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Magnetic fabrics of arc plutons reveal a significant Late Jurassic to Early Cretaceous change in the relative plate motions of the Pacific Ocean basin and North America

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ABSTRACT

Contrasting magnetic fabrics in five successively emplaced syntectonic plutons reveal temporal and spatial variations in tectonic strain in the oceanic terranes of the Blue Mountains province, northeastern Oregon, during the Late Jurassic to Early Cretaceous. The inferred strain regimes changed from: (1) thrusting and sinistral shearing at ca. 160 Ma, to (2) horizontal stretching at ca. 147 Ma (in the forearc–accretionary wedge Baker terrane), to (3) dextral transpression that started from ca. 140 Ma onward and was associated with progressive anticlockwise rotation of the principal horizontal shortening direction from ca. 130 Ma to ca. 126 Ma (in the Wallowa oceanic arc terrane). These progressive strain reorientations are interpreted in terms of an outboard Wallowa-Baker terrane collision, lateral extrusion, docking of the amalgamated Blue Mountains superterrane into a continental-margin reentrant, and onset of oroclinal bending, respectively. The changes in crustal strains are then interpreted as recording a progressive change in relative motions between the Pacific Ocean basin and North America and suggest a transition from Late Jurassic sinistral deformation to Early Cretaceous dextral terrane translations along the paleo-Pacific margin. We speculate that these events may have been linked along large portions of the North American Cordillera, from central California to Blue Mountains, and may have culminated in the onset of accretion in the Franciscan complex and voluminous plutonism in the Sierra Nevada magmatic arc. A similar plate-kinematic change is inferred to have occurred in British Columbia several tens of millions of years later (at ca. 100 Ma), implying that these kinematic transitions may have varied in space and time along the length of the Cordilleran orogen.

INTRODUCTION

The prolonged convergence of the Pacific Ocean basin (composed of several lithospheric plates, e.g., Farallon and Kula) and the North American craton (Laurentia) since the late Paleozoic produced the North American Cordillera and shaped the western margin of the continent (Fig. 1A). The relative motions of lithospheric plates underlying the Pacific Ocean basin with respect to the North American craton have been fairly well documented for Late Cretaceous–Cenozoic to recent times and were characterized by tens of millions of years periods of constant-direction motion, interrupted by sudden changes in relative velocities with duration of perhaps only thousands of years (e.g., Atwater, 1970; Engebretson et al., 1985; Doubrovine and Tarduno, 2008; Doubrovine et al., 2012). Pre-Cenozoic plate motions are increasingly difficult to reconstruct as virtually all of the Kula and most of the Farallon plates have been subducted; hence, plate motions are traditionally inferred from on-land, and often ambiguous, large-scale deformational structures, accretion patterns, petrologic and paleomagnetic data, and radiometric ages. Consequently, significant controversy persists regarding the kinematics of the Pacific and North America plate convergence during the Mesozoic.

Existing Juro–Cretaceous plate tectonic models based on regional structures in various terranes throughout the western North American Cordillera propose conflicting overall plate kinematics including sinistral, orthogonal, and dextral convergence (e.g., Oldow et al., 1984; Avé Lallemant et al., 1985; McClelland et al., 2000; Umhoefer, 2003; Ernst et al., 2008; Anderson, 2015; Saleeby and Dunne, 2015). On the other hand, paleomagnetic and ocean-floor age data indicate a significant kinematic switch during Late Jurassic to Early Cretaceous as the Pacific, Kula, and Farallon plates changed their drift from southward to northward with respect to the cratonal North America. Engebretson et al. (1985) suggested that this change occurred between 145 Ma and 110 Ma; however, Dumitru et al. (2010) subsequently revised its timing to ca. 123 Ma. It has been assumed that the northward drift of the Pacific, Kula, and Farallon plates has continued from this time to the present day.

The Late Jurassic to Early Cretaceous change in relative plate motion was a key geodynamic event for the growth of the Cordilleran margin of North America. The purpose of this contribution is to examine and better constrain the exact kinematics and timing of this change. We use variations in magnetic fabrics derived from anisotropy of magnetic susceptibility (AMS) measurements from

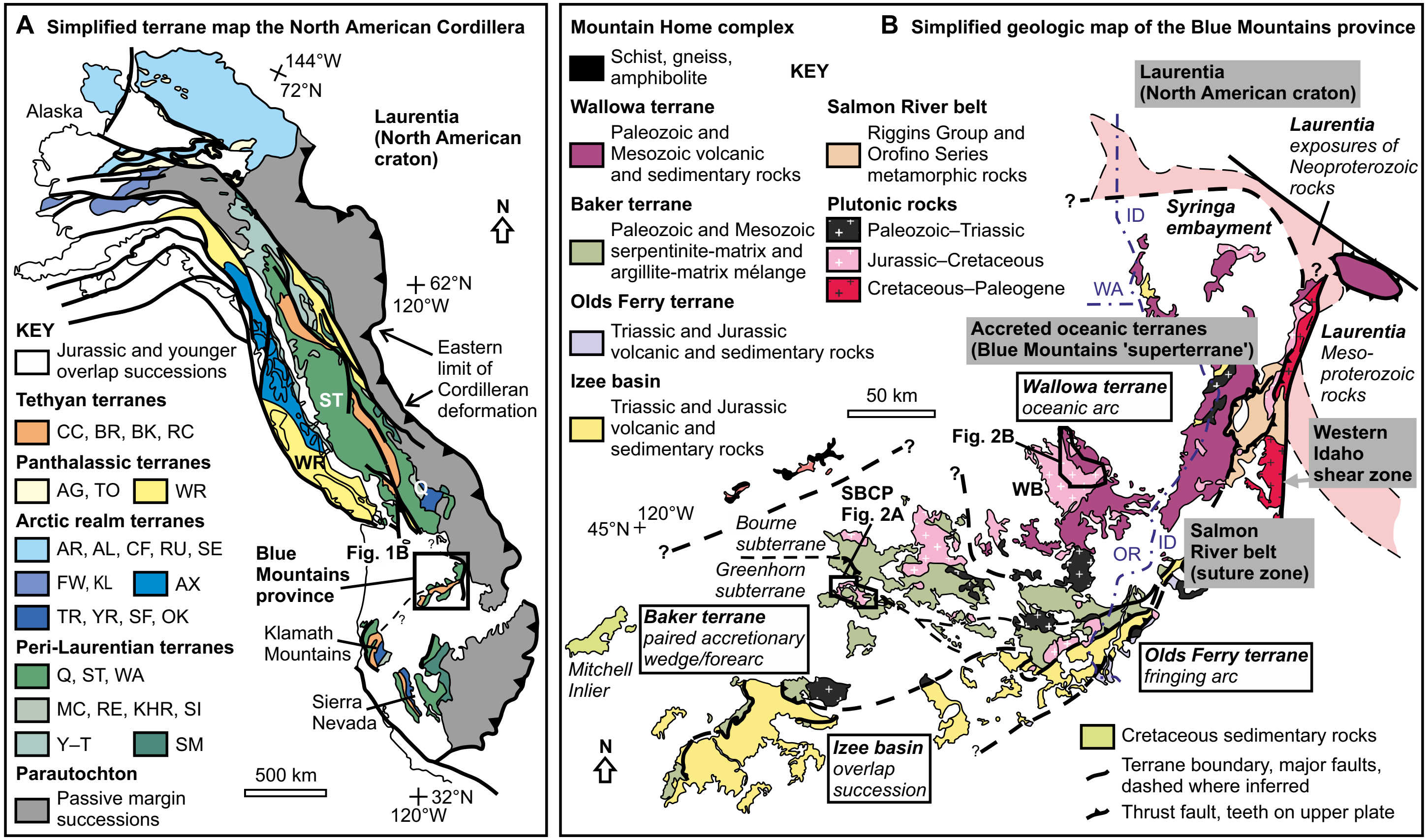

Figure 1. (A) Schematic map showing the principal tectonostratigraphic terranes and their possible affinities in the North American Cordillera. Base map modified after Piercey and Colpron (2009). Terranes: AG—Angayuchan; AL—Alaska; AR—Arctic; AX—Alexander; BK—Baker; BR—Bridge River; CC—Cache Creek; CF—Coldfoot; FW—Farewell; KHR—Klinkit and Harper River; KL—Kilbuck; MC—McCloud; OK—Okanagan; Q—Quesnellia; RC—Rattlesnake Creek; RE—Redding; RU—Ruby; SE—Seward; SF—Shoo Fly; SI—Stikine; SM—Slide Mountain; ST—Stikinia; TO—Tozitna; TR—Trinity; WA—Wallowa; WR—Wrangellia; Y-T—Yukon-Tanana; YR—Yreka. (B) Simplified geologic map showing terranes, their boundaries, other principal tectonic features, and main plutonic units in the Blue Mountains Province accreted to the North American craton. Redrafted after Schwartz et al. (2011a). Blue dashed lines indicate state borders (ID—Idaho; OR—Oregon; WA—Washington). Plutons in question: SBCP—Sunrise Butte composite pluton; WB—Wallowa batholith.

several successively emplaced, syntectonic Late Jurassic to Early Cretaceous plutons in the Blue Mountains province of northeastern Oregon to infer temporal strain variations through time (Fig. 1B). We synthesize conclusions and interpretations from our two earlier papers (Žák et al., 2012, 2015), where the original AMS data are described in full, and we use this synthesis to place constraints on conflicting tectonic models. In combination with the existing U-Pb sensitive high-resolution ion microprobe (SHRIMP) zircon ages, we discuss the inferred strain history in light of possible plate movements during growth of this portion of the North America Cordillera and discuss broader implications for the Mesozoic to Cenozoic paleogeographic reconstructions of the Pacific Ocean basin.

LATE JURASSIC TO EARLY CRETACEOUS PLUTONS IN THE BLUE MOUNTAINS PROVINCE

The Blue Mountains province (Fig. 1B) is a large erosional inlier composed of three Permian to Early Jurassic oceanic terranes (the outboard Wallowa oceanic arc, the Baker forearc–accretionary wedge, and the inboard Olds Ferry arc; e.g., Vallier and Brooks, 1995; Dorsey and LaMaskin, 2007, 2008; Schwartz et al., 2011a; LaMaskin et al., 2015) that were variably correlated with terranes in British Columbia to the northwest and in the Klamath Mountains to the southwest (see Snoke and Barnes, 2006, for an overview; Fig. 1A). Recent models suggest that the terranes first collided outboard of the continental margin during the Late Jurassic (159–154 Ma) and were then accreted as an already amalgamated "superterrane" to the North American craton during the Early Cretaceous (ca. 140–125 Ma; Schwartz et al., 2011b).

In the Blue Mountains Province, terrane boundaries generally trend ~NNE-SSW in the east near the North American craton margin but continuously reorient to ~E-W trend in the west (Fig. 1B). The curved terrane boundaries thus define an orocline (see Žák et al., 2015, for discussion) and, even without considering paleomagnetic data, are suggestive of significant clockwise vertical-axis rotation. By comparing presumed paleopoles for terranes and stable North America, the existing paleomagnetic studies estimated the total amount of this rotation at 60° ± 29° (Wilson and Cox, 1980) and 66° ± 21° (Hillhouse et al., 1982) and suggested no significant latitudinal displacement relative to the North American craton since Jurassic–Cretaceous times. We note that the paleomagnetic data from igneous and metamorphic rocks lack paleohorizontal control and thus involve an unknown amount of tilt of the sampled units. Cretaceous sedimentary rocks of the Mitchell Inlier (Fig. 1B), recently interpreted by Schwartz and Johnson (2014) as separated from the central Blue Mountains by a large-magnitude shear zone, indicate a lesser amount of rotation (37° ± 7°). The rotation was resolved into 21° from the Mid-Cretaceous to the Early and Middle Eocene and an additional 16° after the Eocene (Housen and Dorsey, 2005; see also Grommé et al., 1986). In summary, large rotations are consistently derived from relatively older rocks in the Blue Mountains province; thus, all of the above estimates may be correct. It should also be noted that the existing interpretations of the relative terrane rotations may be reconsidered in the future in light of recently updated apparent pole wander path models for North America (e.g., Enkin, 2006; Kent and Irving, 2010; Kent et al., 2015).

The prolonged Late Jurassic to Early Cretaceous terrane convergence in the Blue Mountains province was accompanied by episodic but locally voluminous dioritic to granitic plutonism (see Schwartz et al., 2011b, for overview). We have examined a number of these syntectonic plutons, but here we provide a brief description of only those five that preserve internal magmatic fabrics bearing important regional kinematic information (Figs. 1B and 2; Table 1).

Late Jurassic Syntectonic Plutons Intruding the Baker Forearc–Accretionary Wedge Terrane

The Late Jurassic Desolation Creek unit (160.2 ± 2.1 Ma; $^{206}Pb/^{238}U$ SHRIMP–reverse geometry (RG) zircon age after Johnson et al., 2015) is the earliest, northeasterly unit of the Sunrise Butte composite pluton that intruded serpentinite-matrix mélanges and chert-argillite successions of the Baker terrane (Figs. 1B and 2A). The unit is composed of pyroxene-bearing hornblende-biotite quartz diorite and tonalite characterized by low Sr/Y ratios (<40). The Sunrise Butte (146.7 ± 2.3 Ma) and Onion Gulch (147.9 ± 1.8 Ma) units are younger central and southwesterly units of the pluton largely composed of hornblende-biotite granodiorite to tonalite or two-pyroxene diorites and quartz diorites (Onion Gulch), all with high Sr/Y signature (>40; Fig. 2A). The low Sr/Y plutons represent mantle- or arc-derived magmas originated on separated oceanic terranes, whereas the high Sr/Y plutons were interpreted as reflecting partial melting of orogenically thickened crust during outboard terrane amalgamation (Schwartz et al., 2011b; Johnson et al., 2015).

Early Cretaceous Syntectonic Plutons Intruding the Wallowa Arc Terrane

The Pole Bridge (140.2 ± 1.4 Ma) and Hurricane Divide (130.2 ± 1.0 Ma) plutons of the Wallowa batholith (Fig. 1) are broadly of the same lithology, ranging from low-silica tonalite along pluton margins to amphibole-biotite granodiorite in pluton cores ($^{206}Pb/^{238}U$ SHRIMP-RG zircon ages after Johnson et al., 2011). These plutons were interpreted as having been derived from a depleted-mantle source during Late Jurassic–Early Cretaceous crustal thickening broadly coeval with collision of the Blue Mountains superterrane with the North American craton (Johnson et al., 2011). The Craig Mountain pluton (125.6 ± 0.6 Ma) of the same batholith is a felsic granodiorite formed by partial melting of the collision-thickened mafic arc crust (Johnson et al., 2011).

MAGNETIC FABRIC PATTERNS IN THE BLUE MOUNTAINS PLUTONS

Method

In addition to age and compositional differences, the above plutons exhibit contrasting magnetic fabrics as revealed using the anisotropy of magnetic susceptibility (AMS; see Hrouda, 1982; Rochette et al., 1992; Tarling and Hrouda, 1993; Borradaile and Henry, 1997; and Borradaile and Jackson, 2010, for principles of the method). Magnetic susceptibility is a second-rank tensor that relates the induced magnetization of a rock linearly with the intensity of an applied magnetic field:

$$M_i = k_{ij} \times H_j,$$

where M_i (i = 1, 2, 3) are components of the magnetization vector, H_j (j = 1, 2, 3) are components of the vector of intensity of applied magnetic field, and k_{ij} are magnetic susceptibilities, i.e., dimensionless constants of proportionality (e.g., Tarling and Hrouda, 1993). The components k_{11}, k_{22}, k_{33} are also referred to as the maximum (k_1), intermediate (k_2), and minimum (k_3) principal susceptibilities, respectively.

At each sampling site within a given pluton, the AMS method provides several pieces of information, the most relevant of which for regional kinematic analyses is the orientation of the principal magnetic axes. These are calculated

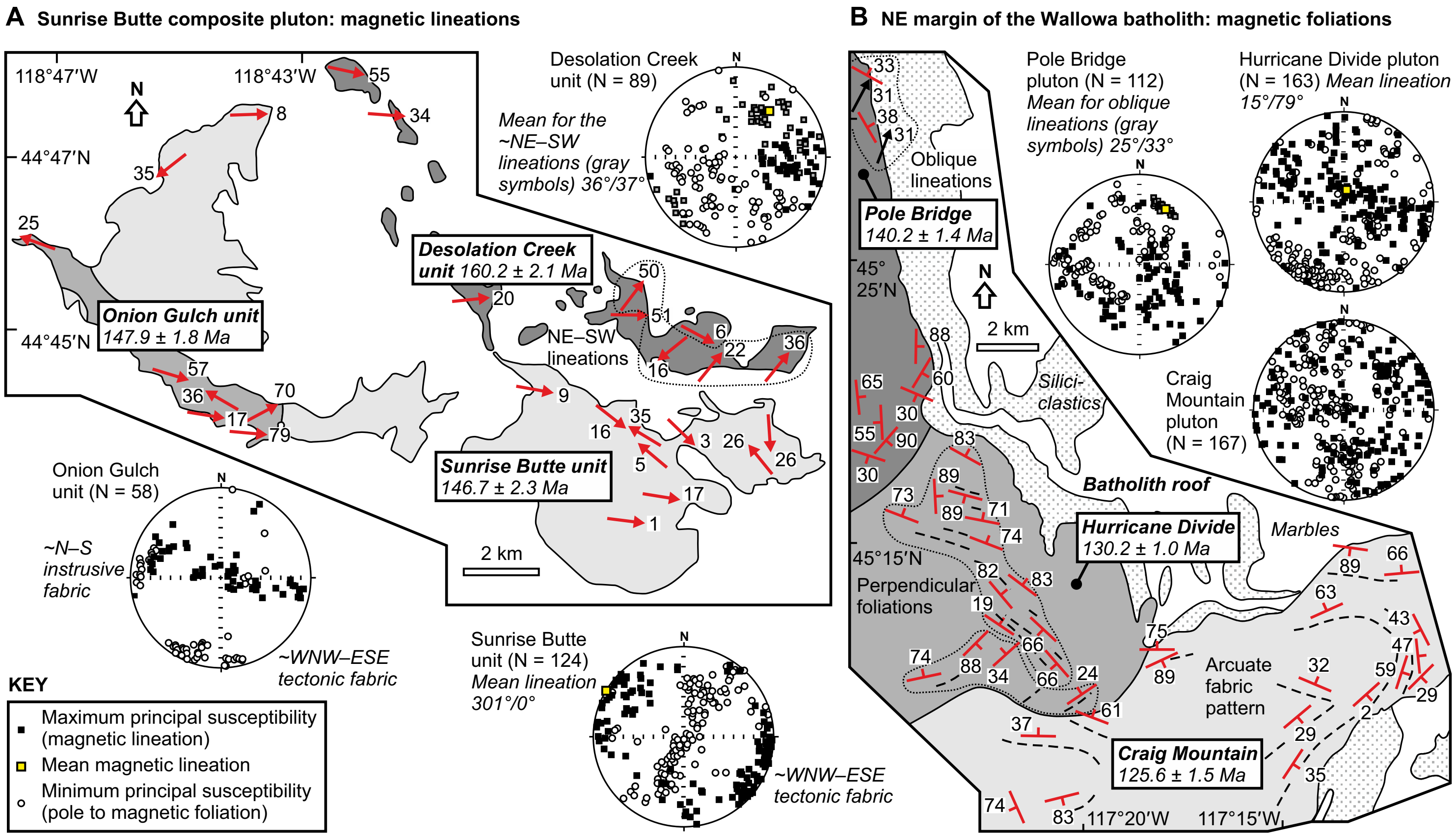

Figure 2. (A) Simplified geologic map of the Sunrise Butte composite pluton with magnetic lineations (trend and plunge shown with arrows) in each intrusive unit (after Žák et al., 2012). Dotted line in the Desolation Creek unit represents boundary of a domain with NE-SW–trending lineations (see text for discussion). (B) Simplified geologic map of the northeastern portion of the Wallowa batholith (after Žák et al., 2015) showing magnetic foliations (strike and dip symbols) on most stations and magnetic lineations (trend and plunge shown with arrows) on two northernmost stations of the Pole Bridge unit; see text for discussion. Dotted lines highlight important fabric domains as discussed in the text; dashed lines show inferred traces of mean magnetic foliation. Stereoplots in both (A) and (B) show orientation of the principal magnetic susceptibilities (equal area, projection on lower hemisphere). Mean values are given only for data relevant for kinematic interpretations (see text).

as a mean of typically 8–12 cylindrical specimens (each ~10 cm^3 in volume) drilled from an oriented block taken at each station (see Jelínek, 1978; and Tarling and Hrouda, 1993, for methodology). The orientation of the mean AMS axes with respect to geographic coordinates then corresponds to the orientation of magnetic fabric, i.e., directions of magnetic lineation (k_1) and a pole (normal) to magnetic foliation (k_3) at a sampling site. These mean foliations and lineations are then used to construct maps showing a magnetic fabric pattern within a pluton, whereas all data (all individual specimens) are summarized in stereonets to show overall statistical orientation distribution of the principal susceptibilities (Fig. 2).

Data Description

Below, we summarize the regional magnetic fabric patterns in the five selected plutons, or their parts (Fig. 2; a full presentation of the original data sets, including discussion on magnetic mineralogy, is given in Žák et al., 2012, 2015). It is also important to note that the plutons also show macroscopically apparent magmatic fabric (defined by shape-preferred orientation of hornblende, biotite, and feldspar grains and by microgranular enclaves and xenoliths; Fig. 3) with generally little macroscopic and microscopic evidence of solid-state deformation except at a few localities. Hence, the magnetic fabrics

TABLE 1. SUMMARY OF MAGNETIC FABRICS IN PLUTONS OF THE BLUE MOUNTAINS PROVINCE

Unit	U-Pb age (Ma) (see text for references)	Key magnetic fabric parameters	Tectonic strain interpretation	Inferred Farallon–North America plate convergence
Desolation Creek	160.2 ± 2.1	Mean L = 36°/37°, foliations dip to the ~NE at moderate angles	Left-oblique intraterrane thrusting	Sinistral
Sunrise Butte	146.7 ± 2.3	Mean L = 301°/00°, girdle-like foliation orientation distribution, prolate fabric	Terrane-parallel stretching and lateral extrusion of the Baker terrane	Orthogonal
Pole Bridge	140.2 ± 1.4	Mean L = 25°/33° oblique to ~NNW-SSE host rock bedding	~NE-SW transpressional shortening during dextral convergence	Dextral, terrane impingement into continental margin reentrant
Hurricane Divide	130.2 ± 1.0	Steep mean L (15°/79°), steep ~NW-SE foliations	~NNE-SSW shortening and vertical stretching	Dextral, increasingly oblique convergence
Craig Mountain	125.6 ± 1.5	Map-scale arcuate foliation and lineation pattern	Magma flow into tensional domain along an axial plane of the oroclinal fold	Rotation of southern portion of the Blue Mountains superterrane

are mostly interpreted in terms of hypersolidus, magmatic to submagmatic strains (Fig. 4; defined using criteria outlined in Paterson et al., 1989, 1998). In most cases, the mesoscopic foliation and lineation defined by paramagnetic mafic minerals correspond well to the measured principal susceptibility axes, interpreted as representing the shape or distribution anisotropy of magnetite grains or aggregates (see Žák et al., 2012, 2015, for details). Furthermore, the measured magnetic fabrics are homogeneously oriented at most of the stations, their means are well defined, and the fabrics show significant inter-site consistency and systematic patterns on the maps (Fig. 2).

(1) The ca. 160 Ma Desolation Creek unit exhibits an unusually complex internal structure over a small outcrop area, but the most conspicuous feature is the presence of two subgroups of magnetic lineations (Fig. 2A). One subgroup includes lineations plunging gently to moderately to the ~NE (Fig. 2A; mean k_1 for this data subgroup is 036°/37°; trend/plunge convention is used throughout this paper), whereas the other subgroup includes those plunging to the ~E (mean k_1 is 098°/39°). Magnetic foliations scatter widely but statistically define a mean foliation dipping moderately to the ~NE (mean k_3 is 228°/41°; Fig. 2A). At all but one station, the NE-plunging lineations occur in the eastern exposure (that one dated at ca. 160 Ma), whereas the E-plunging lineations occur in the northwestern exposures of unknown radiometric age.

(2) The magnetic fabrics of the ca. 148–147 Ma Sunrise Butte and Onion Gulch units are characterized by subhorizontal ~NW-SE–trending magnetic lineations (with a mean k_1 of 301°/00°) associated with ~NW-SE–striking magnetic foliations that dip moderately to steeply to the ~SW or ~NE (Fig. 2A). On a stereoplot, poles to magnetic foliation (the k_3 axes) from all specimens in the Sunrise Butte unit define a pronounced girdle about the strongly clustered subhorizontal magnetic lineations (Fig. 2A), a relation frequently observed in prolate magnetic fabrics (Žák et al., 2012).

(3) Mean magnetic foliations in the ca. 140 Ma Pole Bridge pluton strike ~N-S to ~NW-SE and dip moderately to steeply to the W or to the NE (Fig. 2B). The foliations are roughly subparallel to the pluton margin and to the bedding in the Late Triassic to Early Jurassic metaclastic host rocks (Fig. 2B). Magnetic lineations exhibit moderate plunges, and their trends scatter widely to almost all directions but notably cluster around a ~NNE direction (mean k_1 is 25°/33°) at two stations in the northern portion of the pluton where they are parallel to stretching lineation on bedding planes (Žák et al., 2015). Thus both types of lineation are oblique to the pluton–host contact (Fig. 2B) and to the strike of bedding in the metaclastic rocks (Žák et al., 2015).

(4) In the ca. 130 Ma Hurricane Divide pluton, magnetic fabric exhibits two distinct orientations. In the NE, magnetic foliations are steep and strike ~NW-SE to ~WNW-ESE, and they are at a high angle to the nearby flat-lying pluton roof but, at the same time, are roughly concordant with foliations in the pluton roof (Fig. 2B). Lineations vary from mostly subvertical to shallowly plunging to the ~ESE or ~WNW (Fig. 2B), i.e., are distributed in a girdle-like pattern along the mean foliation plane. In the SE, magnetic foliations are almost perpendicular to the above, striking ~NE-SW and being associated with variably trending lineations (Fig. 2B).

(5) An entirely different fabric pattern is observed in the adjacent ca. 126 Ma Craig Mountain pluton (Fig. 2B). Along both pluton margins, magnetic foliations are oriented systematically at an angle of ~30°–45° to the nearby pluton–host rock contact, and this angle increases toward the pluton center (Fig. 2B). Lineations generally follow the same pattern and, altogether, both define a pronounced asymmetric arcuate map-scale pattern that seems to be continuous with deflected lithologic contacts, bedding, and metamorphic foliation in the host rock on both sides of the pluton (Fig. 2B).

DISCUSSION

Temporal and Spatial Strain Variations and Regional Kinematics Recorded in the Blue Mountains Plutons

The AMS patterns in each of the five plutons were interpreted as recording increments of tectonic strains during pluton solidification (e.g., Fig. 3D; see also Žák et al., 2012, 2015, for detailed discussion) and thus reveal a temporal sequence of regional tectonic events (referred to as "stages" hereinafter; Table 1). Furthermore, given the uncertainties attached to the paleomagnetic

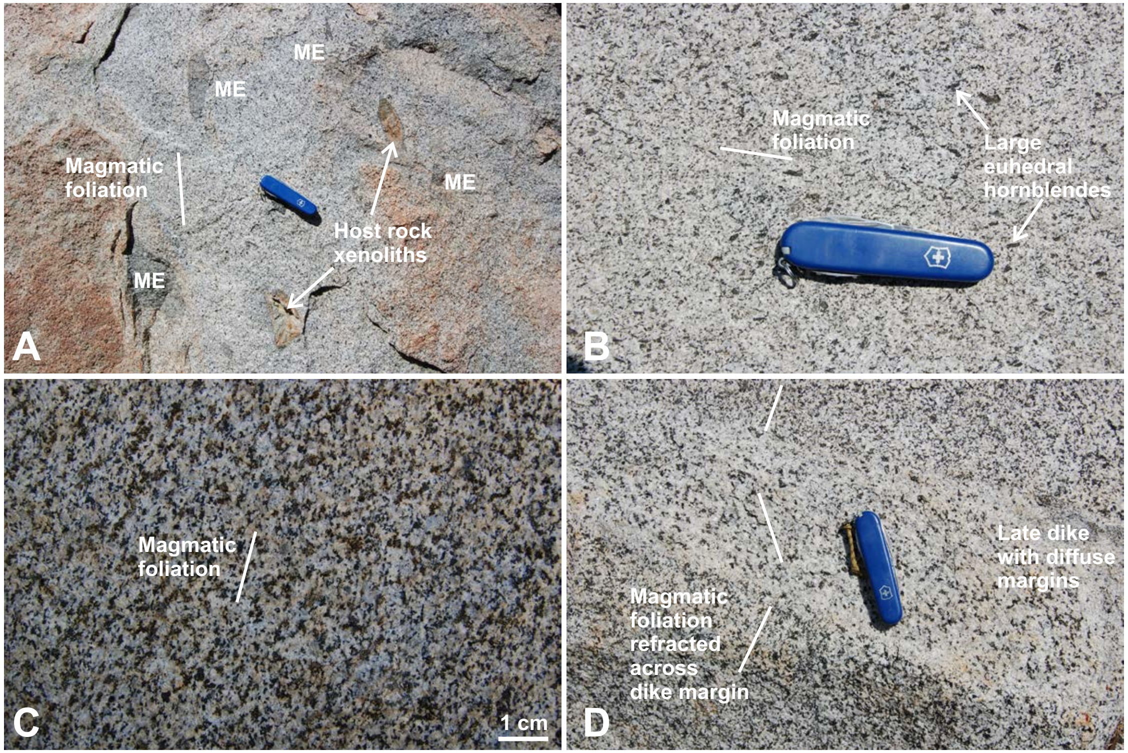

Figure 3. Examples of magmatic fabrics in the Blue Mountains plutons. (A) Mineral foliation (defined by mafic silicates), flattened microgranular enclaves (ME), and host rock xenoliths aligned parallel in the Sunrise Butte granodiorite. Swiss Army penknife is 9 cm long. (B) Close-up of magmatic foliation in the Sunrise Butte granodiorite defined by mafic silicates including euhedral hornblende phenocrysts up to 1 cm long. Swiss Army penknife is 9 cm long. (C) Close-up of strong magmatic foliation in the Hurricane Divide granodiorite defined by mafic silicates. (D) Magmatic foliation overprinting diffuse margins of a late dike in the Hurricane Divide granodiorite. Swiss Army penknife is 9 cm long.

data (as outlined above and also recently pointed out by Mirzaei et al., 2016), the AMS may shed light on the nature and timing of terrane displacements and tectonic rotations in the Blue Mountains province over ~35 m.y. from ca. 160 Ma to ca. 126 Ma. This issue has been hotly debated. The opposing views suggest that the Blue Mountains terranes were attached to the continent already by ca. 160 Ma (e.g., LaMaskin and Dorsey, 2016) or significantly later, at ca. 144–128 Ma (e.g., Selverstone et al., 1992; Getty et al., 1993; Gray and Oldow, 2005; Giorgis et al., 2008; Stowell et al., 2011). Our AMS data corroborate the belief that the tectonic history of the Blue Mountains province was complex and are consistent with the following kinematic evolution of the terrane-continent convergence during Late Jurassic to Early Cretaceous:

Stage 1. The NE-plunging magnetic lineations in the ca. 160 Ma Desolation Creek unit (Fig. 2A) are interpreted as reflecting strain during Wallowa and Baker terrane convergence and SW-directed backthrusting onto the Olds Ferry arc (Žák et al., 2012; present-day coordinates). Regardless of how much of the postemplacement tectonic rotation is removed, the obliquity of the NE-plunging lineations and of the inferred principal stretching direction to the terrane and subterrane boundaries indicates an overall sinistral sense of shear along terrane boundaries at 160 Ma as shown in Fig. 5A. The other subgroup of E-plunging lineations was interpreted as reflecting the onset of strain axes reorientation toward ~WNW-ESE horizontal stretching of the subsequent Stage 2 (Fig. 2A; Žák et al., 2012).

Stage 2. At ca. 148–147 Ma (age of the Sunrise Butte and Onion Gulch units), magnetic lineations and the inferred principal stretching directions are terrane parallel. Prolate shape of the AMS ellipsoids and girdle-like orientation distribution of magnetic foliations in the Sunrise Butte unit (Fig. 2A) suggest that, rather than wrench-dominated shearing, these lineations record uniaxial stretching and lateral extrusion of the Baker terrane after outboard terrane amalgamation (Fig. 5B; see also Žák et al., 2012). At this time, the amalgamated Blue Mountains superterrane was presumably approaching the North American craton margin at the expense of an intervening oceanic basin in the Salmon River suture zone during approximately orthogonal convergence (Fig. 5B). Magnetic fabric of the Onion Gulch unit is somewhat more complicated and is interpreted as recording both intrusive (steep lineations associated with ~N-S foliations parallel to the nearby intrusive contact) and tectonic strain (~WNW-ESE–trending lineations; Fig. 2A; Žák et al., 2012).

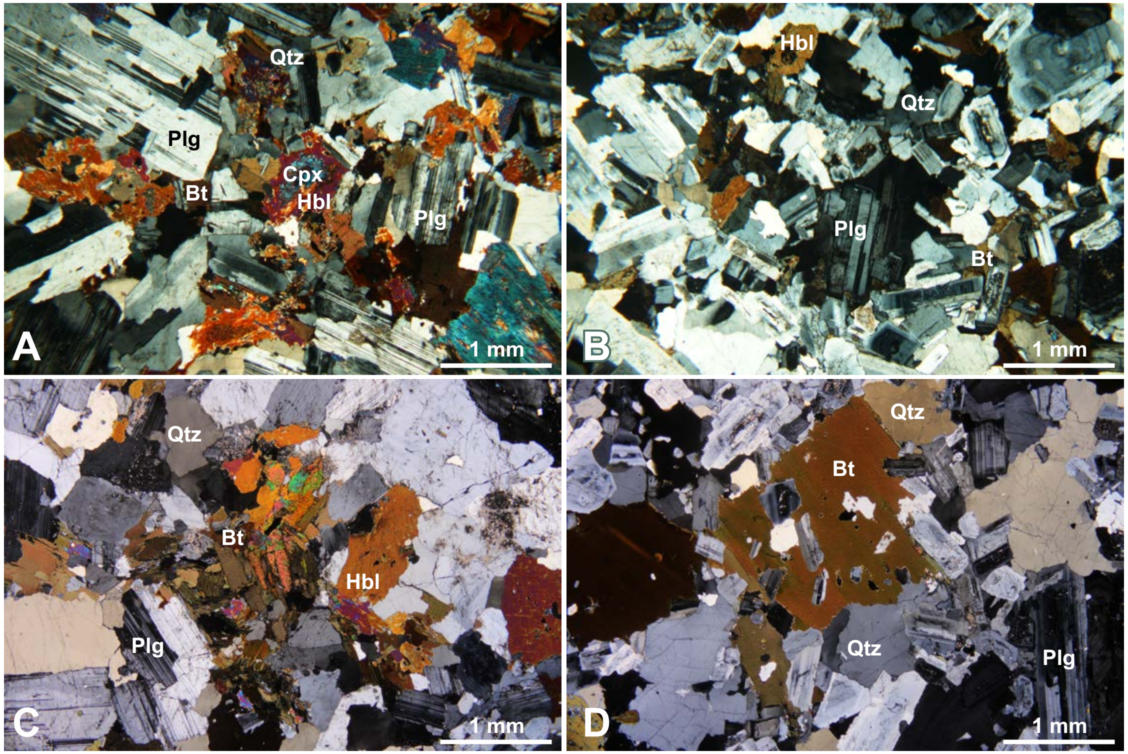

Figure 4. Examples of magmatic to submagmatic microstructures that are typical of the Blue Mountains plutons. (A) Pyroxene-hornblende-biotite granodiorite of the Desolation Creek unit, crossed polars. (B) Hornblende-biotite granodiorite of the Sunrise Butte unit, crossed polars. (C) Hornblende-biotite tonalite to granodiorite of the Hurricane Divide unit, crossed polars. (D) Coarse-grained biotite granodiorite of the Craig Mountain unit, crossed polars. Mineral abbreviations: Bt—biotite; Cpx—clinopyroxene (augite); Hbl—hornblende; Plg—plagioclase; Qtz—quartz.

Stage 3. Plutons in the Wallowa batholith (see below) intruded into the eastern portion of the Wallowa terrane, which roughly parallels the overall ~NNW-SSE "Cordilleran" structural grain (Fig. 1). We thus suggest that these plutons likely have not undergone a significant oroclinal rotation as compared to the Sunrise Butte composite pluton and that the kinematic information can be obtained directly using the present-day coordinates. It should be noted, however, that this inference challenges some of the existing paleomagnetic data (cf. Wilson and Cox, 1980, their sites W13 and W19; but see also Mirzaei et al., 2016).

The ca. 140 Ma Pole Bridge pluton and its host rock record ~NE-SW shortening, transpressional folding, and SW-directed oblique thrusting (Žák et al., 2015) where magnetic lineations are parallel to bedding-oblique flexural-slip lineations in the metaclastic host rock (Fig. 2B). At a regional scale, this deformational event was broadly coeval with crustal thickening along the terrane-continent suture zone farther to the east at ca. 141–124 Ma (the Salmon River suture zone in Fig. 1B; Selverstone et al., 1992; Getty et al., 1993; Gray and Oldow, 2005), and we interpret this deformation as an early phase of the prolonged attachment of the Blue Mountains superterrane to the North American continental margin. The obliquity of the inferred principal shortening direction with respect to the ~NNW-SSE–trending terrane boundaries implies that the frontal convergence switched to dextral and thus northward displacement of the superterrane from 140 Ma onwards (Fig. 5C).

Stage 4. The AMS in the ca. 130 Ma Hurricane Divide pluton records vertical stretching (thickening) of the crust associated with two nearly perpendicular horizontal shortening directions, the ~NNE-SSW shortening being dominant (Fig. 5D; associated with oblate AMS ellipsoid; see Žák et al., 2015, for discussion). Based on paleomagnetic and geochronologic studies, Tikoff et al. (2014) suggested that the North American craton margin was stepped and consisted of a 330°-trending rift zone and a 60°-trending transform fault before the superterrane attachment. We envisage that the Stage 4 deformation was caused by the superterrane impingement into this westward-concave reentrant consistent with continued metamorphism and loading in the Salmon River suture zone (the Syringa embayment; Figs. 1B and 3D; see also Strayer et al., 1989; Lund et al., 2008; Stowell et al., 2011; and Žák et al., 2015, for discussions).

Stage 5. As a consequence of progressive squeezing of the Blue Mountains superterrane into the presumed continental margin reentrant, its northern por-

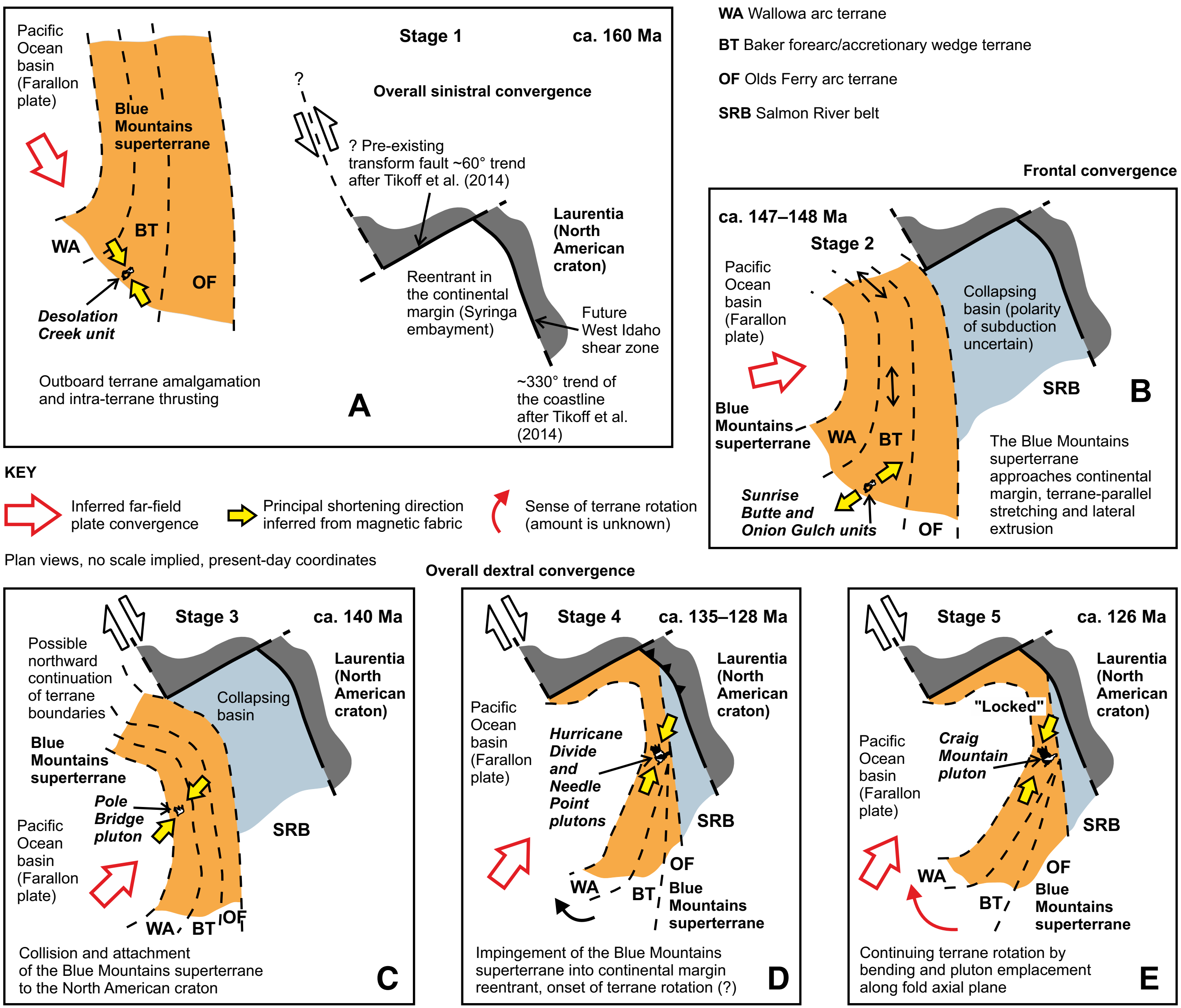

Figure 5. Hypothetical scenario for the Pacific basin–North America plate convergence and regional kinematics inferred from magnetic fabric of Late Jurassic to Early Cretaceous plutons of the Blue Mountains province. Inferred principal shortening axes in reconstructions (A) and (B) are restored by 66° anticlockwise rotation. See text for discussion. Terranes and other lithotectonic units: BT—forearc and accretionary wedge Baker terrane; OF—Olds Ferry arc terrane; SRB—Salmon River belt; WA—Wallowa arc terrane.

tion became more difficult to further deform by horizontal shortening and vertical stretching. We propose that the continuing and increasingly oblique dextral convergence initiated crustal-scale oroclinal bending and clockwise rotation of the southern, still deformable portion of the superterrane (largely outboard of the reentrant) about a vertical axis (Fig. 5E). The ca. 126 Ma Craig Mountain pluton was emplaced into a local tensional domain along the axial plane of this initiating crustal-scale fold, and its internal magmatic fabric records strain during progressive fold development (Fig. 5E; see Žák et al., 2015, for details). By ca. 118 Ma, ductile deformation became localized mainly along the dextral transpressive western Idaho shear zone (Fig. 1B), accommodating continued convergence of the Blue Mountains province and North American craton until Late Cretaceous times (e.g., McClelland et al., 2000; Giorgis et al., 2008).

Inferences on Plate Kinematics from the AMS

The pioneering studies of Benn et al. (2001) and Cao et al. (2015) have shown that, under favorable circumstances, mesoscopic and magnetic fabric patterns in plutons may be used to infer regional kinematics and to track past plate motions (plate displacement vectors). Similarly, we suggest that the orientation of the principal AMS axes with respect to the terrane boundaries and to the adjacent North American craton margin may provide key information about changing strain fields in the Blue Mountains province (Stages 1–5; Table 1) and, in turn, aid in reconstructing kinematics of convergence between the Farallon and North America plates during the Late Jurassic to Early Cretaceous interval when previous studies indicated a major change in plate motions. This approach, however, involves three assumptions: (1) on a specimen scale, the AMS axes are assumed to coincide with the principal strain axes; (2) on a regional scale, the principal strain axes inferred from the AMS are assumed to reflect plate movements in such a way that magnetic lineations are parallel to the overall tectonic transport direction and parallel to the plate motion vector (Benn et al., 2001); and (3) the plutons have not experienced significant tilting. The latter assumption is supported by regionally consistent patterns of foliations, lineations, and fold axes (overview in Avé Lallemant, 1995).

Two important conclusions can be deduced from the above discussed plate-tectonic scenario:

First, our pluton fabric data do not support models invoking only orthogonal or dextral convergence between the Farallon and North American plates during Late Jurassic to earliest Cretaceous times as proposed in some earlier reconstructions (e.g., Wernicke and Klepacki, 1988; Ernst et al., 2008). Instead, we favor a hypothesis involving the southward displacement of the Blue Mountains terranes outboard of the truncated North American continental margin at ca. 160 Ma (e.g., Avé Lallemant et al., 1985; Avé Lallemant and Oldow, 1988; Monger, 1997; Beck and Housen, 2003; Umhoefer, 2003; Anderson, 2015).

Second, we present a refined hypothesis for the inferred Late Jurassic to Early Cretaceous change in the plate motions. Dextral shear was proposed to control deformation along various segments of the Cordilleran margin of North America (from central California to Oregon) by Oldow et al. (1984) from ca. 100 Ma onwards, by McClelland et al. (2000) since ca. 130 Ma, and by Lahren and Schweickert (1989) and Grasse et al. (2001) between ca. 148–120 Ma. The inferred rotation of strain axes in the Blue Mountains plutons constrains this transition more precisely from orthogonal to dextral kinematics between ca. 148 Ma (Stage 2) and ca. 140 Ma (Stage 3) and is consistent with further increase in obliquity of plate convergence from ca. 130 Ma to 126 Ma (Stages 4 and 5).

Finally, we note that the latter, ca. 130–126 Ma event in the Blue Mountains province temporally overlaps with a series of interlinked tectonic events in the northern and central Californian portion of the U.S. Cordillera, including (1) onset of strongly accretionary behavior in the Franciscan complex; (2) a break in the deposition of siliciclastic detritus in the Great Valley forearc basin; and (3) the beginning of a Mid- to Late Cretaceous magmatic flare-up period in the Sierra Nevada arc (see Dumitru et al., 2010, for a summary). This tentative connection of the Late Jurassic to Early Cretaceous tectonic events in Oregon and California is interpreted here as reflecting changes in the plate velocity vectors and a reversal from southward to northward drift of the Pacific, Kula, and Farallon plates with respect to North America (e.g., Miller et al., 2002; Umhoefer, 2003; Dumitru et al., 2010).

In the Coast Plutonic Complex, British Columbia, Israel et al. (2006, 2013) and Monger (2014), among others, suggested a similar change from Early Cretaceous sinistral through Mid-Cretaceous compressive to Late Cretaceous dextral deformation. Based on a geochronologic study from the same unit, Gehrels et al. (2009) proposed that a transition from sinistral to dextral motions of the Kula and Farallon plates with respect to North America occurred at ca. 100 Ma. Thus while the above hypotheses suggest the same relative plate motion change, they imply it was recorded earlier in the southerly terranes, including the Blue Mountains province, but was younger in British Columbia by several tens of millions of years. It remains an open question for future research how exactly these events and plate-scale kinematic transitions link along strike of the North American Cordillera.

CONCLUSIONS

(1) Contrasting magnetic fabrics in five successively emplaced plutons reveal temporal and spatial variations in regional tectonic strain in oceanic terranes of the Blue Mountains province during the Late Jurassic to Early Cretaceous times.

(2) The inferred strain regimes evolved from thrusting and sinistral shearing at ca. 160 Ma through horizontal stretching at ca. 147 Ma (Greenhorn subterrane of the Baker terrane) to dextral transpression at ca. 140 Ma, followed by progressive anticlockwise rotation of the principal horizontal shortening direction from ca. 130 Ma to ca. 126 Ma (Wallowa terrane).

(3) The progressive reorientations of the regional principal strain axes are interpreted in terms of an outboard Wallowa and Baker terrane amalgamation, lateral extrusion of the Greenhorn subterrane, docking of the amalgamated Blue Mountains superterrane into a continental-margin reentrant, and onset of oroclinal folding.

(4) The documented changes in crustal strains are perhaps linked to a progressive change in the kinematics of oceanic plates of the Pacific basin relative to North America and suggest overall Late Jurassic sinistral and Early Cretaceous dextral terrane translations along the continental edge. Finally, we propose that these events may have been linked along large portions of the orogen, at least from central California to Blue Mountains, and may have culminated in the onset of accretion in the Franciscan complex and voluminous plutonism in the Sierra Nevada arc.

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