Zircon U-Pb ages and petrologic evolution of the English Peak granitic pluton: Jurassic crustal growth in northwestern California

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ABSTRACT

In the central Klamath Mountains, the English Peak plutonic complex (EPC) invaded the faulted contact between the outboard Eastern Hayfork and inboard North Fork terranes of the Western Paleozoic and Triassic Belt (WTrPz). This calc-alkaline igneous complex is composed of two small, ~1–2-km-diameter, relatively mafic satellite plutons peripheral to the younger, much larger, ~10–15-km-diameter English Peak zoned granitic pluton. The EPC magmas were mantle derived and reflect temporary residence and mixing at various depths in the overlying crust, with initial storage and modification near the Moho, and uppermost crustal emplacement at 5–10 km depths. Phase assemblages suggest pre-emplacement magma storage at a depth of ~20–25 km for the early satellite plutons, versus ~15–20 km for samples from the larger zoned granitic pluton. We obtained zircon U-Pb geochronologic results (reported as internal and external weighted-mean \(^{207}\)Pb-corrected \(^{206}\)Pb/\(^{238}\)U ages, 95% confidence level) from seven samples in the complex via laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS). The 172.3 ± 2.0 [3.7] Ma Uncles Creek and 166.9 ± 1.6 [3.4] Ma Heiney Bar satellite plutons range from gabbro–quartz diorite to granodiorite in bulk-rock composition. The main English Peak pluton consists of an early stage of gabbro–tonalite (three samples: 160.4 ± 1.1 [3.1] Ma, 158.1 ± 1.1 [3.1] Ma, and 158.0 ± 1.2 [3.1] Ma) and a late stage (two samples: 156.3 ± 1.3 [3.1] Ma and 155.3 ± 1.2 [3.0] Ma) passing inward from tonalite through granodiorite to a central zone of granite. The 172 Ma age of the Uncles Creek pluton makes it coeval with Middle Jurassic Western Hayfork arc magmatism. In contrast, Heiney Bar and the main English Peak igneous ages overlap some of the oldest and youngest components, respectively, of the Middle to Late Jurassic Woolley Creek plutonic suite. Study of this multiple-intrusion complex provides an illuminating example of the gradual intermediate-to-felsic modification of the upper crust in the central Klamath Mountains. Inherited zircon ages of ca. 172 Ma in two other EPC samples indicate potential Middle Jurassic crustal sources or contaminants. Geochronologic correlation of the EPC with geologic histories of other Klamath terranes provides fresh insights for understanding spatial and temporal elements of Middle to Late Jurassic arc magmatism in the Klamath Mountains sector of the Cordilleran margin. This igneous activity illuminates some petrotectonic processes whereby accreted ophiolitic basement terranes were modified and incorporated into the evolving Jurassic continental crust. It took place prior to the earliest Cretaceous onset of westward transport of the stack of Klamath allochthons relative to the active Jura-Cretaceous Sierran calc-alkaline arc.

INTRODUCTION TO THE REGIONAL GEOLOGY

The iconic Klamath Mountains Province provides a classic example of the Phanerozoic growth of transitional continental crust. Its imbricated lithotectonic belts testify to successive (1) arrival of far-traveled oceanic crust and overlying deep-sea sediments, (2) underflow and off-loading along the convergent plate junction, (3) suprasubduction-zone arc generation, and (4) erosional supply of arc debris to the accreting ophiolitic basement terranes. This late Paleozoic–Mesozoic development of northern California was typified by chiefly margin-parallel slip, episodic surftising of ophiolite complexes and their spatially associated chert-argillite terranes, concurrent construction of volcanic-plutonic arcs, plus the aprons of derived calcic sediments (Saleeby, 1981, 1982, 1983; Ernst et al., 2008).

The terrane assembly of the Klamath Mountains has been correlated with the northern Sierran Foothills based on similar rock types, structures, terrane ages, the oceanward assembly of successively younger geologic units, and their times of orogeny (Davis, 1969; Davis et al., 1980; Wright and Fahan, 1988; Wright and Wyld, 1994; Irwin, 2003). However, the accreted Sierran Foothill terranes stand nearly vertically, whereas the Klamath thrust sheets root gently to the east. Scattered, chiefly calc-alkaline igneous activity characterized the Late Triassic margin, but most lithologic sections of late Paleozoic–early Mesozoic age are oceanic in their genesis. However, a major Andean arc began to form in the Sierra Nevada and Klamath Mountains by ca. 175 Ma during transpressive eastward underflow of oceanic lithosphere (Dunne et al., 1998; Irwin, 2003; Dickinson, 2008). This magmatic arc shed clastic detritus into the realm of the accreting ophiolitic basement terranes of both the Klamath Mountains and Sierran Foothills (Miller and Saleeby, 1995; Scherer et al., 2006).

Figure 1 presents the regional geology of the Klamath Mountains Province, as well as published geochronology of various mafic-to-felsic plutons. The orogen is a terrane collage consisting of four major lithotectonic zones. From east to west, these are the Eastern Klamath Belt, the Central Metamorphic Belt,
Figure 1. Lithotectonic divisions of the Klamath Mountains, after Irwin and Wooden (1999) and with additions from Snoke and Barnes (2006). The Fort Jones terrane is also termed the Stuart Fork terrane. Plutons are color coded according to age group. In the key, “ttg suite” refers to earliest Cretaceous tonalite-trondhjemite-granodiorite plutons. Numbers associated with each pluton indicate ages (Ma) determined by U-Pb zircon analyses except for those indicated by t (U-Pb on titanite), h and b (K-Ar on hornblende and biotite, respectively), and H and p (40Ar/39Ar on hornblende and plagioclase, respectively).

EXPLANATION
- Cretaceous overlap assemblages: Includes Great Valley sequence and Hornbrook Formation
- Western Klamath terrane: Includes Smith River, Rogue Valley, Dry Butte, and Briggs Creek subterranes
- May Creek terrane
- Condrey Mountain terrane
- Rattlesnake Creek terrane
- Western Hayfork terrane
- Eastern Hayfork terrane
- North Fork terrane
- Fort Jones terrane
- Central Metamorphic terrane
- Redding subterrane
- Trinity subterrane
- Eastern Klamath terrane
- Yreka subterrane

- Granodioritic suite
- Ttg suite
- Siskiyou suite
- Wooly Creek suite
- Chetco complex
- Ironside Mtn. batholith
- western Hayfork-related plutons
- Rattlesnake Creek-related plutons
the Western Paleozoic and Triassic Belt, and the Western Jurassic Belt (Irwin, 1960). Individual allochthons that constitute each belt are dominantly upright. Most are bounded by gently east-dipping, mid-Paleozoic to Late Jurassic thrust faults (Irwin, 1994). Most Klamath terranes contain mafic-intermediate volcanic and plutonic oceanic rocks as well as aprons of arc- and continent-derived clastic sedimentary rocks. Thin layers of deep-sea chert ± limestone cap some of the tectonically dismembered ophiolitic allochthons. The west-vergent terranes accreted progressively outward (westward in modern coordinates), reflecting a component of eastward oceanic plate underflow from Permo-Triassic through Cretaceous time (Irwin, 1981; Ando et al., 1983; Mankinen et al., 1996; Scherer and Ernst, 2008; Saleeby and Dunne, 2015).

The WTrPz is the largest of the four major lithotectonic belts and hosts the EPC. The belt consists of regionally metamorphosed sedimentary, volcanic, and ultramafic rocks intruded by numerous plutons, some of which are metamorphosed. In the southern Klamath Mountains, Irwin (1972) divided the WTrPz from east to west into the North Fork, Hayfork, and Rattlesnake Creek terranes. Later, the inboard Stuart Fork high-pressure (HP) metamorphic terrane was defined (Hotz et al., 1977; Goodge, 1989), and the Hayfork terrane was divided into distinct eastern and western terranes (Wright, 1982; Goodge, 1989). Hacker et al. (1993, 1995) and Donato et al. (1996) demonstrated that many of the WTrPz terranes extend through a broad region of the Klamath Mountains. Mesozoic amalgamation of WTrPz terranes involved a series of accretion events, at least one of which was accompanied by regional, locally high-grade metamorphism. The late Middle Jurassic Siskiyou orogeny (Coleman et al., 1988) involved extintion of the Middle Jurassic arc (Western Hayfork terrane), thrusting of outboard Western Hayfork and Rattlesnake Creek terranes beneath inboard Eastern Hayfork terrane, and metamorphism that reached granulite-facies conditions 75 km north of the EPC, and greenschist- to lower amphibolite–facies conditions immediately north of the EPC (Barnes et al., 2006; Garlick et al., 2009; Medaris et al., 2009). In addition to terrane amalgamation, Barnes et al. (1992) and Allen and Barnes (2006) argued that the Siskiyou orogeny resulted in reorganization of the lower crust, resulting in chemical and isotopic modification of sources and contaminants of arc magmas. Figure 1 depicts the presently recognized divisions of the Klamath Province into map units (Harper and Wright, 1984; Irwin and Wooden, 1999; Snoke and Barnes, 2006).

Numerous broadly calc-alkaline plutons intruded the WTrPz and older belts during Middle Jurassic to earliest Cretaceous time (Lanphere et al., 1968; Hotz, 1973; Barnes et al., 1992, 2006; Irwin and Wooden, 1999; Allen and Barnes, 2006). These intrusions, along with the coeval outboard Josephine ophiolite (Harper et al., 1994) and the yet further outboard Rogue-Chetco magmatic fringing arc (Garcia, 1979, 1982), occupy transtensional, arc, and backarc settings. Nevadan- and post-Nevadan uplift exposed a crustal section that encompasses upper- to lower-crustal environments (Coleman et al., 1988; Garlick et al., 2009). Consequently, plutons occur over a range of crustal levels. One, the Wooley Creek batholith (WCB), lies directly to the west and northwest of the EPC (Fig. 1). Exposure of the WCB involves >12 km of structural relief (Barnes, 1983; Barnes et al., 1986a, 1986b).

**STATEMENT OF THE PROBLEM**

Multiple, discrete phases of arc magmatism built the English Peak plutonic complex in the central Klamath Mountains. The EPC is one of a large group of Jurassic composite plutons emplaced in a broadly arc setting active from late Middle Jurassic to Late Jurassic time (Allen and Barnes, 2006; Barnes et al., 2006). Seyfert (1965) and Schmidt (1994) showed that the English Peak plutonic complex was emplaced in several distinct pulses. Integrated mineralogic, petrologic, and geochemical investigations by Barnes et al. (2016) described the petrochemical evolution of various pluton stages of the EPC. Based on Al-in-hornblende barometry, pseudosection P-T studies, and oxygen + Sr isotopic analyses, Barnes et al. (2016) concluded that generation of the EPC magmas reflected the arrival of mantle-derived mafic magmas in the deepest part of the crust, followed by mixing, assimilation, storage, and homogenization (MASH), during which magmas were contaminated by older meta-igneous and metasedimentary rocks. Fractional crystallization of these mantle-derived calc-alkaline magmas occurred near Moho depths. Magmas that formed the oldest satellitic plutons were sequestered and underwent partial crystallization at mid-crustal levels (~600 MPa). Younger magmas were stored in a large, recharged magma chamber, or chambers in the upper middle crust (~400 MPa), then rose to form the composite pluton in the upper crust (~200 MPa).

We summarize results of these and prior investigations (e.g., Donato et al., 1982; Ernst, 1998, 1999) to provide a geologic framework for our geochronologic study of the English Peak plutonic complex. Our goal is to determine the longevity and crystallization history of the EPC, to characterize potential source and/or contaminant rocks, and to describe the subsequent geochemical evolution of the derived magmas. We show that the EPC grew episodically by amalgamation of several compositionally and temporally distinct magma batches, that magmatism spanned the important orogenic Siskiyou event, and that magma storage and crystallization occurred in multiple levels of the middle and upper crust. Considering the modern and inferred ancient regional plate-tectonic settings, the central Klamath Mountains and its associated plutons provide instructive examples of processes whereby accreted oceanic terranes were modified and incorporated into the continental crust during Middle and Late Jurassic time.

**LOCAL GEOLOGY**

**Geology of the Sawyers Bar Area**

Figure 2 presents the local geology of the Sawyers Bar area including the English Peak plutonic complex. The mapped bedrock (Irwin, 1980, 1972, 1994; Seyfert, 1965; Ernst, 1998) consists of three tectonically juxtaposed supracrustal units of oceanic and ocean-continental arc margin affinities. (1) On the east, the Stuart Fork HP metabasalt-metagabbro-metagraywacke terrane lies above the low-angle, east-dipping Soap Creek Ridge thrust fault (Goodge, 1995).
Figure 2. General geologic map of the Sawyers Bar map area, after Schmidt (1994), Ernst (1998), and Barnes et al. (2016). Sample sites and U-Pb zircon ages in Ma are indicated for the seven granitic rocks studied in this report (Table 1). In addition, a U-Pb zircon age previously reported by Allen and Barnes (2006) is also located (black asterisk). An early precursor to the Siskiyou contractional event involved nearly tangential suturing (ca. 174 Ma?) of the Eastern Hayfork and North Fork terranes prior to intrusion of the Uncles Creek satellite pluton.
The North Fork ophiolitic terrane occupies a medial zone and consists of the Lower Jurassic (Scherer and Ernst, 2008) St. Clair Creek laminated metacherts and fine-grained silicilastic, feldspar-poor meta-argillites interstratified with and overlain by a pair of sparsely pillowed, mafic metavolcanic suites—the amygdaloidal, Fe + Ti-rich North Fork mildly alkaline basalts and the Mg-rich mid-Jurassic (Hacker et al., 1993, 1995) Salmon River basaltic-diabasic-gabbroic arc theoleites. (3) On the west, the Eastern Hayfork terrane lies in tectonic contact beneath the North Fork terrane along the high-angle Twin Sisters reverse fault. The Eastern Hayfork map unit consists of chert-argillite, broken formation, and micrograywacke mélange hosting various locally derived and exotic blocks (Wright, 1982; Goodge and Renne, 1993; Scherer et al., 2010). The EPC rose and at its present level, stitches the juxtaposed terranes and locally obliterates the Twin Sisters fault.

Mesozoic plutonism began at ca. 174 Ma in the Sawyers Bar area with intrusion of the small, NW-trending Forks of Salmon pluton (Wright and Fahan, 1988; Allen and Barnes, 2006) and continued through emplacement of the EPC and adjacent WCB until as late as 159–156 Ma. The English Peak composite pluton is the largest plutonic complex in the Sawyers Bar map area. Contact metamorphism in the narrow EPC aureole reached maximum temperatures of ~500–600 °C at pressures of 200–300 MPa (Hacker et al., 1992; Ernst, 1999). Fluid exchange with the EPC and heated metasedimentary country rocks resulted in local increase in bulk-rock δ18O values to >15‰ in North Fork mafic metavolcanic rocks (Ernst and Kolodny, 1997). In the Sawyers Bar map area, Late Jurassic granitic plutons include the small, 159.1 ± 1.3 Ma Shelly Lake pluton (Dorais, 1983; Allen and Barnes, 2006), the tiny Black Bear Summit body, a suite of microdiorite dikes injected before and during EPC magmatism, and a group of alaskitic dikes emplaced after intrusion of the English Peak pluton (Ernst, 1993, table 3).

**Geology of the English Peak Plutonic Complex**

Irwin (1960) reported the EPC as broadly granitic. His reconnaissance map showed the plutonic complex continuous with the Wooley Creek batholith on the west. Later mapping by Seyfert (1965) demonstrated that these two plutons are separated by more than 3 km of metasedimentary rocks of the Eastern Hayfork terrane (Donato et al., 1982; Barnes, 1983). Seyfert also showed that the EPC consists of three plutonic units. The main English Peak pluton is nearly circular in outcrop, with a diameter of ~10–15 km (Fig. 2). It invaded the Eastern Hayfork–North Fork tectonic contact adjacent to two small satellite plutons—the Uncles Creek pluton to the northeast and the Heiney Bar pluton to the south. All igneous bodies are essentially undeformed.

The Uncles Creek pluton, containing distinctive elongate hornblende prisms, consists of quartz diorite, tonalite, and minor granodiorite. Based on similar bulk-rock compositions and textures, Barnes et al. (2016) identified the small northern appendage of the EPC (Fig. 2) as part of the Uncles Creek body. The Heiney Bar pluton exhibits a roughly concentric arrangement of gabbro through granodiorite.

We selected seven large, unweathered granitic rocks for zircon U-Pb geochronology from samples collected during the 2014 field season as well as from suites of EPC samples (>300 specimens) previously studied by Schmidt (1994) and by Ernst (1998). The investigated specimens are: Heiney Bar, RBEP-005; Uncles Creek, 180M; early stage, RBEP-010, RBEP-011, and 687M; Yellow Jacket Ridge–Chimney Rock contact zone, 906M; Chimney Rock, RBEP-022. These are all medium- to coarse-grained, massive rocks devoid of mafic inclusions and schlieren. Table 1 lists petrographically estimated modes and U-Pb zircon crystallization ages (see next section). Barnes et al. (2016) provided detailed
mineralogic, textural, and geochemical data and inferred genetic relationships among the wide range of intergradational rock types. Zircons were separated and purified from four rocks at GeoSep Services, LLC, Moscow, Idaho, and from the other three at Texas Tech University. Both facilities employed conventional grinding, magnetic, and heavy-liquid separation techniques.

### Zircon Cathodoluminescence (CL) Imagery

Zircon CL textures vary in the relative broadness or narrowness of discrete growth zones (e.g., Corfu et al., 2003), with a general correlation observable between higher modal proportion of biotite and broader growth zones (Fig. 3A). The broadest growth zones are present in zircon from Heiney Bar and early-stage samples (RBEP-005, RBEP-010, RBEP-011, and 687M), all of which contain ≥10% modal biotite. However, a few grains in RBEP-010, RBEP-011, and 687M display indistinct zonation (Supplemental Fig. S1).

**LA-ICP-MS Zircon U-Pb Analysis**

About 50–70 zircon grains from each sample along with zircon age standards (Temora2 as primary; R33 as secondary) were arranged in 1 × 0.1 cm rows on double-sided tape, encased in transparent epoxy, and polished ~30 μm through grain surfaces to expose their interiors. After polishing, mounts were gold coated and imaged at the Stanford–U.S. Geological Survey (USGS) Micro Analysis Center using secondary electron and cathodoluminescence detectors on a JEOL LV5600 scanning electron microscope equipped with a Hamamatsu photomultiplier tube. The images allowed distinction of zircon crystals from other minerals and guided the placement of analytical ablation pits into parts of grains devoid of cracks and non-zircon inclusions.

**Zircon CL Imagery**

**Table 1. Visually Estimated Modes of U-Pb Dated English Peak Plutonic Complex Rocks**

<table>
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<tr>
<th>Mineral (vol%)</th>
<th>Sample number</th>
<th>180M</th>
<th>RBEP-005</th>
<th>687M</th>
<th>RBEP-010</th>
<th>RBEP-011</th>
<th>RBEP-022</th>
<th>906M</th>
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<td>26</td>
<td>11</td>
<td>11</td>
<td>10</td>
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<td>48</td>
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<tr>
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<td>10</td>
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<td>18</td>
<td>28</td>
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</table>

**Table Footnote:** *Age ignoring six grains average: 176.5 ± 2.4 [4.0] Ma. **Age ignoring three grains average: 172.2 ± 3.2 [4.5] Ma.

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*1Supplemental Materials. LA-ICP-MS zircon U-Pb data, cathodoluminescence images of zircons analyzed, and plots used for age determination of intrusions and inheritance. Please visit [dx.doi.org/10.1130/GES01340.S1](http://dx.doi.org/10.1130/GES01340.S1) or the full-text article on www.gsapubs.org to view the Supplemental Materials.*
transported by helium carrier gas into the plasma source of an Element XR ICP MS, from which a positively charged ion beam was extracted and manipulated to measure the intensities of atomic masses $^{202}$Hg, $^{204}$Pb, $^{206}$Pb, $^{207}$Pb, $^{208}$Pb, $^{232}$Th, $^{235}$U, and $^{238}$U in single-collector mode. Raw data were reduced using the Iolite add-on for IgorPro to correct for down-hole fractionation and instrument background and to propagate associated random errors (Paton et al., 2010, 2011). Reduced ratios and error-propagated uncertainties of $^{206}$Pb/$^{238}$U, $^{207}$Pb/$^{235}$U, and $^{207}$Pb/$^{206}$Pb (uncorrected for common Pb) from individual analyses were exported from Iolite and used for age calculations (Supplemental Table S1 [see footnote 1]). A $^{207}$Pb correction-based approach was used to subtract nonradiogenic Pb from isochron ratios, under the assumption that common Pb measured was due to surficial contamination and can be subtracted using $0.836 \pm 0.005$ for upper $^{207}$Pb/$^{206}$Pb intercept as modern terrestrial common Pb ratio (Stacey and Kramers, 1975). The $^{207}$Pb-based approach is preferred over a $^{204}$Pb-based method to mitigate for low signal and poor precision of $^{204}$Pb measurements because internal uncertainties (at 2SE) of measured $^{204}$Pb count rates overlap negative values in 94 of 236 unknown measurements (without accounting for isobaric Hg interference) and exceed 50% of the measured count rates in 201 of 236 measurements. Thus, precisions of any ratios calculated using $^{204}$Pb results would be greatly impacted by propagation of these uncertainties. Analyses with significant common Pb are easily discernable in Supplemental Table S1 (see footnote 1) on the basis of higher $^{207}$Pb/$^{206}$Pb ratios.
Isoplot 3.75 (Ludwig, 2012) was used to calculate $^{207}\text{Pb}/^{206}\text{U}$ ages and $^{206}\text{Pb}/^{207}\text{Pb}$ ages (uncorrected for common Pb) for individual analyses and inverse concordia (uncorrected for common Pb) and $^{206}\text{Pb}/^{207}\text{Pb}$ weighted-mean age results. The weighted-mean $^{206}\text{Pb}/^{207}\text{Pb}$ age (418.6 ± 2.3 Ma) and inverse concordia age (419.5 ± 2.6 Ma) results (95% confidence level) from R33 secondary standard (419 Ma, Black et al., 2004) demonstrate the effective accuracy of the Temora2 primary standard. As a gauge of systematic error, the reproducibility (stated as % error) of downwhole-corrected $^{206}\text{Pb}/^{238}\text{U}$, $^{207}\text{Pb}/^{235}\text{U}$, and $^{207}\text{Pb}/^{206}\text{Pb}$ ratios measured in the R33 secondary standard was calculated from the (internal only) standard error and mean square of weighted deviates of each ratio category, yielding precisions of 1.7%, 1.8%, and 1.0% for the respective ratios at 95% confidence prior to propagation of excess error in the Temora2 standard. The $^{206}\text{Pb}/^{238}\text{U}$ weighted-mean age results from each sample are reported in Table 1 and are shown alongside inverse concordia plots as Supplementary Materials (see footnote 1). All uncertainties in text and figures are shown at the 95% confidence level, and as a conservative measure, we propagate a systematic 1.8% error (based on the poorest reproducibility of R33 analyses during the analytical session), with the total uncertainty shown in square brackets after the analytical uncertainty.

**U-Pb Zircon Ages and Interpretations**

The crystallization ages determined for the sampled intrusions indicate that they were emplaced over a 15–20 m.y. span (Fig. 3B, Table 1, and Supplemental Fig. S2 [see footnote 1]). The Uncles Creek (180M) and Heiney Bar (RBEP-005) metasomatized yield the oldest ages at 172.3 ± 2.0 [3.7] Ma and 166.9 ± 1.6 [3.4] Ma, respectively (Fig. 3B). Zircons from both rocks commonly are rimmed by dark CL domains (Fig. 3A). Samples that contain the most modal calcic pyroxene (RBEP-010, RBEP-011, and 687M) are all from the early stage of the main English Peak pluton and yield overlapping ages of 158.1 ± 1.1 [3.1] Ma, 158.0 ± 1.2 [3.1] Ma, and 160.4 ± 1.1 [3.1] Ma, respectively (Fig. 3B). The youngest ages are from two late-stage samples, one (RBEP-022) from the core Chimney Rock unit, the other (906M) from the Yellow Jacket Ridge unit straddling the gradational contact with the Chimney Rock unit. These samples yield overlapping ages of 156.3 ± 1.3 [3.1] Ma and 155.3 ± 1.2 [3.0] Ma, respectively (Fig. 3B).

Allen and Barnes (2006) obtained a LA-ICP-MS U-Pb age for one EPC sample, FPE-288, a quartz diorite from the early stage of the main English Peak pluton. Their reported age of 156.2 ± 1.0 Ma is younger than any of the three early-stage rocks reported here; but among all four samples, FPE-288 lies closest to the late-stage intrusions (Fig. 2). Assuming that different laboratory analytical results are comparable, it seems possible that early and late stages of the main pluton are compositionally and temporally intergradational.

Two samples investigated in this study appear to contain inherited or xenocrystic zircon. Of the 30 zircons analyzed from the Chimney Rock specimen, three have concordant, statistically older ages that define a common Pb intercept at 172.2 ± 3.2 [4.5] Ma; and of 30 Heiney Bar analyses, six concordant ages define a common Pb intercept at 176.5 ± 2.4 [4.0] Ma (Fig. 4A). The zircons that yielded these ages lack distinct cores in CL images (Fig. 3A). Most of the grains that yield older ages exhibit minimally sloped time-series age spectra on LA-ICP-MS analysis, consistent with a wholly xenocrystic origin to explain their older ages (e.g., grains 3 from RBEP-005 and grain 30 from RBEP-022; Fig. 4B). Conversely, two of the nine analyses with apparent inheritance exhibit a step function in the time-series age spectra (Fig. 4B), suggesting that a slightly older core domain was ablated during these two analyses. In both of the latter examples, the age of the base of the step function is identical to the crystallization age determined for the sample. However, the spectrum of each older domain shows progressively increasing age to an upper plateau, suggesting that the plateau represents an inherited component and the slope between base and plateau results from mixing of these components (Fig. 4B). In both cases, the age determined from the plateau is older than the $^{206}\text{Pb}/^{238}\text{U}$ age of the older results in each sample (Fig. 4). Based on these observations, the 176.5 ± 2.4 [4.0] Ma and 172.2 ± 3.2 [4.5] Ma pre-magmatic ages shown in Figure 4A may accurately represent the ages of some inherited material, but inheritance of additional older material (likely Early Jurassic >185 Ma; time scale of Walker et al., 2012) is also possible. Background-corrected $^{206}\text{Pb}$ and $^{207}\text{Pb}$ signal intensities from each of the analyses shown in Figure 4B indicate nominal amounts of nonradiogenic Pb but relatively elevated $^{206}\text{Pb}$ count rates in the analyses that yield older results. The latter observation, qualitatively suggesting higher U content in inherited zircon, is consistent with those domains having previously crystallized from relatively small volume melts (e.g., Claiborne et al., 2010).

At least four tectonic explanations for these older zircons can be proposed. (1) They could be xenocrysts derived from host rocks of the North Fork terrane, metasediments of which contain a suite of Early Jurassic zircons (Scherer and Ernst, 2008) or from the Uncles Creek pluton. (2) Alternatively, they could represent deitral zircons from the Western Hayfork terrane (WHT). Figure 5 presents a diagrammatic scenario for magmatic emplacement, differentiation, and rearrangement of the chiefly oceanic terrane amalgam in the Sawyers Bar area, modified from Barnes et al. (2016). If our reconstruction of the crustal section is correct, then it is probable that mid-crustal reservoirs for EPC magmas were hosted in the WHT. However, petrographic examination of >200 samples of the WHT has failed to identify deitral zircons (C.G. Barnes, personal commun., 2016), suggesting that this possibility is unlikely. (3) A third explanation is that the older zircons reflect inheritance from a lower-crustal source. Such a contaminant could represent the deep plutonic underpinnings of the Middle Jurassic arc. (4) Instead, the source could be arc-derived clastic rocks that were regranulated (Hacker et al., 2011) to the base of the crust during the ca. 170–168 Ma Siskiyou orogenic event (Coleman et al., 1988). It is noteworthy that some samples of the coeval WCB to the west and northwest of the EPC also contain inherited and/or xenocrystic zircons with Middle Jurassic ages (N. Coint and C.G. Barnes, personal commun., 2016). Inasmuch as Wooley Creek magmas did not intrude rocks of the North Fork terrane, the possibility exists that Middle Jurassic inheritance from deep crustal levels may be widespread among post-Siskiyou plutons in the Klamath Mountains.
Figure 4. Details of geochronologic analyses from inheritance-bearing samples RBEP-005 and RBEP-022. (A) Tera-Wasserburg concordia plots (uncorrected for common Pb) with error ellipses color coded to show interpreted inheritance-influenced age results (black) versus pluton age results (red). Common Pb chords (dashed lines) shown with upper concordia intercept set at 0.836 ± 0.005 (modern terrestrial common Pb, Stacey and Kramers, 1975). Age results are 207Pb/206Pb weighted means. Total uncertainty includes 1.8% systematic error discussed in methods. (B) Waveform spectra of down-hole fractionation-corrected 206Pb/238U age results in Ma (y-axis) plotted versus time (x-axis) from selected analyses. Zircon cathodoluminescence (CL) images of these grains are shown in Figure 3A. Each waveform shows ~20 seconds of data. Rectangles show time-integration windows used to calculate ages. Ages shown at top of each plot under analysis labels are those reported in Supplemental Table 1 (see footnote 1). Far left plots from each sample show examples of waveforms from analyses that appear older than the crystallization age determined for the respective sample. Center plots show waveforms with “step-function” character, suggesting mixing of two discretely aged components (see text). Black filled rectangle in center plots show the average of the entire integration, whereas the open rectangles and ages labeled on center plots show model ages resulting from breaking integrations into multiple components. Far right plots are example waveforms from zircon analyses that yield ages overlapping the determined crystallization ages of the samples. Gray filled horizontal rectangles provide comparisons of the crystallization age spectra to the spectra from inherited zircons, illustrating overlap of crystallization ages with younger components in “step-function” spectra shown in center, but younger than ages of inherited components. Age errors (2σ) calculated by Iolite as internal and propagated errors shown with propagated error in brackets and displayed as rectangle heights. Age uncertainty shown does not include propagation of 1.8% systematic error discussed in Methods section. Background-subtracted 204Pb and 206Pb signal intensities shown with 2σ internal uncertainties.
As noted above, both cathodoluminescence and LA-ICP-MS analyses failed to identify distinct, old cores in any of the analyzed zircons from the seven dated English Peak rocks. The overall U-Pb zircon age relations support the petrologic history summarized in previous sections. The magmas that formed the Uncles Creek and Heiney Bar satellitic plutons rose from mid-crustal reservoirs and solidified ca. 172 and ca. 167 Ma, respectively. About 7–12 m.y. later, a series of magmatic pulses built the concentrically zoned English Peak pluton during the interval ca. 160–155 Ma, beginning with the early mafic stages and ending with development of the concentrically zoned late stages. Judging from the substantial time gap reported here, as well as contrasting bulk-rock geochemical and isotopic data suggest that the latter evolved from the former (Barnes et al., 2016). The contrast in CL appearance between zircon from early- versus late-stage samples (Fig. 3A) also suggests contrasts in the zircon crystallizing environments of the respective magmatic suites.

An interesting outcome of our study is the unexpectedly old age of the Uncles Creek pluton. At ca. 172 Ma, this body is coeval with magmatism in the outboard Western Hayfork terrane (Hacker et al., 1995; Donato et al., 1996) and potentially with magmatism associated with detrital zircons derived from the North Fork terrane. It is also coeval with the Forks of Salmon pluton, which crops out directly to the west and southwest of the EPC (Fig. 2). In contrast, the 167 Ma Heiney Bar pluton is too young to be related to the WHT, but it is coeval with the oldest plutons of the Wooley Creek suite—specifically the
Vesa Bluffs and Castle Crags plutons (Fig. 1; Allen and Barnes, 2006). The time gap between emplacement of Uncles Creek and Heiney Bar magmas coincides with regional thrusting and metamorphism termed the Siskiyou orogeny (Coleman et al., 1988). Thus the pervasive low-temperature alteration of Uncles Creek rocks may be due to Siskiyou-age metamorphism. In contrast, the main English Peak pluton was emplaced during the peak of Wooley Creek suite magmatism, and its extended compositional range, from gabbro to granite, exemplifies this group of plutons (Allen and Barnes, 2006).

**CRUSTAL EVOLUTION OF THE CENTRAL KLAMATH MOUNTAINS**

These new insights on igneous geochronology and petrology of the Sawyers Bar area and relationships to the geologic history of the Klamath Mountains Province help support a tectonic model for this sector of the North American Cordillera. Ernst (1999) proposed a speculative petrotectonic history for the Sawyers Bar area and adjacent parts of the WTrPz, here updated slightly. During late Paleozoic–early Mesozoic time, paleo-Pacific oceanic crust approached and was subducted beneath the Klamath margin during long periods of transpression. Concomitantly, clastic debris eroded from the accreting, west-facing arc was supplied seaward and came to rest in the incoming ophiolitic basement. Eastward underflow of the oceanic lithosphere resulted in formation, accretion, and HP recrystallization of the Stuart Fork blueschist ± eclogite complex, followed by its exhumation at ca. 227 Ma (Hotz et al., 1977; Goodge, 1989, 1995). Arc tholeiite lavas, alkaline basalt flows, and distal turbidites were deposited and progressively accreted outboard of the Stuart Fork lithotectonic unit in deep marine (Eastern Hayfork) and marginal arc (North Fork) settings during end-of-Permian to earliest Jurassic time (Wright, 1982; Ernst et al., 1991; Scherer and Ernst, 2008). Suturing of the North Fork–Eastern Hayfork terrane amalgam against the yet farther outboard Western Hayfork calc-alkaline arc rocks and their Rattlesnake Creek oceanic melange basement probably occurred by ca. 170–168 Ma. In the Sawyers Bar area, this accretion (Siskiyou orogeny) was attended by regional folding, granitic pluton intrusions, and prehnite-pumpellyite to biotite-grade greenschist-facies metamorphism at 300–425 °C and 300 ± 100 MPa (Donato, 1989; Hacker et al., 1992; Wright and Wyld, 1994; Ernst, 1999; Allen and Barnes, 2006; Barnes et al., 2006).

The arcuate Klamath Mountains stack of allochthons is now sited ~100–150 km west of the trend of the Sierra Nevada Range of northern California, and still farther outboard from the Blue Mountains (Schwartz et al., 2011; Johnson et al., 2015; LaMaskin et al., 2015) of eastern Oregon. A left-lateral offset of the Klamath salient seems required by the spatial disposition of Upper Jurassic on-lap strata resting on the western Sierran Foothills and western Klamath Mountains, whereas Cretaceous Great Valley strata lie inboard of the Klamaths and outboard of the Sierran arc (Ernst, 2012). Palinspastic reconstruction combined with clockwise back-rotation of 20° of the Klamath salient, as shown in Figure 6, would restore the complex to an end-of-Jurassic, curvilinear Andean-type margin (Ernst, 2012). A 20° back-rotation also would minimize the large
apparent offset between the Klamath Mountains and, speculatively, correla-
tive units in the Blue Mountains. This restoration does not remove the accru-
ate bulge (i.e., eastern concavity) reflecting ~50 km of additional deformation
induced by differential slip of the Klamath Mountains salient along ENE-trend-
ning transform faults relative to the adjacent lithospheric plate segments of
the formerly continuous, broadly calc-alkaline arc (Ernst, 2015; fig. 3).

How relative displacement of the Klamath lithotectonic stack took place
is obscure, but areal disposition of the sedimentary overlap strata indicates
a mainly earliest Cretaceous (ca. 140–136 Ma) westward transportation and
minor counterclockwise rotation of the salient relative to the active Sierran
Arc. A CCW rotation of ~20° would also account for the more westerly trend of
the Jurassic Andean arc relative to its Cretaceous NNW trend. Thermochrono-
logic research in the Western Klamath terrane by Batt et al. (2010) has docu-
mented an episode of 40Ar/39Ar-based cooling-degassing of rocks and min-
erals at ca. 135–126 Ma, compatible with an earliest Cretaceous oceanward
transport of the Klamath Mountains salient away from the Sierran Nevada arc.
Combined with fission-track ages, Batt et al. (2010) interpreted their data to re-
flect thermal annealing-recrystallization attending exhumation of the Klamath
Mountains and erosional stripping of a widespread cover sequence (see also
Sliter et al., 1984).

This outboard extrusion of the Klamath Mountains stack of allochthons
may have been a tectonic consequence of the arrival and subduction of a seg-
ment of thin, young, hot oceanic lithosphere (Wang et al., 2013). Bordered on
both north and south across ENE-trending sinistral faults by old, cold, much
thicker oceanic lithosphere (e.g., Sager et al., 1999; Wells et al., 2014), the
Klamath slab must have been largely decoupled from the superjacent stack
of gently east-rooting crustal allochthons. Collision of the thick oceanic litho-
sphere on both north and south could have produced contraction and east-
ward displacement of the continental margin relative to the Klamath Moun-
tains, which would thus assume its outboard location. Moreover, shortening
in the Sierran arc might have caused rotation of the Foothills terrane collage
to the present near-vertical stack of imbricate sheets. As the Klamath salient
was displaced relatively westward from the trend of the active Cordilleran vol-
canic-plutonic arc during earliest Cretaceous time, it evidently moved off the
deep-seated magmagenic zone and failed to participate in the massive Sierra

Various pulses of magmatic activity in the Klamath Mountains attest to the
progressive construction of the Jurassic arc along this part of the Cordilleran
margin. English Peak plutonic complex magmatism exemplifies the gradual
intermediate-to-felsic modification of the upper crust in the central Klamath
Mountains. The much larger Sierra Nevada and Peninsular Range batholiths
exhibit an outboard, NW-trending belt composed chiefly of Jurassic mafic plu-
ton, whereas the voluminous inboard, NNW-trending zone of mainly Creta-
ceous plutons is more felsic in bulk-rock chemistry (e.g., Kistler and Petersen,
1973, 1978; Silver et al., 1979; Todd and Shaw, 1985; Ernst et al., 2009, fig. 6). Overall, the Klamath salient shows little evidence of this Andean-type arc evo-
lution, perhaps reflecting post-Siskiyou tectonic unrest. As documented in this
study, Middle to Late Jurassic igneous activity preceded earliest Cretaceous
onset of westward displacement of the crustal stack of Klamath allochthons,
thereby abandoning the upper mantle site of magma genesis fueling the active
Cordilleran arc.

**SUMMARY**

The inferred magmatic intrusion, differentiation, and terrane accretion of
the dominantly oceanic assemblage in the Sawyers Bar area is summarized in
Figure 5. As the WTrPz accreted due to the episodic arrival of outboard ophio-
litic units, terrigenous debris was sourced and shed from landward Klamath
lithotectonic belts, forming clastic sedimentary wedges interdigitating with
the allochthonous ocean crust and overlying deep-sea sediments. Continu-
ing transpressive plate underflow, low-grade regional recrystallization (300–
425 °C, ~300 MPa), and later contact metamorphism (500–600 °C, ~250 MPa)
accompanied the sequential intrusion of granitic plutons (172 + 167 Ma and
160–155 Ma) derived from the upper mantle and basal parts of the accreting
arc crust. Ascent of crystallizing plutons gradually enriched the intermediate
bulk-compositional nature of the upper crust in sialic components, not only
in the Sawyers Bar map area, but regionally throughout the central Klamath
Mountains. Modification of the crust by magma-driven differentiation and em-
placement declined abruptly in earliest Cretaceous time as the west-vergent
Klamath stack of thrust sheets gradually moved off the upper mantle realm of
calc-alkaline magma production.

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