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# *Paleomagnetism and rotation history of the Blue Mountains, Oregon, USA*

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## ABSTRACT

**An important element in reconstructions of the Cordilleran margin of North America includes longstanding debate regarding the timing and amount of rotation of the Blue Mountains in eastern Oregon, and the origin of geometric features such as the Columbia Embayment, which was a subject of some of Bill Dickinson's early research. Suppositions of significant clockwise rotation of the Blue Mountains derived from Dickinson's work were confirmed in the 1980s by paleomagnetic results from Late Jurassic–Early Cretaceous plutonic rocks, and secondary directions from Permian–Triassic units of the Wallowa–Seven Devils arc that indicate ~60° clockwise rotation of the Blue Mountains.**

**This study reports new paleomagnetic data from additional locations of these Late Jurassic–Early Cretaceous plutonic rocks, as well as Jurassic sedimentary rocks of the Suplee-Izee area. Samples from three sites from the Bald Mountain Batholith, two sites from small intrusive bodies near Ritter, Oregon, and six sites from the Wallowa Batholith have well-defined magnetization components essentially identical to those found by previous workers. The combined mean direction of both sets of data from these Late Jurassic to Early Cretaceous intrusive rocks is D = 30, I = 63, $\alpha_{95}$ = 6°.**

**Samples from Jurassic sedimentary rocks in the Suplee-Izee area include four sites of the Lonesome Formation, three sites of andesitic volcanics in the Snowshoe Formation, and three sites from the Trowbridge Formation. The Lonesome and Trowbridge samples all had very well-defined, two component magnetizations. The in-situ mean of the combined Lonesome and Trowbridge Formations is D = 28, I = 63, $\alpha_{95}$ = 15°. Upon tilt-correction, the site means of these units scatter and fail the paleomagnetic fold test in spectacular fashion. The similarity between the directions obtained from the remagnetized Jurassic rocks, and from the Late Jurassic to Early Cretaceous plutonic rocks suggests that a widespread remagnetization accompanied emplacement of the intrusives. Similar overprints are found in Permian and Triassic rocks of the Blue Mountains. Directions from 64 sites of these rocks yields a mean of D = 33°, I = 64°, k= 26, $\alpha_{95}$ = 3.7°. Comparing the directions with North America**

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**reference poles, a clockwise rotation of 60° ± 9° with translation of 1000 ± 500 km is found. Together with data from Cretaceous and Eocene rocks, clockwise rotation of the Blue Mountains has occurred throughout the past ca. 130 Ma, with long-term rotation rates of 0.4 to 1 °/Ma. Approximately 1000 km of northward translation also occurred during some of this time.**

## INTRODUCTION

This paper includes paleomagnetic results from a reconnaissance study of Jurassic sedimentary rocks of the Suplee-Izee area (Dickinson and Vigrass, 1965) of the Blue Mountains in east-central Oregon. The Suplee-Izee area was investigated by Bill Dickinson as part of his Ph.D. work, and the published results are one of the earliest examples of the many research contributions he made over the course of his long career. The objective of the project was to use the paleomagnetic signal recorded by those sediments to test paleogeographic models of the North American Cordillera and its accreted terranes (e.g., Dickinson, 2004). As will become clear, the paleomagnetic signal recorded by these rocks was acquired after they were tilted. This post-tilting remagnetization negates the use of the Suplee-Izee rock's paleomagnetism to examine their Jurassic paleolatitude. Instead, these results are combined with new data from Late Jurassic–Early Cretaceous plutonic rocks that intrude the Blue Mountains, and focuses on another longstanding subject of study by Bill Dickinson—the origin and significance of the Columbia Embayment (Dickinson and Thayer, 1978; Dickinson, 2004), and the rotation history of the Blue Mountains and related terranes (Dickinson, 2002).

### Columbia Embayment and the Blue Mountains

A 50°–60°CW (clockwise) rotation of the Blue Mountains (Fig. 1) is a common feature of many tectonic reconstructions of the North American Cordillera (e.g., Hamilton, 1969; Dickinson and Thayer, 1978; Dickinson, 2002, 2004; Riddihough et al., 1986; Wyld and Wright, 2001; Wyld et al., 2006). The age of this rotation is variably interpreted as either post–Late Jurassic to Early Cretaceous time (see, for example, Riddihough et al., 1986; Žák et al., 2015), or younger, i.e., from post-Cretaceous time. In particular, Dickinson (2002) proposed a model for Basin and Range extension that called for an Eocene age for the CW rotation of the Blue Mountains. The majority of these models also call for rotation of the Blue Mountains as a single, large block, with restoration of the CW rotation reorienting the Blue Mountains to form an elongate, north-south–striking arc system that connects to the Klamath Mountains terranes to the south.

### Geology and Paleomagnetic Sampling

Rocks in the Blue Mountains of eastern Oregon and western Idaho (Fig. 2) have been divided into four terranes that trend generally east and northeast toward the Salmon River suture zone (Silberling et al., 1984). The Wallowa and Olds Ferry terranes are composed of Permian to Upper Triassic plutonic and volcanic rocks that formed in a magmatic arc and are overlain by Upper Triassic to Jurassic marine sedimentary rocks (Vallier, 1995). The Baker terrane is a mélange complex of deformed and metamorphosed Triassic argillite and chert, with olistostromal blocks of Permian limestone, that formed by marine sedimentation followed by intense deformation in an oceanic subduction zone (e.g., Schwartz et al., 2010). The Izee terrane consists of Upper Triassic to Upper Jurassic sedimentary rocks with a range of ages and depositional environments (dominantly shallow to deep marine). These strata depositionally overlie rocks of the Wallowa, Olds Ferry, and Baker terranes and were proposed as an overlap assemblage that linked the three other terranes to each other by Late–Middle Jurassic time (White et al., 1992; Dorsey and LaMaskin, 2007). The nature

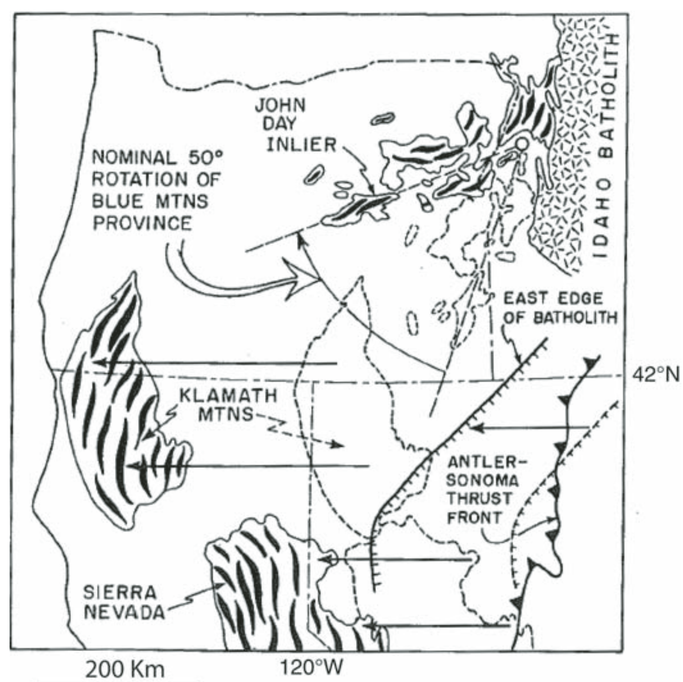


Figure 1. Summary tectonic map from Dickinson and Thayer (1978, their figure 13), illustrating a clockwise rotation of the Blue Mountains that would restore the strike of the range to a north-south orientation, close the Columbia embayment, and produce an along-strike linkage between the Klamath Mountains and the Blue Mountains.

of this proposed overlap was questioned by LaMaskin et al. (2015), who determined that correlations between units such as the Coon Hollow Formation in the Wallowa terrane and the Suplee-Izee strata are questionable and thus do not establish a firm link between these terranes during Jurassic time. Late Jurassic to Early Cretaceous granitic plutons, such as the Bald Mountain and Wallowa Batholiths, crosscut these earlier units and constrain the age of amalgamation of the Blue Mountain terranes (LaMaskin et al., 2015). Isolated areas located mainly in the western portion of the Blue Mountains have exposures of Upper Cretaceous marine sedimentary rocks. The largest of these exposures are of the Hudspeth and Gable Creek Formations in the Mitchell Inlier (Oles and Enlows, 1971; Housen and Dorsey, 2005; Surpless and Gulliver, this volume). Finally, Eocene volcaniclastic sedimentary rocks, volcanics, and shallow-level intrusives of the Clarno Formation (Grommé et al., 1986) occur in the Mitchell and John Day area.

Previous paleomagnetic studies in Blue Mountains have investigated Late Permian and Middle Triassic volcanic rocks, the Late Jurassic to Early Cretaceous plutons, the Cretaceous sediments of the Mitchell Inlier, and the volcanics and volcaniclastic sediments of the Eocene Clarno Formation. Results from 29 sites of volcanic rocks and volcaniclastic sedimentary rocks from the Middle to Upper Triassic (Ladinian–Carnian) Wild Sheep Creek Formation of the Seven Devils Group (Wallowa terrane) and the Upper Triassic (Carnian–Norian) Huntington Formation (Olds Ferry terrane) were reported in Hillhouse et al. (1982). Using a combination of demagnetization techniques and fold tests, Hillhouse et al. (1982) identified three ancient components of magnetization. Two of these components (designated C1, carried only by Seven Devils rocks, and C2, carried mainly by Huntington rocks) were deemed to be primary (Middle to Late Triassic) magnetizations, because the directions clustered better following tilt correction. The other ancient component (C3) was

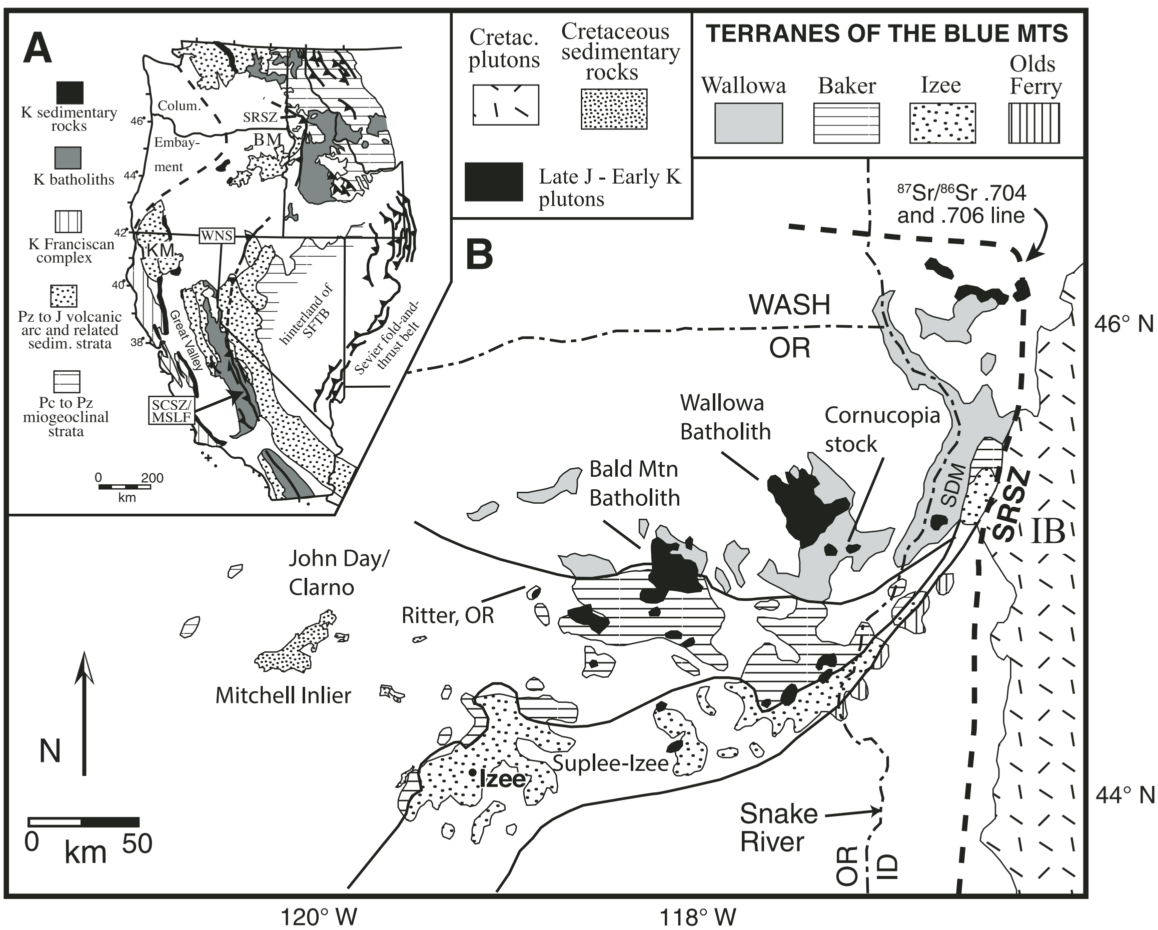


Figure 2. (A) Map of major Cordilleran arc terranes, basins, and structures, modified from Wyld and Wright (2001). (B) Map of terranes of the Blue Mountains, with schematic terrane boundaries shown, modified from Housen and Dorsey (2005). K—Cretaceous; J—Jurassic; Pz—Paleozoic; Pc—Precambrian; OR—Oregon; ID—Idaho; WASH—Washington; IB—Idaho Batholith; SRSZ—Salmon River suture zone; SDM—Seven Devils Mountain; SFTB—Sevier fold and thrust belt; KM—Klamath Mountains; WNS—Western Nevada shear zone; BM—Blue Mountains; SCSZ/MSLF—Sierra Crest shear zone/Mojave–Snow Lake fault.

apparently a postfolding secondary magnetization. Paleomagnetic results from the Upper Permian Hunsaker Formation in the Blue Mountains (Harbert et al., 1995) indicated magnetization in the Northern Hemisphere during the Late Permian Kiaman reversed superchron. This result resolved the hemisphere ambiguity of the results of Hillhouse et al. (1982), showing that all units were in the Northern Hemisphere for Middle to Late Triassic time. The pole positions for the C1 and C2 magnetizations are discordant both with each other and with Middle to Late Triassic poles from the North American craton. The discordance can be explained by presuming a 53° counterclockwise (CCW) vertical-axis rotation between the Seven Devils–Wallowa terrane (C1 pole) and primarily Huntington–Olds Ferry terrane (C2 pole) rocks and an additional 20°–40°CCW rotation with respect to North America (C2 pole compared to Middle–Late Triassic North American craton poles). The paleolatitudes obtained for the Seven Devils and Huntington rocks indicate magnetization at 18°N (+11°/–9°) latitude, which is within 4° of the Middle to Late Triassic paleolatitude for the Blue Mountains predicted from the North American apparent polar wander path (APWP; Beck and Housen, 2003; Kent et al., 2015).

Wilson and Cox (1980) reported paleomagnetic results from Late Jurassic to Early Cretaceous plutonic rocks in the Wallowa batholith, the Cornucopia Stock, and a small, unnamed pluton near Ritter, Oregon, in the Baker terrane. They found well-defined magnetizations with both normal and reverse polarity, which they interpreted to represent primary magnetizations. They argued that postmagnetization tilting of these plutons was insignificant because of the overall consistency of the directions from the large geographic region sampled. The pole obtained from magnetization of the plutons is discordant to poles from Late Jurassic to Early Cretaceous rocks of North America. Assuming a Late Jurassic magnetization age, the discordance can be explained by a 60°CW rotation of the Blue Mountains relative to North America (Wilson and Cox, 1980; Hillhouse et al., 1982). The paleolatitude derived from magnetization of the plutons (43°N ± 7°) is concordant with a Late Jurassic expected paleolatitude of the Blue Mountains predicted by North American APWP. The overprint found in the Triassic Seven Devils and Huntington rocks (C3 pole of Hillhouse et al., 1982) is similar to the mean direction of the plutons reported by Wilson and Cox (1980), suggesting that remagnetization of some of the Permian–Triassic rocks may have been coeval with late-stage plutonism in the Blue Mountains. Updated ages of Blue Mountains plutonic rocks may call for reinterpretation of some of the magnetization ages of Wilson and Cox (1980), who reported ages from 150 to 130 Ma for these rocks. Johnson et al. (1997) reported a 118 Ma $^{40}Ar/^{39}Ar$ age for the Cornucopia Stock, and an age of 130 Ma was reported by Schwartz et al. (2011) for the Hurricane Divide pluton of the Wallowa Batholith, the unit sampled by Wilson and Cox (1980). These ages indicate that the plutons and their magnetization are Early Cretaceous, rather than Late Jurassic, in age.

The paleomagnetism of Late Cretaceous (Albian–Cenomanian) marine strata of the Hudspeth and Gable Formations found in the Mitchell Inlier, in the western portion of the Blue Mountains, was reported by Housen and Dorsey (2005). They found that the magnetization of the majority of these rocks passed paleomagnetic fold, conglomerate, and baked contact tests and is therefore primary. The mean direction and resulting paleopole indicated both significant CW rotation (37°) and latitudinal displacement (1200–1700 km) since the Late Cretaceous. Analysis of magnetic anisotropy and site-level directional dispersion suggested that the detrital paleomagnetic inclination error was minor (<5°). A more robust follow-up study (Callebert et al., 2017) resampled these units, collecting ~850 specimens and reporting >400 well-defined paleomagnetic directions from the Gable Creek and Hudspeth Formations. This work yielded mean directions similar to those reported by Housen and Dorsey (2005) and more robust estimates of paleomagnetic inclination error using both anisotropy of partial anhysteretic remanent magnetization (ApARM) fabrics and elongation-distribution analysis (Tauxe et al., 2008). While further refinement of this updated study is pending, the fabric and elongation methods suggest a detrital inclination error of 5°–10°. This result reduces the estimate of latitudinal displacement to ~500 km and increases the inferred CW rotation of these rocks to 48°.

The paleomagnetic study reported in Grommé et al. (1986) included results from 46 sites collected from extrusive volcanics with well-defined flow bedding in the Eocene Clarno volcanics, which crop out in the western and central portions of the Blue Mountains. The paleomagnetic results included both normal and reverse polarity directions that were well clustered and antipodal to each other. Updated geochronology (Bestland et al., 1999) indicates these rocks are 54–43 Ma (early to middle Eocene) in age. The mean direction and resulting paleopole from the Clarno volcanics indicate that 16°CW rotation, with no latitudinal translation, occurred since middle Eocene time. As discussed in Housen and Dorsey (2005), these results collectively indicate a protracted history of CW rotation of the Blue Mountains during the past 130 m.y.

## PALEOMAGNETIC RESULTS

For this study, paleomagnetic samples were collected using either a gas-powered drill, or as oriented block samples. In the Suplee-Izee area, samples were collected from sedimentary rocks at four sites of the Lonesome Formation, three sites of andesitic volcanics of the Snowshoe Formation, and three sites from sedimentary rocks of the Trowbridge Formation. In the central portion of the Blue Mountains, three sites from the Bald Mountain Batholith, two sites from small intrusive bodies near Ritter, Oregon, and seven sites from the Hurricane Divide pluton of the Wallowa Batholith were collected. The site locations and their site-mean paleomagnetic directions (described below) are given in Table 1. The samples were cut into standard (2.2-cm-long) specimens that were demagnetized using either thermal or alternating field methods with remanence measured

TABLE 1. PALEOMAGNETIC SITE LOCATIONS AND SITE MEAN DIRECTIONS

| Rock unit | Site | Lat (°N) | Long (°W) | Dec (°) | Incl (°) | *n* | *k* | $\alpha_{95}$ (°) | Bedding (dd/d) |
|---|---|---|---|---|---|---|---|---|---|
| Lonesome Fm | 01Jlo1 | 44.06 | 119.36 | 035 | 62 | 9 | 28 | 10 | 128/43 |
| Lonesome Fm | 01Jlo2 | 44.06 | 119.36 | 028 | 49 | 6 | 21 | 14 | 116/30 |
| Lonesome Fm | 01Jlo3 | 44.08 | 119.33 | 340 | 73 | 6 | 45 | 10 | 183/73 |
| Lonesome Fm | 01Jlo4 | 44.07 | 119.34 | 037 | 50 | 9 | 47 | 8 | 104/55 |
| Trowbridge Fm | 01Jt1 | 44.11 | 119.29 | 050 | 71 | 7 | 43 | 9 | 059/89 |
| Ritter intrusives | 01JKr1 | 44.85 | 119.04 | 015 | 52 | 3 | 125 | 6.3 | |
| Ritter intrusives | 01JKr2 | 44.85 | 119.05 | 047 | 46 | 4 | 23 | 18.9 | |
| Bald Mtn | 01JKb1 | 44.99 | 118.08 | 035 | 81 | 3 | 26 | 21 | |
| Bald Mtn | 01JKb2 | 44.99 | 118.13 | 007 | 76 | 5 | 18 | 12 | |
| Bald Mtn | 01JKb3 | 44.97 | 118.18 | 011 | 64 | 4 | 34 | 16 | |
| Wallowa | 01JKw1 | 45.26 | 117.38 | 044 | 69 | 5 | 127 | 7 | |
| Wallowa | 01JKw1 | 45.26 | 117.38 | 206 | –71 | 7 | 118 | 6 | |
| Wallowa | 01JKw2 | 45.23 | 117.36 | 194 | –73 | 10 | 79 | 6 | |
| Wallowa | 01JKw3 | 45.39 | 117.42 | 218 | –61 | 7 | 105 | 6 | |
| Wallowa | 01JKw4 | 45.39 | 117.42 | 217 | –68 | 6 | 61 | 9 | |
| Wallowa | 01JKw5 | 45.39 | 117.43 | 208 | –57 | 3 | 31 | 20 | |
| Wallowa | 01JKw6 | 45.37 | 117.42 | 212 | –75 | 6 | 128 | 6 | |
| Wallowa | 01JKw7 | 45.24 | 117.38 | 192 | –72 | 7 | 174 | 5 | |

*Note:* Lat, Long—site latitude, longitude; Dec—declination of site mean direction; Incl—inclination of site mean direction; *n*—number of samples; *k*, $\alpha_{95}$—Fisher precision parameter and radius of 95% confidence; Bedding—dip direction (dd) and dip (d) of bedding plane for site; Fm—Formation; Mtn—Mountain.

in a WSGI 755 DC-SQUID magnetometer, housed in a magnetically shielded space in the Pacific Northwest Paleomagnetism Laboratory at Western Washington University.

The majority of the samples had well-defined magnetizations (Fig. 3) with two components indicated by examination of orthogonal vector plots of the demagnetization results. Most of the Jurassic sedimentary rocks had similar magnetization behavior, with a well-defined second removed component defined by demagnetization steps higher than either 25 mT (alternating field) or 250 °C (thermal; Fig. 3). The in situ mean direction of this component from the Lonesome and Trowbridge Formations was D = 28°, I = 63°, k = 27, $\alpha_{95}$ = 15°, *N* = 5. Correcting these directions for bedding tilts measured at each site significantly increased their scatter (Fig. 4), and so I infer that they are the result of a postdeformation remagnetization event. The andesites of the Jurassic Snowshoe Formation were poorly resolved and did not yield useful directions.

Samples from the plutonic rocks had well-defined directions (Fig. 3), with site mean directions that were very similar to those reported by Wilson and Cox (1980). This work extends the previous work to include well-defined directions from the Bald Mountain Batholith, and additional sites from the Ritter, Oregon, area and the Hurricane Divide pluton of the Wallowa Batholith. The combined mean direction of all of the plutonic rocks (this study plus data from Wilson and Cox, 1980) is D = 29°, I = 66°, k = 56, $\alpha_{95}$ = 4°, *N* = 22 (Fig. 5). A combined mean direction from a total of 64 sites from the remagnetized strata reported by Hillhouse et al. (1982) and Harbert et al. (1995), and from the Suplee-Izee area in this study, and from the plutonic rocks is D = 33°, I = 64°, k = 26, $\alpha_{95}$ = 3.7°, *N* = 64.

## INTERPRETATION AND DISCUSSION

The postfolding age of magnetization of the Jurassic strata in the Suplee-Izee area, and the similarity between the in situ mean direction of these rocks and the combined mean direction of the plutonic rocks strongly suggest that a remagnetization event has affected the Suplee-Izee area (Fig. 6). These strata are folded, though not as severely as underlying units (Dickinson and Vigrass, 1965; Dorsey and LaMaskin, 2007), and they are not metamorphosed. These observations suggest that the remagnetization involved some combination of orogenic fluids (Van der Voo and Torsvik, 2012; Izquierdo-Llavall et al., 2015) and localized pressure solution associated with incipient deformation (e.g., Housen et al., 1993). Both Hillhouse et al. (1982) and Harbert et al. (1995) recognized that many Permian and Triassic rocks in the eastern portion of the Blue Mountains have been remagnetized, and that the similarity between the paleomagnetic directions obtained from these remagnetized strata and the directions obtained from the plutonic rocks reported by Wilson and Cox (1980) suggests that the remagnetization event recorded in the Permian–Triassic rocks was likely coeval, or close in age, with the intrusion of the plutonic rocks (see Fig. 6).

The ages of magnetization of the plutonic rocks reported here, and in Wilson and Cox (1980), range from 140 Ma for the Bald Mountain Batholith (Schwartz et al., 2014), to 135 Ma for the Hurricane Divide pluton of the Wallowa Batholith (Schwartz et al., 2011), to 115 Ma for the Cornucopia Stock (Johnson et al., 1997). There are no known published ages for the plutonic rocks near Ritter, Oregon, but they are presumed to be coeval with the other plutons. The magnetic polarity of these plutons

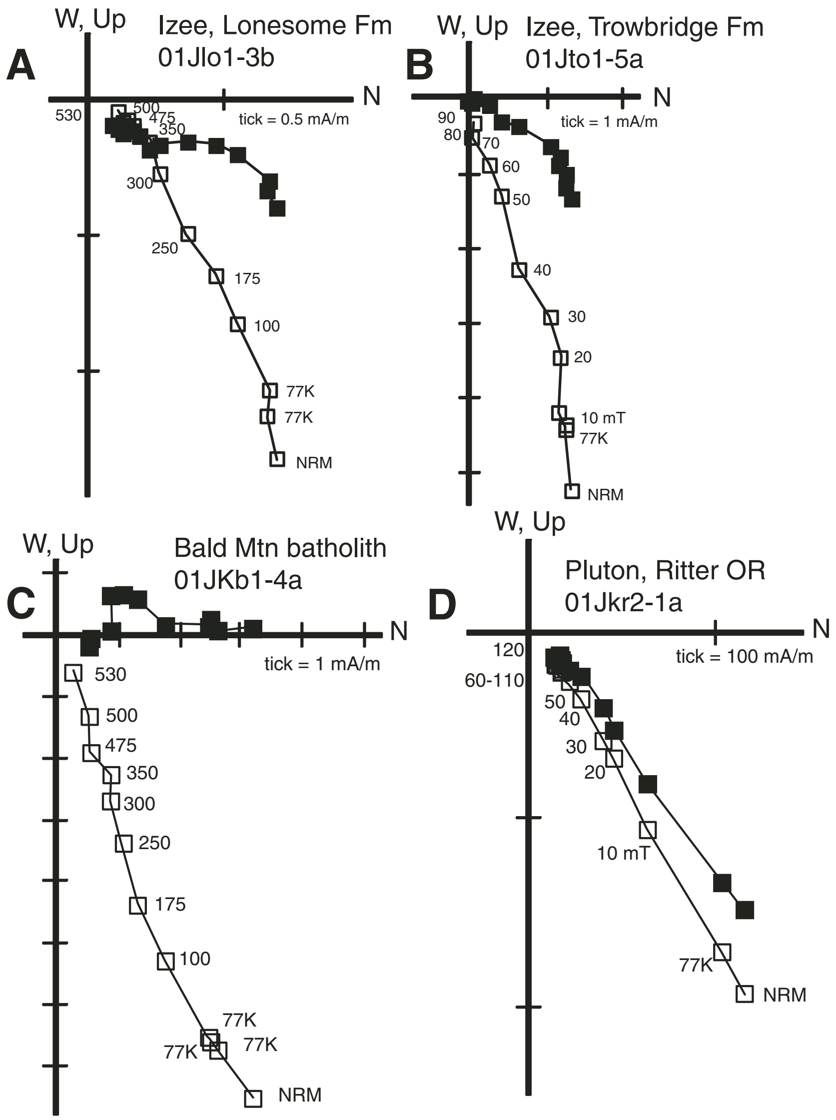


Figure 3. Representative orthogonal vector plots depicting the demagnetization results from this study. Open symbols denote projection of directions on vertical plane; closed symbols denote projection of directions on horizontal plane. Demagnetization steps noted: 77 K for liquid nitrogen treatment; alternating field noted by mT for first step; all others refer to thermal step in degrees Celsius. (A) Thermal demagnetization of a sample of the Jurassic Lonesome Formation. (B) Alternating field demagnetization of a sample from the Jurassic Trowbridge Formation. (C) Thermal demagnetization of a sample from the Bald Mountain Batholith. (D) Alternating field demagnetization of a sample from small plutonic body near Ritter, Oregon. NRM—natural remanent magnetization.

can provide some additional constraints on their magnetization ages via a comparison with the geomagnetic polarity time scale (Gradstein et al., 2004). The normal polarity of the Cornucopia Stock is consistent with a magnetization age during the Cretaceous long-normal superchron (125–83 Ma). In addition, all of the in situ directions from remagnetized strata of the Blue Mountains have normal magnetic polarity; this may suggest that the remagnetization in the Blue Mountains occurred during the long-normal superchron, following the intrusion of most of the Blue Mountains plutons.

Previous comparisons between the paleomagnetic results from the Blue Mountains plutons (Wilson and Cox, 1980), and the results obtained from remagnetized strata (Hillhouse et al., 1982; Harbert et al., 1995) have largely presumed a Late Jurassic magnetization age for comparisons with paleomagnetic reference poles from North America. As discussed above, it is clear that the magnetization ages for both the plutonic rocks and the remagnetized strata of the Blue Mountains are Early Cretaceous. While there are some significant differences in the Jurassic portions of the North American APWP (Beck and Housen, 2003; Torsvik et al., 2008; Kent and Irving, 2010; Kent et al., 2015), there is close agreement between different APWP compilations for Cretaceous time. The main feature of the North American APWP for this time is the clustering of paleomagnetic poles, indicating very little motion of the North American craton with respect to the spin axis between 135 Ma and 85 Ma. Using the APWP compilations of Beck and Housen (2003) and Kent et al. (2015), an expected paleolatitude versus time for a location in the center of the Blue Mountains can be calculated (Fig. 7). Both compilations indicate rapid northward motion of the North American margin throughout Jurassic time, with very rapid motion, to very high paleolatitudes, indicated by the Kent et al. (2015) compilation.

Paleomagnetic directions from both the plutons of the Blue Mountains and those obtained from remagnetized strata of

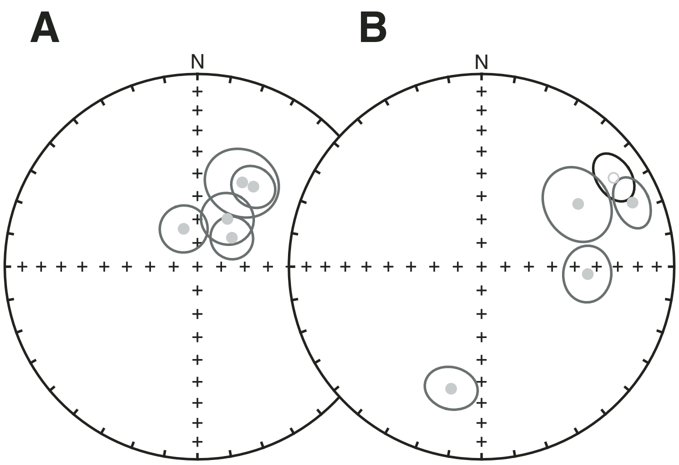


Figure 4. Equal-area projections with site means from Jurassic sedimentary rocks of the Suplee-Izee area. In situ directions on the left; tilt-corrected directions on the right. Closed symbols note downward directions; open symbols note upward directions. The marked increase in scatter for the tilt-corrected directions indicates these rocks fail a paleomagnetic tilt test and so were magnetized after the strata were tilted. The mean directions in in situ coordinates are noted.

Permian–Jurassic rocks lack robust constraints on paleohorizontal for the time of their magnetization. In many evaluations of discordant paleomagnetic data from the North Cascades–Coast plutonic complex (e.g., Butler et al., 1991), or coastal and Baja California (Dickinson and Butler, 1998), Bill Dickinson and colleagues consistently ascribed the discordance to large-scale crustal tilting rather than a combination of latitudinal translation and rotation (e.g., Beck, 1976; Irving et al., 1996; Cowan et al., 1997). Interpretation of the paleomagnetic results obtained by Wilson and Cox (1980), and those of the plutons and remagnetized strata presented here are also made uncertain by a lack of paleohorizontal control. While there is some evidence for deformation of the Blue Mountains plutons (see, for example, Žák et al., 2015), there are no systematic studies of barometry or differential uplift that can be used to evaluate or correct for possible postmagnetization tilt of these rock units. The paleomagnetic directions are not significantly streaked or elongate, which does rule out tilt, deformation, or rotation during cooling and acquisition of magnetization (Beck, 1992), but postcooling tilt cannot be ruled out using those considerations.

A compilation of paleomagnetic data from Early to Late Cretaceous rocks from cratonic North America in Housen et al. (2003) has been updated with additional results (Housen, 2017); the resulting mean pole (71.8°N, 192.7°E, $A_{95}$ = 2.4°, $N$ = 27, derived from units 130–85 Ma in age) provides a robust reference for the paleogeographic position of North America. The expected direction for the Blue Mountains calculated from this reference pole (Ix = 71°, Dx = 333°, expected paleolatitude = 55°N) differs significantly from the mean direction obtained from the plutonic rocks of the Blue Mountains (Fig. 6). One end-member interpretation would attribute the entire difference to a tilt of 25°

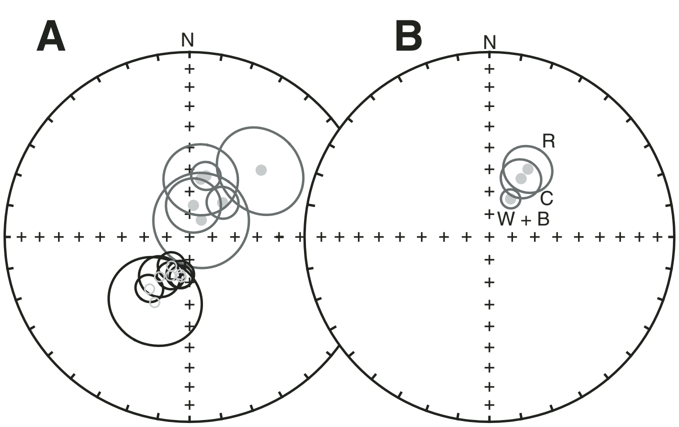


Figure 5. Equal-angle projections with site means for plutonic rocks of the Blue Mountains. (A) Directions for all site mean directions from the pluton rocks reported here. (B) Mean directions of the combined sites from the Cornucopia Stock (C), Ritter, Oregon, plutonics (R), and Bald Mountain and Wallowa Batholiths (W + B), with reverse-polarity results inverted.

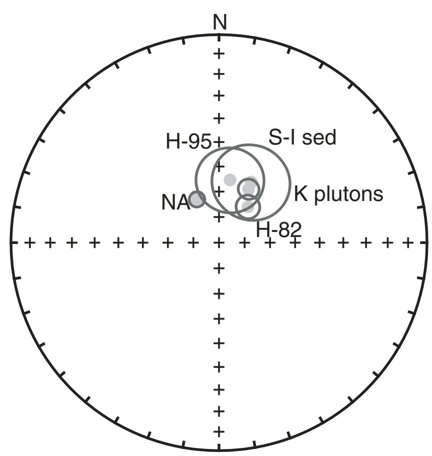


Figure 6. Equal-angle projection showing combined mean directions for the remagnetized strata of the Suplee-Izee area (S-I), the Blue Mountains plutons (K plutons), the remagnetized strata of the Hunsaker Formation (Harbert et al., 1995; H-95), and remagnetized strata of the Wild Sheep Creek and Huntington Formations (Hillhouse et al., 1982; H-82). The expected direction calculated for the present location of the Blue Mountains from the North American (NA) apparent polar wander path (Housen, 2017) is indicated. The directions from the Blue Mountains rocks are discordant from the expected direction; this can be explained by a tilt of 25° (top-to-W) about an axis trended 350°, or by a combination of clockwise rotation (60°) and ~1000 km latitudinal translation (see text).

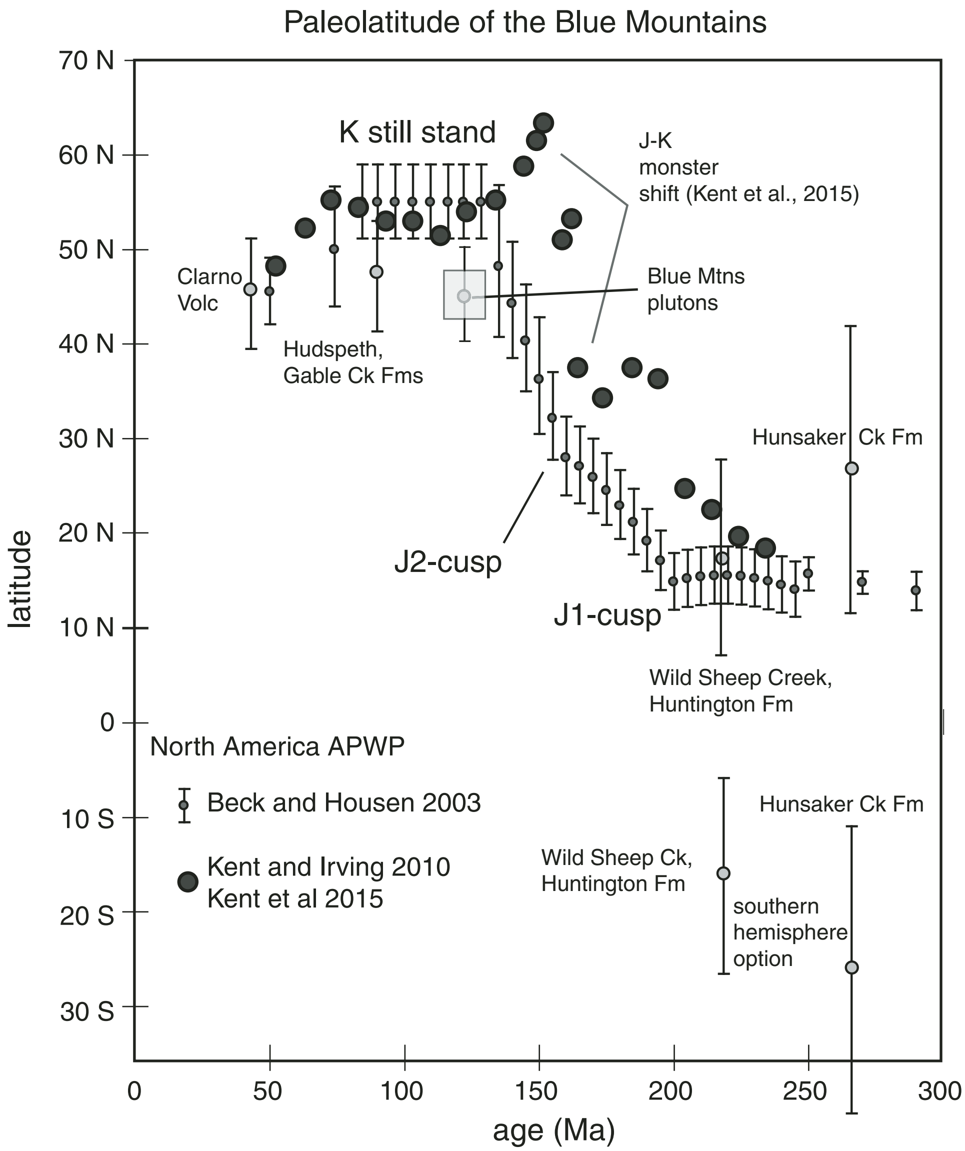


Figure 7. Expected and paleomagnetically inferred paleolatitudes of the Blue Mountains, showing calculated paleolatitude versus time for the Blue Mountains, using the apparent polar wander path (APWP) of Kent and Irving (2010) and Kent et al. (2015; larger circles), and from Beck and Housen, 2003 (smaller circles), for the past 300 m.y. Notable differences in these two apparent polar wander paths are the very rapid northward motion of the North American margin called for by the Kent et al. (2015) path, along with generally higher paleolatitudes throughout Jurassic (J) time. Both apparent polar wander path compilations indicate very little latitudinal motion for North America between 130 and 85 Ma—the Cretaceous (K) stillstand. Paleomagnetic results from the Blue Mountains plutons and remagnetized strata (130–115 Ma) have a paleolatitude that is ~10° farther south than the present location of the Blue Mountains, indicating 1000 km of latitudinal displacement after ca. 120 Ma. This displacement is similar to the 1200 km estimated for the Hudspeth and Gable Creek (Ck) Formations (Fm) of the Mitchell Inlier (Housen and Dorsey, 2005).

(top-up-to-the-west) about a horizontal axis with an azimuth of 350° (Fig. 6). The other end member would attribute the entire difference to a 60° ± 9° vertical-axis rotation and 1000 (±500) km of latitudinal translation (for examples, see Beck and Nosen, 1972; Beck, 1980). While it is not possible to rule out either of these end-member interpretations, substantial postmagnetization tilting of the Blue Mountains is unlikely for the following reasons. The area in question is ~200 km wide (Fig. 2), so that uniform application of a large (25°) tilt of the Blue Mountains as a rigid block implies exposure of unrealistically deep (>100 km) rock on the eastern side. Tilt of smaller, discrete crustal blocks or panels (as in Butler et al., 1991) would be possible, but it would be implausibly uniform to produce the consistent pattern of directions in plutons and remagnetized sedimentary rocks over a 200 km × 300 km area as observed here. The preferred interpretation is that postmagnetization tilt of the plutonic and remagnetized rocks is negligible.

The paleomagnetic results summarized here can be used to constrain the rotation history of the Blue Mountains as follows. Very robust estimates of rotation are provided by the units that have good paleohorizontal control. The Clarno volcanics (Grommé et al., 1986) have directions that indicate 16° ± 10°CW rotation after 45 Ma, and the Gable Creek and Hudspeth Formations of the Mitchell Inlier (Housen and Dorsey, 2005) have directions that indicate 37° ± 7°CW rotation after 90 Ma. Results of a larger study of the Cretaceous sedimentary rocks of the Mitchell Inlier (Callebert et al., 2017) have more easterly declinations than reported by Housen and Dorsey (2005) and may indicate larger (48°) CW rotation for these rocks. The rotation estimate from the combined plutonic rock/remagnetized strata is 60° ± 9°CW (assuming tilt is negligible). Given the ages of the youngest plutonic results and the normal polarity of the remagnetized directions, the rotation should be considered to have occurred after

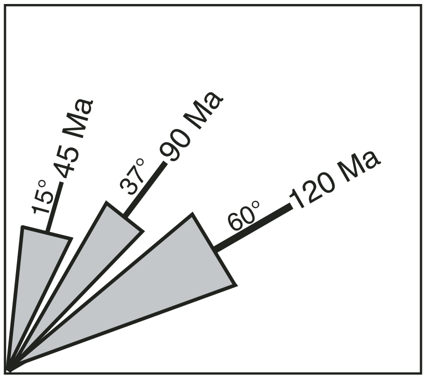


Figure 8. Illustration of vertical-axis rotation of the Blue Mountains. All rotations are relative to North America. Results from this study indicate 60° ± 9° clockwise (CW) rotation since 120 Ma, those from Housen and Dorsey (2005) indicate 37° ± 7°CW rotation since 90 Ma, and those from Grommé et al. (1985) indicate 15° ± 10°CW rotation since 45 Ma.

110–120 Ma. Taken together, these results indicate that the Blue Mountains have experienced a consistent pattern of CW rotation throughout most of the past 120 m.y. (Fig. 8). The majority of this rotation (~45°) has taken place between either 120 Ma and 45 Ma (if tilt is neglected) or between 90 Ma and 45 Ma (if only results with paleohorizontal are used). The corresponding rotation rates range between 0.6°/m.y. and 1.0°/m.y. If the age of rotation of the Blue Mountains is presumed to be younger, as proposed by Dickinson (2002), who linked CW rotation of the Blue Mountains to rotation observed in the Paleocene rocks of the Oregon and Washington Coast Ranges, then the rates of rotation would be much higher (2–3°/m.y.).

The paleomagnetic results discussed here also suggest that the Blue Mountains have experienced moderate-scale latitudinal displacement since Early Cretaceous time (Fig. 7). Assuming that tilt of the plutonic and remagnetized rocks is negligible, then the Early Cretaceous magnetization age (and comparable North American reference pole) indicate that the Blue Mountains mean inclination from these rocks provides a paleolatitude of 46°N (±5°). Using the Early Cretaceous reference pole discussed previously, the expected paleolatitude of the Blue Mountains is 55°N, implying a statistically significant poleward displacement of 1000 ± 500 km since ca. 120 Ma. The Blue Mountains would have been at the latitude of central Nevada and the northern portion of the Sierra Nevada. This moderate displacement is compatible with the low-end (1200 km) displacement estimated for the sedimentary rocks of the Mitchell Inlier by Housen and Dorsey (2005), but it is somewhat higher than the more robust estimate (~500 km) emerging from the restudy by Callebert et al. (2017). The displacement estimates for the Blue Mountains are very similar to those obtained from the Spences Bridge volcanics and related rocks of the Intermontane superterrane (Irving et al., 1995; Haskin et al., 2003), and from untilted plutonic rocks of Knight Inlet (Rusmore et al., 2013). Collectively the data support linkages between the Intermontane superterrane and the Blue Mountains. The inferred displacement does not agree with the fault-based reconstructions of Wyld et al. (2006), who proposed essentially zero post–90 Ma displacement of the Blue Mountains, and it is in excess of the <500 km displacement inferred from recent provenance studies (Surpless and Gulliver, this volume). However, the displacement proposed here is in agreement with several provenance-based constraints such as those proposed by Wyld and Wright (2001), Dorsey and LaMaskin (2007), and LaMaskin et al. (2011). As discussed in Housen and Dorsey (2005), the occurrence of a consistent and long-lived pattern of vertical-axis rotations of the Blue Mountains (Fig. 8) is consistent with both long-lived dextral shear of this portion of the Cordilleran margin and translation of outboard terranes as proposed by Beck (1976).

Alternatively, the anomalous inclination of the plutonic and remagnetized strata could be ascribed to postmagnetization tilting or (in the unremagnetized sedimentary rocks) unrecognized detrital inclination error. Invoking tilt would necessarily preclude use of the paleomagnetic directions from the plutons to constrain the rotation of the Blue Mountains, in which case, the only remaining evidence for CW rotation of the Blue Mountains would be from units younger than 90 Ma.

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## REFERENCES CITED

Beck, M.E., Jr., 1976, Discordant paleomagnetic pole positions as evidence of regional shear in the western Cordillera of North America: American Journal of Science, v. 276, p. 694–712, https://doi.org/10.2475/ajs.276.6.694.

Beck, M.E., Jr., 1980, Paleomagnetic record of plate-margin tectonic processes along the western edge of North America: Journal of Geophysical Research, v. 85, p. 7115–7131, https://doi.org/10.1029/JB085iB12p07115.

Beck, M.E., Jr., 1992, Some thermal and paleomagnetic consequences of tilting a batholith: Tectonics, v. 11, p. 297–302, https://doi.org/10.1029/91TC02340.

Beck, M.E., Jr., and Housen, B.A., 2003, Absolute velocity of North America during the Mesozoic from paleomagnetic data: Tectonophysics, v. 377, p. 33–54, https://doi.org/10.1016/j.tecto.2003.08.018.

Beck, M.E., Jr., and Nosen, L., 1972, Anomalous paleolatitudes in Cretaceous granitic rocks: Nature–Physical Science (London), v. 235, p. 11–13, https://doi.org/10.1038/physci235011a0.

Bestland, E.A., Hammond, E., Blackwell, D.L.S., Kays, M.A., Retallack, G.J., and Stimac, J., 1999, Geologic framework of the Clarno Unit, John Day Fossil Beds National Monument, central Oregon: Oregon Geology, v. 61, p. 3–19.

Butler, R.F., Dickinson, W., and Gehrels, G., 1991, Paleomagnetism of coastal California and Baja California: Alternatives to large-scale northward transport: Tectonics, v. 10, p. 561–576, https://doi.org/10.1029/90TC02780.

Callebert, W., Housen, B., and Surpless, K., 2017, Assessment of inclination shallowing in Upper-Cretaceous turbidites, Ochoco Basin, central Oregon: Implications for Cordilleran terrane transport: Geological Society of America Abstracts with Programs, v. 49, no. 6, paper 292-4.

Cowan, D.S., Brandon, M.T., and Garver, J.I., 1997, Geologic tests of hypotheses for large coastwise displacements—A critique illustrated by the Baja–British Columbia controversy: American Journal of Science, v. 297, p. 117–173, https://doi.org/10.2475/ajs.297.2.117.

Dickinson, W.R., 2002, The Basin and Range Province as a composite extensional domain: International Geology Review, v. 44, p. 1–38, https://doi.org/10.2747/0020-6814.44.1.1.

Dickinson, W.R., 2004, Evolution of the North American Cordillera: Annual Review of Earth and Planetary Sciences, v. 32, p. 13–45, https://doi.org/10.1146/annurev.earth.32.101802.120257.

Dickinson, W.R., and Butler, R.F., 1998, Coastal and Baja California paleomagnetism, reconsidered: Geological Society of America Bulletin, v. 110, p. 1268–1280, https://doi.org/10.1130/0016-7606(1998)110<1268:CABCPR>2.3.CO;2.

Dickinson, W.R., and Thayer, T., 1978, Paleogeographic and paleotectonic implications of Mesozoic stratigraphy and structure in the John Day inlier of central Oregon, *in* Howell, D.G., and McDougall, K.A., eds., Mesozoic Paleogeography of the Western United States: Los Angeles, California, Pacific Section, Society of Economic Paleontologists and Mineralogists, Paleogeography Symposium 2, p. 147– 161.

Dickinson, W.R., and Vigrass, L.W., 1965, Geology of the Suplee-Izee Area, Crook, Grant, and Harney Counties, Oregon: Oregon Department of Geology and Mineral Industries Bulletin 58, 109 p.

Dorsey, R.J., and LaMaskin, T.A., 2007, Stratigraphic record of Triassic–Jurassic collisional tectonics in the Blue Mountains Province, northeastern Oregon: American Journal of Science, v. 307, p. 1167–1193, https://doi.org/10.2475/10.2007.03.

Gradstein, F., Ogg, J.G., and Smith, A.G., eds., 2004, A Geologic Time Scale: Cambridge, UK, Cambridge University, 610 p.

Grommé, C.S., Beck, M.E., Jr., and Engebretson, D.C., 1986, Paleomagnetism of the Tertiary Clarno Formation of central Oregon and its significance for the tectonic history of the Pacific Northwest: Journal of Geophysical Research, v. 91, p. 14,089–14,103, https://doi.org/10.1029/JB091iB14p14089.

Hamilton, W., 1969, Mesozoic California and the underflow of Pacific mantle: Geological Society of America Bulletin, v. 80, p. 2409–2430, https://doi.org/10.1130/0016-7606(1969)80[2409:MCATUO]2.0.CO;2.

Harbert, W., Hillhouse, J., and Vallier, T., 1995, Paleomagnetism of the Permian Wallowa terrane: Implications for terrane migration and orogeny: Journal of Geophysical Research, v. 100, p. 12,573–12,588, https://doi.org/10.1029/94JB02129.

Haskin, M.L., Enkin, R.J., Mahoney, J.B., Mustard, P.S., and Baker, J., 2003, Deciphering shallow paleomagnetic inclinations: 1. Implications from correlation of Albian volcanic rocks along the Insular/Intermontane superterrane boundary in the southern Canadian Cordillera: Journal of Geophysical Research, v. 108, no. B4, 2185, https://doi.org/10.1029/2002JB001982.

Hillhouse, J.W., Gromme, C.S., and Vallier, T.L., 1982, Paleomagnetism and Mesozoic tectonics of the Seven Devils volcanic arc in northeastern Oregon: Journal of Geophysical Research, ser. B, Solid Earth and Planets, v. 87, p. 3777–3794, https://doi.org/10.1029/JB087iB05p03777.

Housen, B.A., 2017, A synopsis of paleomagnetic data from Cretaceous rocks of North America and Cordilleran terranes: Geological Society of America Abstracts with Programs, v. 49, no. 6, paper 223-3.

Housen, B.A., and Dorsey, R.J., 2005, Paleomagnetism and tectonic significance of Albian and Cenomanian turbidites, Ochoco Basin, Mitchell inlier, central Oregon: Journal of Geophysical Research, v. 110, B07102, https://doi.org/10.1029/2004JB003458.

Housen, B.A., van der Pluijm, B.A., and Van der Voo, R., 1993, Magnetite dissolution and neocrystallization during cleavage formation: Paleomagnetic study of the Martinsburg Formation, Lehigh Gap, Pennsylvania: Journal of Geophysical Research, v. 98, p. 13,799–13,813, https://doi.org/10.1029/93JB01088.

Housen, B.A., Beck, M.E., Jr., Burmester, R.F., Fawcett, T., Petro, G., Sargent, R., Addis, K., Curtis, K., Ladd, J., Liner, N., Molitor, B., Montgomery, T., Mynatt, I., Palmer, B., Tucker, D., and White, I., 2003, Paleomagnetism of the Mount Stuart Batholith revisited again: What has been learned since 1972?: American Journal of Science, v. 303, p. 263–299, https://doi.org/10.2475/ajs.303.4.263.

Irving, E., Thorkelson, D.J., Wheadon, P.M., and Enkin, R.J., 1995, Paleomagnetism of the Spences Group and northward displacements of the Intermontane belt, British Columbia: A second look: Journal of Geophysical Research, v. 100, p. 6057–6071, https://doi.org/10.1029/94JB03012.

Irving, E., Wynne, P.J., Thorkelson, D.J., and Schiarizza, P., 1996, Large (1000 to 4000 km) northward movements of tectonic domains in the northern Cordillera, 83–45 Ma: Journal of Geophysical Research, v. 101, p. 17,901–17,916, https://doi.org/10.1029/96JB01181.

Izquierdo-Llavall, E., Saina, A.C., Oliva-Urcia, B., Burmester, R., Pueyo, E.L., and Housen, B., 2015, Multi-episodic remagnetization related to deformation in the Pyrenean Internal Sierras: Geophysical Journal International, v. 201, p. 891–914, https://doi.org/10.1093/gji/ggv042.

Johnson, K., Barnes, C.G., and Miller, C.A., 1997, Petrology, geochemistry, and genesis of high-Al tonalite and trondhjemites of the Cornucopia Stock, Blue Mountains, northeastern Oregon: Journal of Petrology, v. 38, p. 1585–1611, https://doi.org/10.1093/petroj/38.11.1585.

Kent, D.V., and Irving, E., 2010, Influence of inclination error in sedimentary rocks on the Triassic and Jurassic apparent polar wander path for North America and implications for Cordilleran tectonics: Journal of Geophysical Research, v. 115, B10103, https://doi.org/10110.11029/12009JB007205.

Kent, D.V., Kjarsgaard, B.A., Gee, J.S., Muttoni, G., and Heaman, L.M., 2015, Tracking the Late Jurassic apparent (or true) polar shift in U-Pb-dated kimberlites from cratonic North America (Superior Province of Canada): Geochemistry Geophysics Geosystems, v. 16, p. 983–994, https://doi.org/10.1002/2015GC005734.

LaMaskin, T.A., Vervoort, J.D., and Dorsey, R.J., 2011, Early Mesozoic paleogeography and tectonic evolution of the western United States: Insights from detrital zircon U-Pb geochronology of the Blue Mountains Province, northeastern Oregon, USA: Geological Society of America Bulletin, v. 123, p. 1939–1965, https://doi.org/10.1130/B30260.1.

LaMaskin, T.A., Dorsey, R.J., Vervoort, J.D., Schmitz, M.D., Tumpane, K.P., and Moore, N.O., 2015, Westward growth of Laurentia by pre–Late Jurassic terrane accretion, eastern Oregon and western Idaho, United States: The Journal of Geology, v. 123, no. 3, p. 233–267, https://doi.org/10.1086/681724.

Oles, K.F., and Enlows, H.E., 1971, Bedrock Geology of the Mitchell Quadrangle, Wheeler County, Oregon: State of Oregon Department of Geology and Mineral Resources Bulletin 72, 62 p.

Riddihough, R., Finn, C., and Couch, R., 1986, Klamath–Blue Mountain lineament, Oregon: Geology, v. 14, p. 528–531, https://doi.org/10.1130/0091-7613(1986)14<528:KMLO>2.0.CO;2.

Rusmore, M.E., Bogue, S.W., and Woodsworth, G.J., 2013, Paleogeography of the Insular and Intermontane terranes reconsidered: Evidence from the southern Coast Mountains Batholith, British Columbia: Lithosphere, v. 5, p. 521–536, https://doi.org/10.1130/L288.1.

Schwartz, J.J., Snoke, A.W., Frost, C.D., Barnes, C.G., Gromet, L.P., and Johnson, K., 2010, Analysis of the Wsallowa-Baker terrane boundary: Implications for tectonic accretion in the Blue Mountains province, northeastern Oregon: Geological Society of America Bulletin, v. 122, p. 517–536, https://doi.org/10.1130/B26493.1.

Schwartz, J.J., Johnson, K., Miranda, E.A., and Wooden, J.L., 2011, The generation of high Sr/Y plutons following Late Jurassic arc-arc collision, Blue Mountains Province, NE Oregon: Lithos, v. 126, p. 22–41, https://doi.org/10.1016/j.lithos.2011.05.005.

Schwartz, J.J., Johnson, K., Mueller, P., Valley, J., Strickland, A., and Wooden, J.L., 2014, Time scales and processes of Cordilleran batholith construction and high-Sr/Y magmatic pulses: Evidence from the Bald Mountain

Batholith, northeastern Oregon: Geosphere, v. 10, no. 6, p. 1456–1481, https://doi.org/10.1130/GES01033.1.

Silberling, N.J., Jones, D.L., Blake, M.C., Jr., and Howell, D.G., 1984, Lithotectonic terrane map of the western conterminous United States, part C, *in* Silberling, N.J., and Jones, D.L., eds., Lithotectonic Terrane Maps of the North American Cordillera: U.S. Geological Survey Open File Report 84-523, 43 p.

Surpless, K.D., and Gulliver, K.D.H., 2018, this volume, Provenance analysis of the Ochoco basin, central Oregon: A window into the Late Cretaceous paleogeography of the northern U.S. Cordillera, *in* Ingersoll, R.V., Lawton, T.F., and Graham, S.A., eds., Tectonics, Sedimentary Basins, and Provenance: A Celebration of William R. Dickinson's Career: Geological Society of America Special Paper 540, https://doi.org/10.1130/2018.2540(11).

Tauxe, L., Kodama, K.P., and Kent, D.V., 2008, Testing corrections for paleomagnetic inclination error in sedimentary rocks: A comparative approach: Physics of the Earth and Planetary Interiors, v. 169, p. 152–165, https://doi.org/10.1016/j.pepi.2008.05.006.

Torsvik, T.H., Müller, R.D., Van der Voo, R., Steinberger, B., and Gaina, C., 2008, Global plate motion frames: Towards a unified model: Reviews of Geophysics, v. 46, RG3004, https://doi.org/10.1029/2007RG000227.

Vallier, T.L., 1995, Petrology of pre-Tertiary igneous rocks in the Blue Mountains region of Oregon, Idaho, and Washington: Implications for the geologic evolution of a complex island arc, *in* Vallier, T.L., and Brooks, H.C., eds., Geology of the Blue Mountains Region of Oregon, Idaho, and Washington: Petrology and Tectonic Evolution of Pre-Tertiary Rocks of the Blue Mountains Region: U.S. Geological Survey Professional Paper 1438, p. 125–209.

Van der Voo, R., and Torsvik, T.H., 2012, The history of remagnetization of sedimentary rocks: Deceptions, developments and discoveries, *in* Elmore, R.D., Muxworthy, A.R., Aldana, M.M., and Mena, M., eds., Remagnetization and Chemical Alteration of Sedimentary Rocks: Geological Society, London, Special Publication 371, p. 23–53, https://doi.org/10.1144/SP371.2.

White, J.D.L., White, D.L., Vallier, T.L., Stanley, G.D., Jr., and Ash, S.R., 1992, Middle Jurassic strata link Wallowa, Olds Ferry, and Izee terranes in the accreted Blue Mountains island arc, northeastern Oregon: Geology, v. 20, p. 729–732, https://doi.org/10.1130/0091-7613(1992)020<0729:MJSLWO>2.3.CO;2.

Wilson, D., and Cox, A., 1980, Paleomagnetic evidence for tectonic rotation of Jurassic plutons in Blue Mountains, eastern Oregon: Journal of Geophysical Research, v. 85, p. 3681–3689, https://doi.org/10.1029/JB085iB07p03681.

Wyld, S.J., and Wright, J.E., 2001, New evidence for Cretaceous strike-slip faulting in the United States Cordillera and implications for terrane-displacement, deformation patterns, and plutonism: American Journal of Science, v. 301, p. 150–181, https://doi.org/10.2475/ajs.301.2.150.

Wyld, S.J., Umhoefer, P.J., and Wright, J.E., 2006, Reconstructing northern Cordilleran terranes along known Cretaceous and Cenozoic strike-slip faults: Implications for the Baja–British Columbia hypothesis and other models, *in* Haggart, J.W., Enkin, R.J., and Monger, J.W.H., eds., Paleogeography of the North American Cordillera: Evidence For and Against Large-Scale Displacements: Geological Association of Canada Special Paper 46, p. 277–298.

Žák, J., Verner, K., Tomek, F., Holub, F.V., Johnson, K., and Schwartz, J.J., 2015, Simultaneous batholith emplacement, terrane/continent collision, and oroclinal bending in the Blue Mountains Province, North American Cordillera: Tectonics, v. 34, p. 1107–1128, https://doi.org/10.1002/2015TC003859.

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