Earliest Cretaceous Pacificward offset of the Klamath Mountains salient, NW California–SW Oregon

W.G. Ernst
DEPARTMENT OF GEOLOGICAL AND ENVIRONMENTAL SCIENCES, STANFORD UNIVERSITY, STANFORD, CALIFORNIA 94305-2115, USA

ABSTRACT

Although Late Triassic igneous rocks are present, the Sierra Nevada–Klamath calc-alkaline arc began massive construction along the continental margin at ca. 170 Ma during oblique underflow of paleo-Pacific oceanic lithosphere; intense activity continued throughout the volcanic-plutonic belt until at least ca. 140 Ma. This volcanic-plutonic arc supplied detritus to the Mariposa-Galice proximal clastic sequence starting by ca. 165–160 Ma. After onset of uppermost Jurassic Myrtle overlap sedimentation on the western flank of the Klamath Mountains, but before Hornbrook and Valanginian Great Valley Group overlap deposition on the eastern and southeastern sides, the Klamath Mountains salient was displaced ~200 km westward relative to the igneous arc. The orogen thus moved off the deep-seated magmagenic zone underlying the arc and did not participate in the massive Sierra Nevada igneous flare-up between ca. 125 and ca. 85 Ma. I suggest that, beginning at ca. 140 Ma, underflow of a young, thin oceanic slab beneath the Klamath Mountains slid beneath the gently east-dipping stack of thrust sheets without disturbing their inclinations. Subduction and collision of much thicker oceanic lithosphere on both the north and south caused contraction, eastward relative displacement of the continental margin arc, and ductility-enhanced rotation of the superjacent stack of allochthons into near-vertical dips. After a magmatic lull, heightened igneous activity in the Sierra Nevada recommenced at ca. 125 Ma. The earliest Cretaceous oceanward plate junction rollback lay directly offshore the Klamath imbricate orogen, but to the south trapped the ca. 165 Ma Coast Range ophiolite on the North American side of the suture. After ca. 140 Ma, first-cycle arc detritus began to accumulate on the mafic igneous basement flooring the Great Valley forearc, and turbiditic clastic material also was carried oceanward across the forearc into the coeval Franciscan trench.

INTRODUCTION

Arcuate, shallowly east-dipping thrust sheets in the Klamath Mountains consist mainly of Paleozoic through earliest Late Jurassic oceanic basement terranes and overlying superjacent units that were stranded along the North American margin by chiefly transpressive plate motions. Although high-pressure, low-temperature phase assemblages attest to episodes of Paleozoic to early Mesozoic subduction, the accretion of variably metamorphosed ophiolitic terranes overlain by distal turbidites reflects chiefly transform and transpressive lithospheric slip (Saleeby et al., 1992; Ernst et al., 2008). Old, fault-bounded Klamath Mountain units on the east are structurally high in the accretionary stack, whereas the ages of successively added lower allochthons decrease progressively toward the west (Irwin, 1972, 1994). The tectonized, imbricated collage of west-vergent lithostratigraphic terranes consists of basal ophiolitic units, chiefly overlain by cherts and fine-grained terrigenous strata (e.g., Frost et al., 2006), all invaded by Jurassic calc-alkaline arc plutons. The accreted terrane assembly of the Klamath Mountains has long been correlated with the northern Sierran Foothills based on similar rock types, structures, ages of the rock packages, the progressive oceanward assembly of successively younger geologic units, and their times of deformation (Davis, 1969; Davis et al., 1980; Wright and Fahan, 1988; Wright and Wyld, 1994; Irwin, 2003). However, the juxtaposed Sierran Foothill terranes stand nearly vertically, whereas, in contrast, Klamath thrust sheets root gently to the east.

Figure 1 shows that the Klamath Mountains concave-to-the-east contractual assemblage lies well offshore of the trend of the Sierra Nevada Range. Judging by the map relationships, this salient appears to be situated ~200 km west of the formerly contiguous Sierran segment of the curvilinear arc (Fig. 2). North of the Klamath Mountains promontory, a major eastward jog toward apparently correlational lithologic units in the Blue Mountains (LaMaskin et al., 2011; Schwartz et al., 2011) suggests the possibility of a much greater oceanward offset of the Klamath Mountains relative to the late Mesozoic accretorian continental margin of eastern Oregon (Snow and Barnes, 2006). The manner in which this tectonic offset of the Klamath Mountains collage was accomplished remains obscure. This paper summarizes geologic evidence for the timing of the offset and proposes a speculative mechanism to explain it.

TIME OF OUTBOARD RELATIVE OFFSET OF THE KLAMATH MOUNTAINS

Geologic constraints suggest an earliest Cretaceous westward displacement of the salient relative to the Sierran Foothills. Whether the Klamath Mountains province moved westward geographically, or the Sierra Nevada Range moved eastward, or both were displaced, is unknown. Only the differential offset is considered here.

(1) Late Jurassic deposition of the Galice Formation in the westernmost Klamath Mountains (MacDonald et al., 2006) and the correlational deposition of the Mariposa Formation in the westernmost Sierran Foothills (Snow and Ernst, 2008) exhibit the full ~200 km of apparent sinistral offset; hence, these proximal siliciclastic units evidently were laid down unconformably on the western edge of a continuous Sierra-Klamath arc prior to most of the differential slip (Ernst et al., 2008). Uppermost Jurassic to Lower Cretaceous Myrtle clastic strata overlie the Galice Formation in SW Oregon (Imlay et al., 1959; Dickinson, 2008, fig. 3A) and so were
also displaced oceanward by relative left-lateral offset of the Klamath Mountains salient.

(2) In marked contrast, the mid- and Upper Cretaceous Hornbrook Formation was deposited with angular unconformity on the eastern, landward side of the Klamath Mountains near the California-Oregon border (Sliter et al., 1984; Nilsen, 1993; Surpless, 2011) and so must have accumulated after oceanward displacement. Similarly, Valanginian-Hauterivian (i.e., Lower Cretaceous) Great Valley Group sandstones rest on the uplifted and eroded Shasta Bally Batholith (U-Pb zircon age 136 Ma) and the preexisting eastern Klamath basement directly north of the Cold Fork–Elder Creek fault zone at the northern end of the Sacramento Valley (Jones and Irwin, 1971; Blake et al., 1988, 1999).

(3) Jones and Irwin (1971) recognized and documented an upward nonmarine-marine transition in Great Valley Group strata bordering the SE Klamath Mountains. They reported that this Valanginian paleoshoreline was offset more than 100 km eastward to the south of sinistral “tear faults,” which are now considered as members of the Cold Fork–Elder Creek fault system (Blake et al., 1999). Thus, these offsets must have occurred in post-Valanginian time.

(4) Locations of erosional remnants of siliciclastic strata bordering the Klamath Mountains are shown schematically in Figures 1 and 2. Based on the spatial distribution of erosional remnants of the Myrtle, Galice, and Mariposa Formations overlying Jurassic and older basement rocks, outboard relative displacement of the Klamath salient began by ca. 140 Ma. This apparent westward offset was well under way by ca. 136 Ma, prior to Hornbrook + Great Valley Group overlap deposition on the Shasta Bally Batholith and other eastern Klamath units. The seaward offset of the Klamath Mountains apparently occurred during a brief interval of chiefly left-lateral slip along the western margin of North America (Saleeby, 1992; Saleeby et al., 1992; Harper et al., 1994) that terminated shortly after development of the Kimmeridgian–Tithonian cusp in the American apparent polar wander paths (May and Butler, 1986; Schettino and Scotese, 2005).

(5) Geologic relationships among the Klamath Mountains, the Franciscan Complex, and the Great Valley Group in the vicinity of the so-called Yolla Bolly triple junction (Blake et al., 1999) are shown in Figure 3. In addition to the terrane-bounding, NW-trending South Fork and Coast Range faults, a family of transverse breaks transects Great Valley Group stratigraphic units in this somewhat more detailed map area. Especially significant faults include, from north to south, the Oak Flat, Sulphur Spring, Cold Fork, and Elder Creek structures. The Oak Flat–Sulphur Spring structures strike ENE and are appropriately oriented to represent the inferred zone of earliest Cretaceous sinistral slip, although the offset is slightly less than 80 km (see Figs. 2 and 3). On the south, the Cold Fork–Elder Creek fault zone has been interpreted by Wright and Wyld (2007) as an important junction accommodating several hundred kilometers of dextral slip. Judging by the field relations documented in Figure 3, the Cold Fork–Elder Creek fault zone and its subparallel breaks truncate the Oak Flat–Sulphur Spring
Klamath salient offset

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Structures. Thus, outboard displacement of the Klamath promontory was pre-Hauterivian, prior to right-lateral motion described by Wright and Wyld—which would represent a post-Barremian event. Thicknesses of the Hauterivian–Barremian (i.e., lowermost Cretaceous) Great Valley Group sections in the Yolla Bolly triple junction area monotonically increase northward, so this group of faults underwent at least some slip to ca. 125 Ma (Constenius et al., 2000; Wright and Wyld, 2007).

6. Although igneous activity commenced in the Sierran arc in Late Triassic time (e.g., Stern et al., 1981; Dilles and Wright, 1988), voluminous calc-alkaline granitic plutons intruded the Klamath-Sierran arc over the interval 170–140 Ma (Hacker and Ernst, 1993; Hacker et al., 1993; Irwin and Wooden, 1999; Irwin, 2003; Snoke and Barnes, 2006); the 170 Ma to 140 Ma igneous bodies are scattered among the comparably abundant Late Jurassic granitoids, and at least the Late Jurassic and earliest Cretaceous granitoids sparsely intrude the Galice and Mariposa units on the west as well as the eastern extent of the superjacent wall rocks. Thus, a continuous Klamath–Sierra Nevada volcanic-plutonic arc—now offset—clearly was located above the magmagenic zone supplying the calc-alkaline arc at least until ca. 140 Ma.

7. Recent thermochronologic research in the Western Klamath terrane reported by Batt et al. (2010) documented an episode of 40Ar/39Ar-based cooling-degassing of rocks and minerals at ca. 135–126 Ma, more or less compatible with earliest Cretaceous rifting and transportation of the Klamath Mountains province away from the Sierra Nevada arc. Coupled with new fission-track ages, Batt et al. also interpreted their data to reflect thermal events associated with Late Cretaceous thermal annealing-recrystallization attending exhumation of the Klamath Mountains province and erosional stripping of a widespread, thick Hornbrook cover sequence (see also Sliter et al., 1984).

8. As a result of the oceanward projection of the salient, the convergent plate boundary rolled back to directly west of the Klamath Mountains. On the south, this earliest Cretaceous step-out of the transpressive plate junction stranded an inboard Middle and Upper Jurassic section of oceanic crust–capped lithosphere as the Coast Range ophiolite, forming the western basement of the Great Valley forearc basin (Ernst et al., 2008; Ernst, 2011). Such a rollback of the oceanic plate requires that re-establishment of the subduction-deprived magmagenic zone beneath the Sierran arc would have involved a period of eastward underflow, possibly accounting for the ca. 140–125 Ma magmatic lull observed in the Early Cretaceous Andean-type arc (Stern et

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Figure 2. Generalized geologic map of the Klamath Mountains and the western Sierran Foothills, modified after Irwin (1981, 2003), Sharp (1988), Edelman and Sharp (1989), Ernst (1998), and Snow and Scherer (2006). The Western Klamath terrane includes the Galice Formation, and the Upper Jurassic Sequence in the Sierran Foothills includes the Mariposa Formation. Klamath-margin locations of the northernmost Great Valley Group (GVG), Myrtle (M), and Hornbrook (H) Formations are indicated. Also shown is the Oak Creek–Sulphur Spring sinistral fault zone (OF-SS), but not the slightly younger Cold Fork–Elder Creek fault zone. Although the Klamath Mountains are displaced ~200 km from the northern extension of the Jurassic Sierran arc, slip across the Oak Creek–Sulphur Spring fault zone is substantially less than 200 km because of viscous drag and arcuate curvature in the salient.
al., 1981; Chen and Moore, 1982; Hacker et al., 1995; Wooden et al., 1999).

(9) Terrigenous debris derived from the landward calc-alkaline arc began to arrive at the Franciscan oceanic trench and intervening Great Valley Group by ca. 140 Ma (DeGraaff-Surpless et al., 2002; Surpless et al., 2006). Clastic turbiditic strata accumulated in the subduction zone and forearc basin over the next ~90 m.y. (Blake et al., 1988; Cloos and Ukar, 2010; Ernst, 2011). The most voluminous sedimentation took place over the interval ca. 125–60 Ma (Dumitru et al., 2010).

(10) Significantly, the Klamath Mountains did not participate in the Sierran and Peninsular Ranges flare-up in igneous activity between ca. 125 and ca. 85 Ma (Stern et al., 1981; Bateman, 1992; Saleeby et al., 1992; Coleman et al., 2003). This massive production of arc intrusives ± extrusives may have resulted from rapid, nearly orthogonal oceanic plate subduction (Ernst et al., 2009a). In any case, mid- and Upper Cretaceous erosion of the continental-margin arc supplied sedimentary debris to the Great Valley forearc directly east of the Klamath salient, as well as to the Cretaceous Franciscan trench on the west.

(11) Several periods of profound subduction are attested to not only by landward volcanic-plutonic arc assemblages and their erosional debris, but also by recovered high-pressure, low-temperature blueschists and eclogites that recrystallized at ca. 225 Ma, ca. 170–155 Ma, and ca. 135–85 Ma (e.g., Wakabayashi, 1992, 1999; Ernst, 2011). The generations of these high-pressure metamorphic rocks testify to intervals characterized by substantial components of plate subduction—clearly, these were not times of across-the-arc transform faulting along the Californian continental margin. Aspects of these geologic constraints are summarized in Figure 4.

(12) The $^{87}\text{Sr}/^{86}\text{Sr} = 0.706$ isopleth for post-Paleozoic silicic igneous bulk-rock compositions (Kistler and Peterman, 1973, 1978; Burchfiel et al., 1992) marks the approximate western margin of Precambrian-Paleozoic North American basement. This 0.706 line runs N-S through central Nevada, and on the north apparently is deflected ~200 km to the east (Kistler, 1990; Cowan and Bruhn, 1992) at the latitude of the Klamath Mountains—a rough mirror image of the posited westward relative offset of the Klamath salient. Much of the continental crust west of the ancient North American basement edge consists of far-traveled oceanic terranes, so any bilateral E-W extension would necessarily have been accommodated chiefly within these Jurassic and older accreted terranes.

To conclude, the E-W relative offset of the Klamath Mountains–Sierran Foothill belts apparently occurred during a brief period at the beginning of the Cretaceous, involving ~200 km sinistral slip along the southern margin of the salient, and probably more substantial dextral offset along its northern edge. The intrusion of
Paleozoic–Mesozoic construction of the Blue Mountains–Klamath Mountains–Sierra Nevada lithotectonic complex on the western margin and nearby offshore of North America took place through episodic arrival and suturing of exotic ophiolitic terranes, accretionary assembly of largely clastic sedimentary units, and the Middle Jurassic–Cretaceous construction of a calc-alkaline volcanic-plutonic arc. Exhumation and erosion of the arc supplied massive amounts of first-cycle detritus to the Great Valley forearc bordering the continental margin, as well as to the outboard paleo-Pacific Franciscan trench.

This geohistory seems to be well established (e.g., Hamilton, 1969; Dickinson, 1970, 2008; Irwin, 2003). However, the postulated westward displacement of the arcuate, imbricate Klamath Mountain terranes relative to the Andean-type margin probably reflects an anomaly in the plate-tectonic evolution of this sector of western North America. Lithospheric plates generally are carried along by asthenospheric flow, so the ultimate cause of emplacement of the Klamath salient requires us to decipher the regional history of earliest Cretaceous upper-mantle circulation. However, ancient mantle kinematics must be ascertained from the effects of crustal deformation, and deep-seated forces responsible for generating the Klamath Mountains salient almost certainly would have been obliterated later along the convergent or transpressive plate junction.

During Early Cretaceous time, the broad Farallon plate evidently impinged against the western edge of the continent in a dextral transpressive mode (Engelbreton et al., 1984; May and Butler, 1986; Schettino and Scotese, 2005; Sager, 2007; Wright and Wyld, 2007). Scenarios attempting to account for the structure and displacement of the Klamath Mountains salient relative to the calc-alkaline arc involve the arrival of far-traveled oceanic lithosphere transporting: (1) a mantle plume head; (2) a spreading ridge; (3) a thermal anomaly localizing backarc spreading; (4) an exotic microcontinental fragment or island arc; (5) an oceanic plateau; or (6) a subparallel brace of major-offset transform faults and bounding escarpments.

Underflow of a mantle plume head would have resulted in a high-heat-flow regime, likely generating substantial amounts of ca. 140 Ma and younger mafic + felsic magmas as well as extensional disruption of the Klamath arc, none of which is evident in the geologic record. Collision with a N–S–trending spreading ridge ought to show a lengthy set of continental-margin offsets and thermal highs ± postcollision igneous activity, rather than the current curvilinear calc-alkaline arc marked by just a single promontory; thus, impingement of a long, segmented ridge would not seem to replicate the Klamath Mountains salient. Widespread backarc spreading would also result in post–140 Ma ophiolitic rocks, but such are not recognized. The only important, far-traveled oceanic lithosphere transport appears to be the Central metamorphic belt, and this lithostratigraphic unit collided with the landward terrane assembly prior to Late Triassic blueschist-facies metamorphism developed in the outboard Stuart Fork terrane, so microcontinental collision also fails to account for the salient. However, the earliest Cretaceous underflow of either a buoyant
oceanic plateau or a section of ancient, thick, low-density oceanic lithosphere bounded to the north and south by major ENE transforms could produce flow-parallel–trending crustal faults bounding the Klamath promontory; subhorizontal impingement of a thick, cold slab of lithosphere characterized by a low-heat-flow regime would cause the extinction of calc-alkaline magmatism in the Klamath Mountains. However, the underflow an old, high-riding, thick lithospheric platelet resulting in oceanward instead of landward displacement of the salient relative to a curvilinear, vigorously active coeval igneous arc seems counterintuitive.

Perhaps a more likely scenario, illustrated schematically in Figure 6, involves the hypothesized convergence of a young, relatively warm, thick lithospheric platelet resulting in oceanward instead of landward displacement of the salient relative to a curvilinear, vigorously active coeval igneous arc seems counterintuitive.

Figure 5. Schematic petro-tectonic scenario for the mid-to-late Mesozoic evolution of northern and central California, modified from Ernst et al. (2008). It postulates: (A) late Paleozoic through Early Jurassic, mainly dextral strike-slip arrival of oceanic terranes along the continental margin; (B) an interval of calc-alkaline arc-building transpression at ca. 170–140 Ma; (C) arc activity temporarily decreased by westward displacement of the Klamath oceanic arc at ca. 140–136 Ma, oceanward step-out of the Farallon plate, and the stranding of a section of preexisting oceanic lithosphere, the Coast Range ophiolite, south of the Klamath Mountains salient; and (D) after a magmatic lull, rapid, nearly orthogonal subduction at 125–85 Ma. The brown and red dashed lines mark the trends of the Middle Jurassic emergent arc and the massive, mid-Cretaceous calc-alkaline arc, respectively, after the compilation by Irwin (2003). Abbreviations: M—Myrtle, H—Hornbrook, GVG—Great Valley Group.

CONCLUSIONS

After scattered Late Triassic igneous activity, a major calc-alkaline arc began to form in the Sierra Nevada and Klamath Mountains at ca. 170 Ma attending transpressive subduction of paleo-Pacific oceanic lithosphere beneath...
the Klamath accretionary stack. Slightly later, modulated along the Oak Creek–Sulphur Creek motion proposed in this paper was accommodated along the inboard Hornbrook Formation and the outboard Myrtle deposition but prior to that the stacked allochthons in the Sierran Foothills, rotation to essentially vertical inclination of both the north and south caused contraction, and eastward displacement of the continental margin crust, resulting in contraction and rotation of the accreted collages into relatively steeply dipping sections. Arrows show direction of relative crustal shortening ± backarc extension (no differential plate motions); bounding transforms of the Farallon oceanic lithosphere are assumed to have been sub-parallel, with ENE trends only constrained by offsets in the preexisting curvilinear arc.

Figure 6. Diagrammatic sketch of the hypothesized impingement of a segmented Farallon oceanic plate beneath the western North American margin at ca. 140–136 Ma. The thin, warm slab sliding beneath the Klamath Mountains evidently was largely decoupled from the overlying section of gently east-dipping thrust sheets. In contrast, the postulated thicker lithosphere on both the north and south was strongly coupled to the continental margin crust, resulting in contraction and rotation of the accreted collages into relatively steeply dipping sections. Arrows show direction of relative crustal shortening ± backarc extension (no differential plate motions); bounding transforms of the Farallon oceanic lithosphere are assumed to have been sub-parallel, with ENE trends only constrained by offsets in the preexisting curvilinear arc.

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Erratum

Metamorphic constraints on the character and displacement of the South Tibetan fault system, central Bhutanese Himalaya
F.J. Cooper, K.V. Hodges, and B.A. Adams
(v. 5, no. 1, p. 67–81, doi: 10.1130/L221.1)

In the “RSCM Thermometry” section (page 74, paragraph 5), Cooper et al. stated that both the Beyssac et al. (2002a) and Rahl et al. (2005) RSCM calibrations used a micro-Raman system with a 514 nm wavelength laser. In fact, Rahl et al. (2005) used a 532 nm laser, as did this study. Despite this, they chose not to use the Rahl et al. (2005) calibration because of the greater uncertainty stemming from the addition of peak height as a variable in the calculation.