwin Basins could thus be explained by their positions relative to the Conglomerate Mesa Uplift and local tectonics, rather than broad-wavelength dynamic topography [15, 16, 23, 41].

Different basins within the same thrust belt commonly experience coeval uplift and subsidence due to tectonic loading. The Conglomerate Mesa Uplift’s position near the toe of the Last Chance thrust suggests that relative movement of the Lone Pine and Darwin Basins could have been caused by a splay fault in the thrust system that terminated in a fault-
propagation fold. From ca. 283–275 Ma, the shoaling pattern in the Lone Pine Basin could be related to its hypothesized position in the uplifting block of a potential thrust fault responsible for the development of the Conglomerate Mesa Uplift through the folding of the Keeler Canyon Formation. The coeval deepening and thicker section in the Darwin Basin could be related to its hypothesized position in the downthrown block and could be a result of tectonic loading (cf. [41]; Figures 3 and 10). Shoaling after ca. 268 Ma could be related to tectonic uplift and the building of the Cordilleran arc or to middle Permian eustatic regression ([80]; Figure 10).

4.4. Earliest Magmatism Recorded in the Inyo Mountains.
Four samples from the Inyo Mountains yielded Permian and Triassic detrital zircons: two from the Reward Conglomerate and two from member C of the Conglomerate Mesa Formation. Permian and Triassic ages span a range from 268 to 248 Ma, each with a concentration of grains at ca. 255 Ma (Figure 7). The closest Permian plutons are located in the El Paso terrane and record semicontinuous Cordilleran arc magmatism between ca. 275 and 240 Ma ([12]; Figure 1). The similarity in ages suggests that magmatic systems in the El Paso terrane could have sourced zircons found in the Inyo Mountains. Thorium/uranium ratios from zircons in the Reward Conglomerate and Conglomerate Mesa Formation in the Inyo Mountains are similar to Th/U ratios from zircons in the El Paso plutons; ratios of both groups consistently fall between 0.2 and 0.9 (Figure 8(b)), suggesting a possible genetic link between magmatic detritus in the Inyo and the El Paso plutons.

4.5. Tectonic Evolution. Permian strata in the Inyo Mountains were deposited during strike-slip truncation of Laurentia’s western margin, the initiation of subduction, and earliest emplacement of the Cordilleran magmatic arc. The underlying
Pennsylvanian and earliest Permian Keeler Canyon Formation was deposited by turbidity currents and debris flows originating from the Bird Spring carbonate shelf ([29, 81]; Figure 11(a)). Strike-slip faulting along the California-Coahuila transform was ongoing by ca. 300 Ma ([16, 8, 36]; Figure 11(a)). Back-arc thrusting during the transition to subduction, likely related to the Last Chance thrust, caused uplift and folding of the Keeler Canyon Formation and formation of the Conglomerate Mesa Uplift at ca. 295-290 Ma [16, 17, 23], which partitioned the Lone Pine and Darwin Basins and led to the deposition of distinct strata in each basin (Figure 11(b)).

Contrasting shoaling, deepening, and sediment accumulation records are recorded in the Lone Pine and Darwin Basins. In the Lone Pine Basin, member A/B of the Lone Pine Formation was deposited by deep marine, distal turbidites in an outer-submarine-fan setting, and overlying members C and D were deposited in a continental shelf environment (Figure 11(b)). The oldest strata in the Darwin Basin (units 1-5) were deposited by turbidity currents sourced from the Bird Spring carbonate shelf to the east [15]; units 6, 7, and 8 were deposited in a continental shelf environment punctuated by higher-energy flows, with input from the Conglomerate Mesa Uplift. The uppermost units (aside from unit 10) were deposited partially by turbidity currents in a continental slope or basinal environment (Figure 11(c)). Depositional patterns in both basins were likely impacted by continued deformation of the Conglomerate Mesa Uplift.

The late Permain-early Triassic Conglomerate Mesa Formation and the likely correlative Reward Conglomerate were deposited by a fluvial system that transported proximal material uplifted during contraction and subduction initiation outboard and to the west (Figure 11(c)). Permain-Triassic detrital zircon grains in these units were likely sourced by early Cordilleran arc magmatism in the El Paso terrane to the southwest (Figure 11(c); [12]).

5. Conclusions

Inyo Mountain Permian strata were deposited in two basins, the Lone Pine and Darwin Basins. Siliciclastic sediment in the two basins was likely recycled from underlying strata and/or sourced from the Laurentian continent, transported from Appalachia by rivers and then south along the west coast by wind or longshore oceanic currents. Pre-Cordilleran arc detrital zircon age spectra suggest potential provenance sources in Appalachian, Grenville, and Yavapai/Mazatzal provinces. Carbonate sediment in the Darwin Basin was likely sourced from the Bird Spring shelf.

Strata in the Lone Pine Basin show a shoaling-upwards pattern, from marine-basinal to fluvial deposits. Strata in the Darwin Basin show a shoaling-to-deepening-to-shoaling pattern, from marine-basinal, to shelf, to basinal, and back to shelf deposits, and contain a higher abundance of carbonate material. Differing lithologies in the Lone Pine and Darwin Basins and a higher abundance of carbonate grains in the Darwin Basin support the existence of the Conglomerate Mesa Uplift, which blocked sediment mixing between the basins.

Due to the stability of the sea level throughout most of Permian time, shoaling and deepening patterns in the Lone Pine and Darwin Basins are considered to be dominantly induced by local and regional tectonics. Opposing patterns are likely due to the basins’ position relative to progressive uplift of the Conglomerate Mesa Uplift and tectonic loading. The Conglomerate Mesa Uplift was potentially formed by a blind thrust fault that faulted and folded the Keeler Canyon Formation and juxtaposed the Lone Pine and Darwin Basins at ca. 295-290 Ma, with the Lone Pine Basin experiencing local uplift while the Darwin Basin experienced local subsidence. The contrast between the shoaling and deepening patterns of sedimentation in a proto-back-arc setting (this study) and an arc-proximal setting [40] is likely related to thrusting in a back-arc setting, as thrusting can lead to complex uplift and subsidence patterns.

Cordilleran subduction probably initiated between ca. 295 and 285 Ma near the Inyo Mountains and the El Paso terrane, possibly with similar transition times between transcurrent faulting, subduction initiation, and earliest magmatism to the Puysegur subduction zone in New Zealand, and is an example of induced nucleation of a subduction zone. Earliest Cordilleran arc magmatism occurred ca. 275 Ma, as recorded by plutons in the El Paso terrane and Sonora, Mexico. The influx of Permian 268-248 Ma detrital zircons into the latest Permian strata in the Inyo Mountains helps to constrain the earliest magmatism of the Cordilleran arc near the Inyo Mountains and likely is connected to early magmatism in the El Paso Mountains. Detrital zircon trace element geochemistry indicates that these zircons crystallized in magma emplaced into continental crust. Initiation of the Conglomerate Mesa Uplift paleo uplift ca. 295-290 Ma supports contraction as early as 295 Ma, due to either the contractual component of transpressional tectonics prior to subduction initiation or earliest subduction.

Permian strata in the Inyo Mountains provide insight into the development and depositional environment of tectonic basins east of the incipient Cordilleran magmatic arc and shed light on the nature of Cordilleran subduction initiation in the Permian time. These strata are the only known example of the sedimentological response to the transition to subduction initiation in a developing back-arc basin. Such data sets are critical to understanding subduction initiation processes, on a range of temporal and spatial scales.

Data Availability

Data supporting the conclusions of this study can be accessed via the supplementary files and in Leary et al. [57].

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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Supplementary Materials

Supplementary 1. Supplementary Table 1: detrital zircon uranium and lead isotopic data and selected trace element data. Samples 12-02-16-1, 10-11-15-1, 12-03-16-1, 12-03-16-3, 12-03-16-2, 10-12-15-3, 6-20-17-3, and 6-20-17-4 can be found in Leary et al. [57].

Supplementary 2. Supplementary Table 2: point count data used for ternary diagrams from ten thin sections.

References


