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Revisiting the Seven Devils-Wrangellia connection: the paleogeography of triassic rocks in western Idaho.

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REVISITING THE SEVEN DEVILS-WRANGELLIA CONNECTION: THE PALEOGEOGRAPHY OF TRIASSIC ROCKS IN WESTERN IDAHO

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MASTER'S THESIS

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Abstract

The origins of and relationships between allochthonous terranes located west of the $^{87}Sr/^{86}Sr$ 0.706 line (Armstrong et al., 1977) have profound implications for understanding the Mesozoic paleogeography of western North America. The Wallowa-Seven Devils terrane has long been associated with Wrangellia, whose fragments can now be found in British Columbia, Canada and Alaska. However, stratigraphic, fossil, geochemical, structural, and paleomagnetic evidence linking the Wallowa-Seven Devils terrane to Wrangellia is considered equivocal (Follo, 1992). A new paleomagnetic study of the Seven Devils terrane may yield better results than Hillhouse et al. (1982) and, in conjunction with other evidence, support or refute a linkage of the Wallowa-Seven Devils terrane with Wrangellia.

Samples from 22 sites located in the Wild Sheep Creek Formation of the Wallowa-Seven Devils arc were demagnetized and analyzed. Resulting data were divided into groups 1, 2, and 3 based on clustering of paleomagnetic directions calculated from last-removed components. Directions of Group 3 (19 sites) are most common and fail the paleomagnetic fold test. Group 1 (2 sites) and Group 2 (2 sites) directions are significantly different from Group 3 and resemble a subset of sites having similar directions obtained by Hillhouse et al. (1982).

Reanalysis of two sets of magnetic directions reported by Hillhouse et al. (1982) that were interpreted to represent primary (Triassic) magnetizations reveals additional complexity. Directions from sites 7 and 18 may be biased northward by an unresolved magnetic component. Two new Group 1 sites (this study) have been compiled with three Group 1 sites from Hillhouse et al. (1982). These revised Group 1 sites do not pass either of two examples of paleomagnetic fold tests. Group 1 preserves a reversed field if Group 1 rocks originated in the northern hemisphere.

Hillhouse et al. (1982) Group 2 sites were collected from formations that are now interpreted to reside in two distinct tectonostratigraphic terranes. When parsed into their separate terranes, Group 2 sites no longer pass a McElhinny (1964) or a parametric bootstrap (Tauxe and Watson, 1994) fold test. However, direction clustering for both fold tests is highest at 100% untilting suggesting that the Group 2 magnetizations could be primary. Tests comparing the similarity of the directions from the Wallowa and Olds Ferry subgroups indicate that the components used to define the Group 2 magnetization could have been drawn from a similar distribution (cart_hist test of, Tauxe, 1998); this suggests that the Wallowa-Seven Devils and the Olds Ferry terranes shared a common tectonic framework when the Group 2 magnetization was acquired.

Present paleomagnetic data cannot dismiss an association of the Wallowa-Seven Devils terrane with Wrangellia, Stikinia, or Quesnellia. Better structural control and geochronology of the Wild Sheep Creek Formation would greatly benefit any future paleomagnetic studies of the Seven Devils terrane.

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Introduction

Large geographical extents of North America, west of a well-documented line defined by the $^{87}Sr/^{86}Sr$ initial isotopic composition of igneous rocks, the ^{86}Sr 0.706 line (Armstrong et al., 1977), are composed of amalgamations of accreted allochthonous terranes. Since the inception of the terrane concept (Coney et al., 1980) and the emergence of a practical definition for "terrane" (Jones et al., 1983), geoscientists have been using stratigraphic, geochemical, geochronologic, faunal, and paleomagnetic correlations to better understand inter-terrane relationships and to model Mesozoic paleogeography of what now constitutes the bulk of the North American Pacific margin.

A particularly enigmatic portion of the Pacific margin, the Blue Mountain Province (BMP), consists of four major terranes whose origins, amalgamation, and accretion to the North American continental margin remain controversial. These are the Wallowa-Seven Devils, Olds Ferry, Baker, and Izee terranes. The last also is known as the Izee overlap assemblage. Unlike terranes located in Alaska, British Columbia, southern Oregon, and northern and costal California, BMP terranes lie hundreds of kilometers inboard from the present day margin and have been rotated as much as 89° clockwise (Wilson and Cox, 1980). Portions of the BMP are in direct contact with Proterozoic Belt-Purcell Supergroup rocks in a region where the $^{87}Sr/^{86}86$ ^{86}Sr 0.706 gradient, which marks the transition from old to young crust, is pronounced (Giorgis et al., 2005). Flanked and partially covered by tens of thousands of square kilometers of Columbia River Flood Basalts, BMP terranes are relatively isolated from other margin terranes making associations based on extrapolation of large-scale structural features difficult. New zircon/basin development studies are shedding light on the evolution of the BMP (Dorsey and LaMaskin, in press) but existing fossil, geochemical, and paleomagnetic data are insufficient to unequivocally link the BMP to any other North American margin terrane.

The Wallowa-Seven Devils terrane contains the Tethyan-affiliated, fossiliferous Martin Bridge Limestone and is the most extensive, least deformed BMP terrane. For these reasons researchers concerned with the origin and development of the Blue Mountain Province often concentrate on Wallowa-Seven Devils terrane. However, despite decades of study the origin and evolution of the Wallowa-Seven Devils terrane remains largely open to interpretation. Past work in the terrane has led primarily to a paleogeographic association with Wrangellia (Muller, 1977; Jones, 1977; Hillhouse et al., 1982; Dickinson, 2004), but an association with Stikinia also has been proposed (Saleeby, 1983; Mortimer, 1986). Work completed in the mid-1990s emphasized an independent tectonic and evolutionary history for the arc (Avé Lallemant, 1995; Vallier, 1995) and more recent work has noted that structural characteristics of the Wallowa-Seven Devils terrane are similar to characteristics of the Klamath Mountains of southern Oregon and terranes located in the northern Sierra Nevada (Kays et al., 2006). Additional work in stratigraphy, geochronology, paleontology, geochemistry, and paleomagnetism is required if inroads into the problematic BMP will continue to be made: tectonic models that deliver the Wallowa-Seven Devils terrane into the Columbia Embayment (Wernicke and Klepacki, 1988) are in need of considerable substantiation; structures that may have accommodated significant Cretaceous left-lateral shear (Strayer et al., 1989) are in need of further research; and many problem areas in the BMP require more detailed mapping and geochronology. However, new studies in the BMP that utilize geochronology, paleontology, geochemistry, or paleomagnetism will be effective only if they are contextually based in the region's geology. Making conceptual progress also requires understanding the reasons why the Wallowa-Seven Devils terrane has been traditionally associated with Wrangellia and if those reasons are adequate to continue support of the association.

Geologic Setting

The Permian-Jurassic rocks of the Wallowa-Seven Devils terrane are the easternmost rocks of island arc affinity found in Western North America and are exposed in the Seven Devils Mountains, Idaho; Hells Canyon; and in the Wallowa Mountains, Oregon. The area of this study (Figure 1) includes rocks from only the Seven Devils (SD) portion of the Wallowa-Seven Devils terrane. Henceforth the terms Wallowa-Seven Devils terrane and Seven Devils terrane may be used interchangeably.

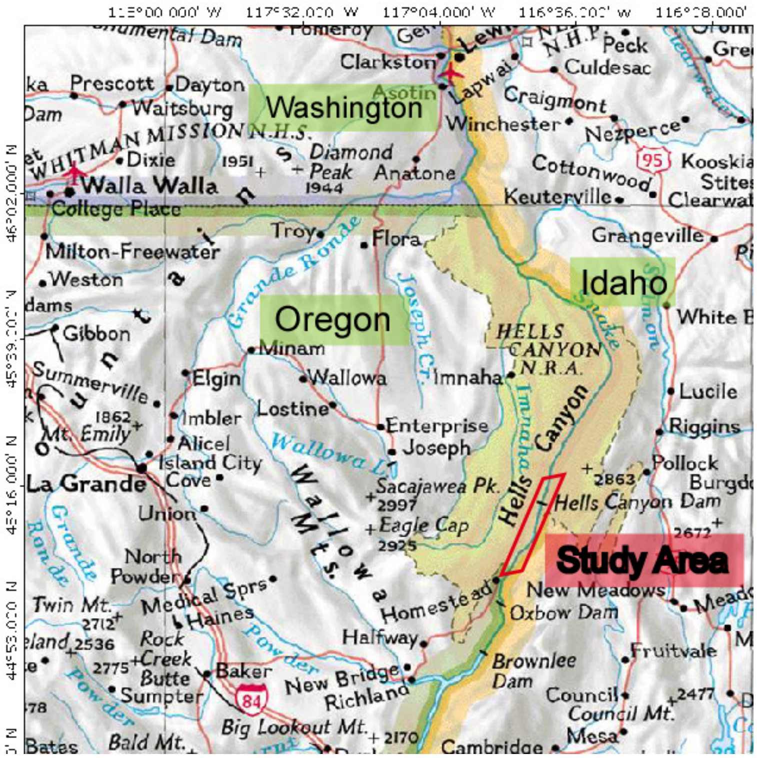

Figure 1. Map with the location of the study area (red parallelogram). Study samples were collected on the east side of the Snake River south of Hells Canyon Dam and North of Homestead, Oregon.

Regionally, the Wallowa-Seven Devils terrane is located in the Blue Mountain Province (Figure 2) and is juxtaposed against the Baker terrane, a oceanic mélange; the Olds Ferry terrane, the deformed remnants of an island arc; and the Izee overlap assemblage, a collection of Triassic-Jurassic clastic sedimentary rocks with minor volcanic interbeds (Dickinson, 1979). Late Jurassic to mid-Cretaceous regional deformation probably produced the present day distribution and structural characteristics of pre-Tertiary BMP rock. This deformation may have culminated with the emplacement of the Idaho Batholith although structures found throughout the BMP suggest that the province underwent earlier deformations; these deformations may have occurred at different times in different portions of the province (Dickinson, 1979).

At least three contractional deformations (D) with associated syntectonic metamorphism affected the Blue Mountain Province between the late Triassic and the late Jurassic (Kays et al., 2006). Widespread, low-grade (zeolite to greenschist facies) hydrothermal metamorphism also affected the province before the first (D_1) deformation (Kays et al., 2006). In the southern portion of the terrane evidence for D_1 consists of axial planar foliation in the Elkhorn Ridge Argillite; in the northern portion of the terrane mylonites in Hells Canyon suggest left-lateral shear at 230-220 Ma (Kays et al.,. 2006). D_2 folding is recognized in the Lower Sedimentary Series and the Hurwall Formation. The second episode of deformation ($D_{2)}$ affected the southern and northern portions of the BMP differently: in the central and northern portions of the province ductile flow was observed but in the south D_2 has been associated with thrusting and fracture cleavage (Kayes et al., 2006). D_2 folds are refolded by D_3 folds. In the southern portion of the BMP D_3 folds are truncated by the Wallowa Batholith providing a minimum D_3 age of approximately 130 Ma (Kays et al., 2006).

Models based on structural and basin analyses have traditionally posited the evolution of the BMP as follows: the Izee overlap assemblage was a long lived Triassic-Jurassic basin that existed as either 1; a traditional forearc located to the northwest of the Olds Ferry arc, or 2; a fault-bounded structural depression that formed between the arc and the margin in an east-verging (reverse polarity) subduction zone (Dickinson, 1979). Alternative models of BMP evolution include arc-continent collisions, protracted arc-continent collisions, and arc-arc collisions preceding arc-continent collisions. However, details of the timing and assemblage of BMP terranes are not agreed upon.

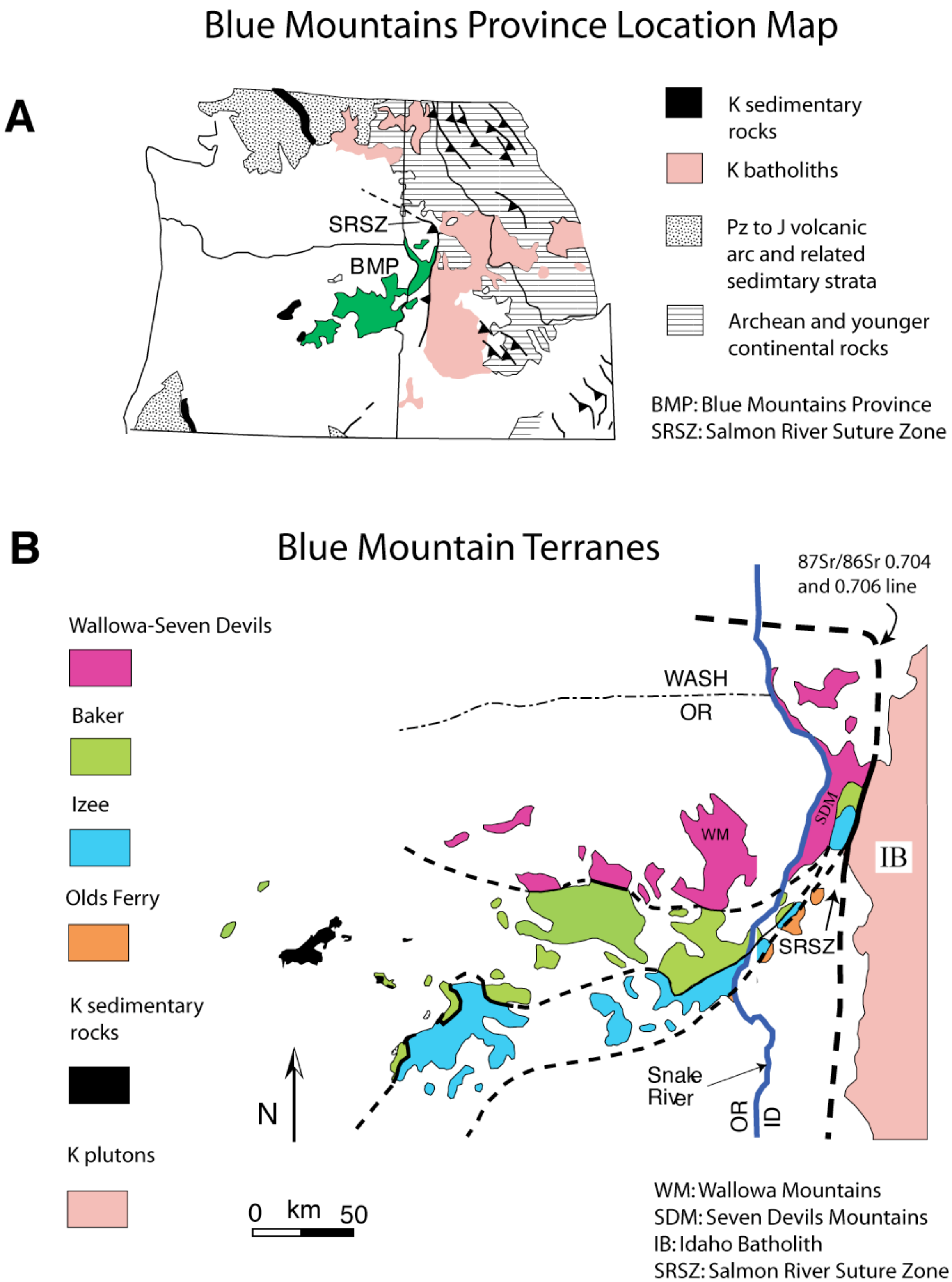

Figure 2: A: location of the Blue Mountains Province (BMP), shown in green. B: location of Blue Mountain terranes and their contacts. WM: Wallowa Mountains. SDM: Seven Devils Mountains. SRSZ: Salmon River suture zone. IB: Idaho Batholith. Figure modified from Dorsey and Lenegan (2007)

Different types of evidence are used to explain exactly how and when the two volcanic portions of the BMP—the Wallowa-Seven Devils arc and the Olds Ferry arc—came into contact. Vallier (1995) suggested that the Olds Ferry and Wallowa arcs were one arc with a complex history. Avé Lallement (1995) presented structural data suggesting the Wallowa-Seven Devils collided with the Olds Ferry in the Late Jurassic. Stratigraphic evidence (Follo, 1992, 1994; Dickinson and Thayer 1978; Dorsey and LaMaskin, in review) has suggested that the Wallowa-Seven Devils arc and the Olds Ferry received detritus from an emergent late Triassic-early Jurassic Baker terrane fold and thrust belt. Hillhouse et al. (1982) showed that the Seven-Devils and Olds Ferry terranes share the same late Triassic paleopole. Given the most current research (Dorsey and LaMaskin, in review) it is reasonable to assume that the Seven Devils and Olds Ferry terranes were acting as a single tectonic unit by the late Triassic, but it also is possible that these two terranes became sutured together at a later time. The terrane associations mentioned above suggest the need to re-examine correlations between BMP terranes and other large tectonostratigraphic units.

The Wallowa-Seven Devils—Wrangellia Association: Stratigraphy and Fossils

Wrangellia was a Mesozoic microplate of Tethyan faunal affinity that broke into pieces that accreted to the North American Pacific margin. Jones et al. (1977) defined the stratigraphic, structural and faunal characteristics of Wrangellia and delineated its distribution (Figure 3). Based on Triassic stratigraphy, structures, and fauna Jones (1977) also proposed that the Wallow-Seven Devils terrane was a southern extension of Wrangellia.

Figure 3. Locations and distributions of accreted terranes in western North America. Modified from Butler (1992). See Coney et al. (1980) for terrane names and descriptions. Wrangellia (**W**) and the Wallowa-Seven Devils (W) are highlighted in red.

Wrangellia stratigraphy is generally similar to Wallowa-Seven Devils stratigraphy in age, composition, thickness, contact-type, and fossil assemblage. Wrangellia stratigraphy consists of Lower Permian chert, siltstone, and fossiliferous shale containing *Daonella degeeri* and D. *frami* overlain by a thick sequence of Middle-Late Triassic tholeiitic flows, pillow basalts, and greenstones. Platform carbonates unconformably overlie the volcanics and are in turn overlain by Late Triassic-Early Jurassic marine sedimentary rocks.

The Seven Devils Group (Figure 4) consists of the Windy Ridge, Hunsaker Creek, Wild Sheep Creek; and Doyle Creek formations (Vallier, 1977). The basal Permian Windy Ridge Formation is composed of keratophyre flows and tuffs. The Hunsaker Creek Formation is composed of breccias, tuffs, conglomerates, sandstones, and argillites (Vallier, 1977). The Wild Sheep Creek Formation is composed primarily of basalt, basaltic andesite, and andesite flows and volcaniclastics—greywacke, argillite, and limestone are more minor constituents (Valier, 1977). The fossil bivalves *Daonella degeeri* and D. *frami* are found in sedimentary interbeds at the base of the Wild Sheep Creek Formation. The Doyle Creek Formation is composed of red conglomerates and breccias with some fine-grained interbeds. The Martin Bridge Limestone caps the volcanic and volcaniclastic units of the Seven Devils Group and contains diverse fauna of similar age and taxa to fauna found in the Chitistone and Nizina limestones located in Alaska (Jones, 1977). Jones et al. (1977) state “in their present geographic locations these two highly diverse yet taxonomically similar faunas seem to be unreasonably separated from one another latitudinally”.

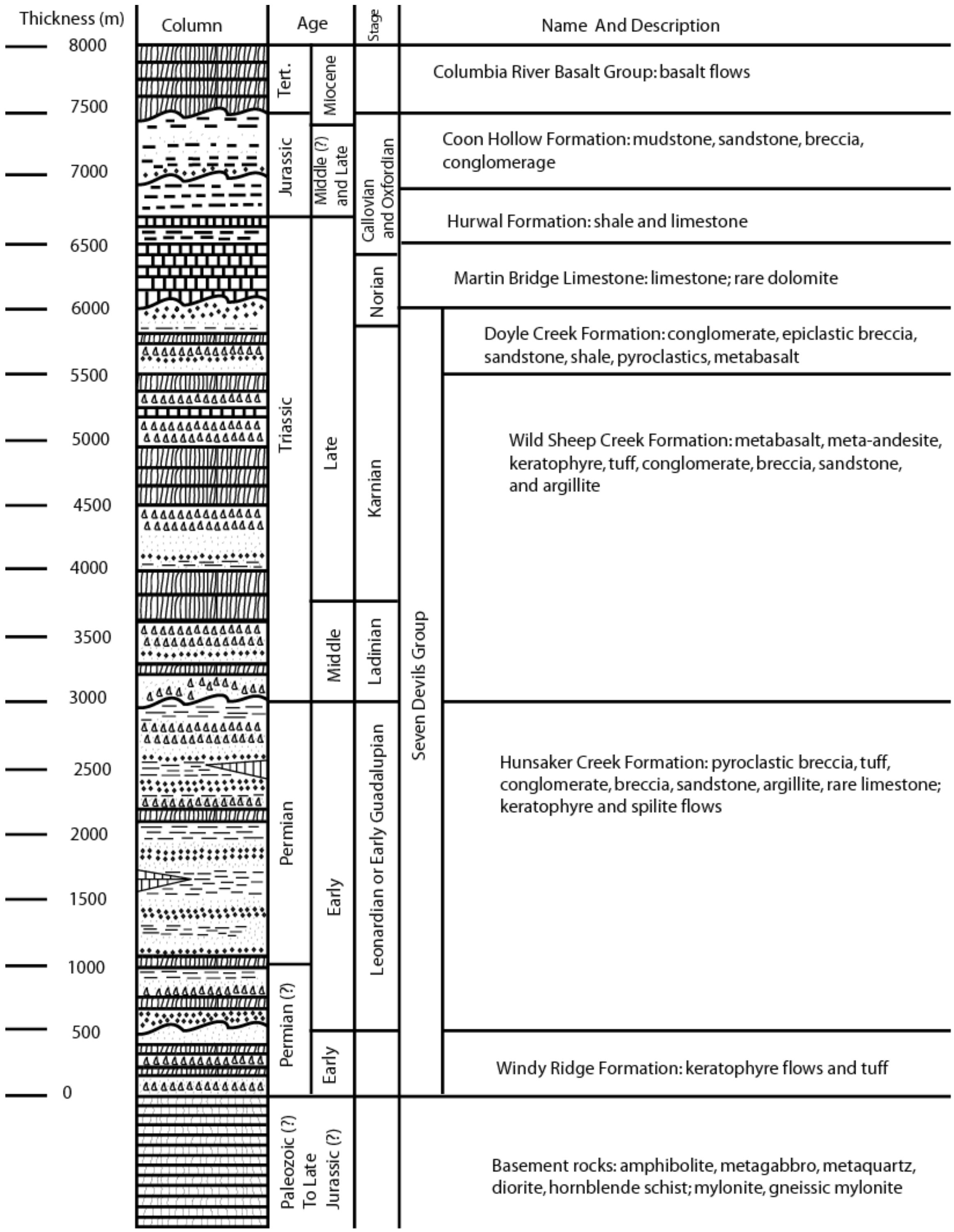

Figure 4. Composite stratigraphic section for the Seven Devils Group. After Vallier, 1977

The Wild Sheep Creek Formation and the Martin Bridge Limestone are the two most diagnostic units in the Seven Devils terrane and have provided the most tangible link to Wrangellia (Figure 5). The Wild Sheep Creek Formation has been correlated with the Karmutsen Formation on Vancouver Island and the Nikolai Greenstone in Alaska on the basis of age, thickness, composition, stratigraphy, and paleomagnetism. As noted above, fossils in the Martin Bridge Limestone are similar to the fossils in the Alaskan Chitistone and Nizina limestones.

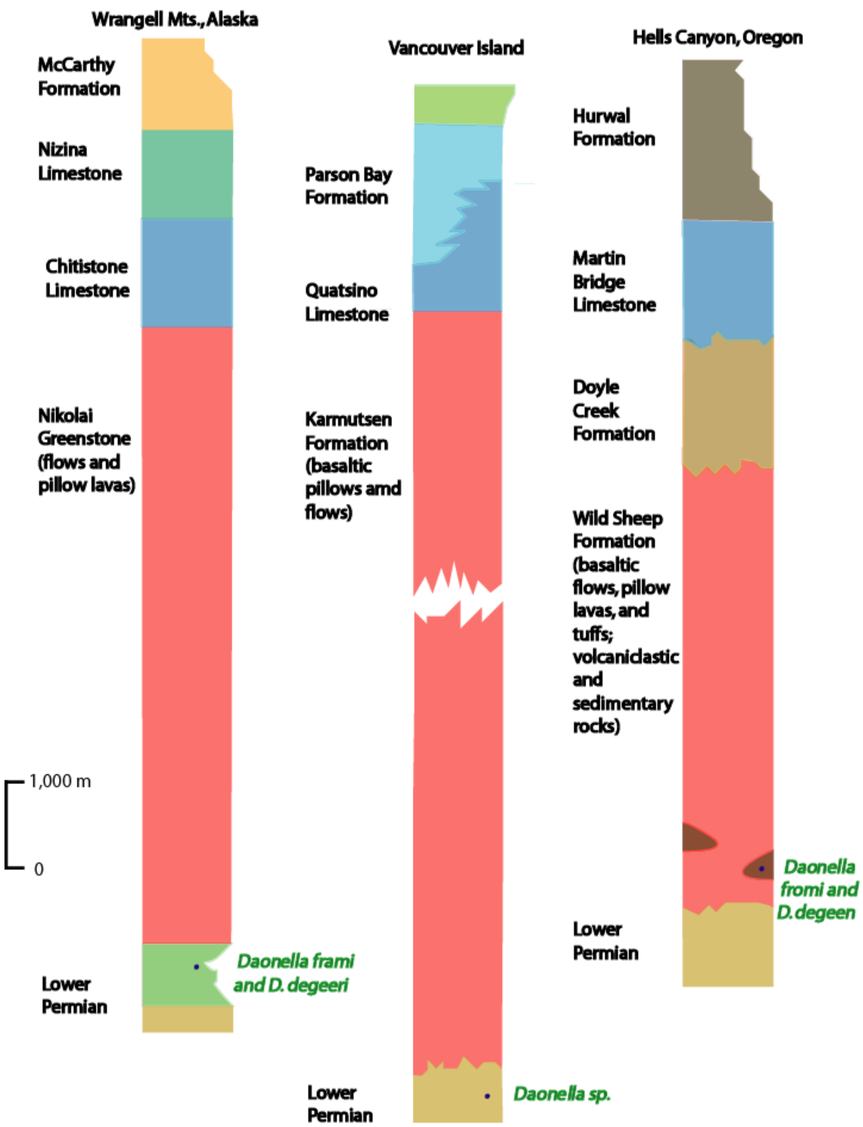

Figure 5. Generalized stratigraphic columns from the Wrangell Mountains, Alaska; Vancouver Island, British Columbia, and Hells Canyon, Oregon illustrate like thicknesses and rock types for geographic areas correlated with Wrangellia, a Mesozoic microplate. After Jones, 1977.

The Wallowa-Seven Devils—Wrangellia Association: Paleomagnetic Evidence

Shallow magnetic inclinations found in some Triassic rocks within the Seven Devils terrane (Hillhouse et al., 1982) fall within the range established for Triassic rocks from other Wrangellia correlatives (Table 1) suggesting that the Seven Devils terrane was once located proximal to now-dispersed Wrangellia fragments. Magnetic inclinations found in Triassic volcanics in Alaska (Hillhouse, 1977; Hillhouse and Grommé, 1980) and in British Columbia (Yole and Irving, 1980) suggest that allochthonous Wrangellia blocks correlated by Jones (1977) all originated from similar paleolatitudes. Discrepancy between paleomagnetic inclinations and current locations of Wrangellia fragments requires northward displacement prior to accretion to the North America continental margin. Note that magnetic inclination data provides no constraint on paleolongitude, so it is possible that large paleo-East-West distances may have separated terranes with similar paleolatitudes from each other, and from North America.

Table 1: Paleolatitudes For Wrangellia—Affiliated Geologic Formations

Formation	Location	Triassic Paleolatitude	Author(s)/Date
Seven Devils/ Huntington	Oregon/Idaho	18° N or S +/-4°	Hillhouse et al., (1982)
Karmutsen	Vancouver Island, BC	13° to 18° N or S	Yole and Irving, (1980)
Nikolai Greenstone	McCarthy, Alaska	15° N or S +/- 14°	Hillhouse, (1977)
Nikolai Greenstone	Mt Hayes and Healy Quadrangles, Alaska	13.9° N or S +/- 3.8°	Hillhouse and Grommé (1984)
Nikolai equivalent basalt	North of McCarthy, Alaska	18° N or S +/- 8°	Hillhouse and Grommé (1980)

Wallowa-Seven Devils—Wrangellia Discrepancies

As Follo (1992) pointed out, much of the geochemical, paleomagnetic, and fossil evidence linking the Seven Devils terrane to Wrangellia is equivocal. Compositional differences between volcanic Wallowa-Seven Devils terrane rocks and volcanic rocks from other Wrangellia correlatives have been used to dispute the Wallowa-Seven Devils—Wrangellia link. A comprehensive geochemical study of the Wild Sheep Creek Formation has yet to be executed but trace element data for five spilites and two keratophyres collected near Rapid River, Idaho, show moderate enrichment in light rare earth elements (REEs) suggesting calc-alkaline rather than tholeiitic volcanism (Sarewitz, 1983). The calc-alkalic character of the Wild Sheep Creek Formation suggests that the Wallowa-Seven Devils terrane had an independent history from Wrangellia or that Wrangellia contained extreme geochemical variation (Sarewitz, 1983). Differences in stratigraphy have also been used to question the Seven-Devils-Wrangellia link. The Wild Sheep Creek Formation is directly overlain by volcaniclastic rocks of the Doyle Creek Formation; volcaniclastic rocks are absent in Wrangellia-affiliated terranes of British Columbia and Alaska. Additionally, the Wild Sheep Creek Formation contains a large proportion of volcaniclastic tuffs, breccias, and interbedded volcaniclastic/flow rocks whereas the Karmutsen Formation and the Nikolai Greenstone are dominated by tholeiitic flows and pillows. The Martin Bridge Limestone of the Wallowa-Seven Devils terrane may have shared a similar depositional environment with Wrangellia carbonate rocks (Whalen, 1988) but differences in carbonate facies have been noted. The Martin Bridge Limestone is only half as thick as the Wrangell Mountains carbonate sequence and it contains shelf break/slope facies that the Wrangell rocks do not contain (Whalen, 1988).

Paleomagnetic evidence has been used to link the Wallowa-Seven Devils terrane with Wrangellia on the basis of shared paleolatitude but paleolatitude cannot be used to discredit a Wallowa-Seven Devils correlation with any non-Wrangellia terrane that possesses a paleolatitude similar to that of the Wallowa-Seven Devils terrane. Mortimer (1986) noted that Late Triassic Paleolatitude estimates for the Seven Devils terrane were "permissibly identical" to both Wrangellia and Stikinia. Stikinia is a terrane located in British Columbia that shares coarse volcanic/eruptive characteristics with the Wallow-Seven Devils terrane (Mortimer, 1986).

Faunal similarities between the Martin Bridge limestone and the Chitistone and Nizina limestones suggest that the Wallowa-Seven Devils terrane may have been located proximal to portions of Wrangellia now found in Alaska (Jones, 1977). However, not all paleontologists agree that fossils found in the Wallowa-Seven Devils terrane are similar enough to warrant a link between the Wallowa-Seven Devils terrane and Wrangellia. Whalen (1988) stated that the Wrangellia and Wallowa faunas are not "strikingly similar" and that despite high generic similarity indices for bivalve mollusks, "species-level similarity of coelenterates and sclerosponges . . . is moderate at best and low between samples from the Wallowa and Wrangell Mountains." Many corals and spongiomorphs from displaced terranes in North America are similar to corals and spongiomorphs found in the Martin Bridge Limestone (Stanley and Whalen, 1989). Fossil spongiomorphs and corals link the Wallowa-Seven Devils terrane most strongly with a locality near Lewiston Idaho, but localities in the Alexander terrane of Alaska, Sonomia of Nevada, the Peninsular terrane of southern Alaska, and Southern Vancouver Island contain similar fossil species (Stanley and Whalen, 1989). More generally, 21 para-autochthonous species of Norian coral and spongiomorph link the Wallowa-Seven Devils terrane to the western Tethys; the Pamir Mountains, U.S.S.R.; and the island of Timor (Stanley and Whalen, 1989). Eleven of the twenty-one species studied by Stanley and Whalen (1989) are found only in displaced terranes and four Hells Canyon taxa previously thought to be endemic to North American terranes have been found in the Koryak terrane of northeastern USSR. Based only on spongiomorph and coral the Wallowa-Seven Devils terrane is more similar to the Koryak terrane than it is to Wrangellia (Stanley and Whalen, 1989).

Shallow paleomagnetic inclinations determined from Wallowa-Seven Devils terrane rocks prevent the hemisphere of origin for the Wallowa-Seven Devils terrane to be determined with certainty. Originally a southern-hemisphere origin was favored but most researchers now favor the northern hemisphere as the hemisphere of origin for the Wallow-Seven Devils terrane. A range from zero to over 3500 kilometers of latitudinal translation for the Seven Devils terrane has been proposed but recent work has favored local translations. Wyld and Wright (2001) suggested that major fault systems and suture zones found throughout the North American Cordillera are part of a single structural boundary that accommodated up to several hundred kilometers of early Cretaceous dextral strike-slip. An Early Cretaceous paleogeographic reconstruction that accounts for dextral strike-slip and basin and range extension places the Blue Mountain Province just outboard of the Black Rock terrane, a terrane that is located in northwestern Nevada. Harbert et al. (1995) paleomagnetic data suggests a northern hemisphere location (24 +/- 12° N) for the Wallowa-Seven Devils terrane in the Permian with possible subsequent southward transport.

Problem Statement

If the Jones et al. (1977) and Hillhouse et al. (1982) correlation between Seven Devils terrane rocks and Wrangellia rocks is correct, then paleolatitudes of Triassic rocks from dispersed Wrangellia fragments should be in agreement with Seven Devils paleolatitudes. Alternatively, if the paleolatitudes of Seven Devils rocks are significantly different from Wrangellia then inclusion of the Seven Devils in Wrangellia is not supported.

A paleomagnetic study of the Seven Devils Group utilizing new collection sites and modern paleomagnetic laboratory procedures may yield better results than Hillhouse et al. (1982) and, in conjunction with other types of geological evidence, support or refute genetic linkage of the Wallowa-Seven Devils terrane with Wrangellia. Paleomagnetism is a diagnostic tool that can be used to constrain the latitude at which a rock or group of rocks was deposited given that 1: the rocks retain the direction of the geomagnetic field at the location and time of their creation; 2: that this direction can be isolated through laboratory procedures; 3: that the rocks acquired their magnetization over a time span sufficiently long enough to average out paleomagnetic secular variation; and 4: that the Geocentric Axial Dipole (GAD) hypothesis accurately describes the geometry and behavior of the Earth's geomagnetic field. The latter is well supported by numerous studies (McElhinny, 2004) although it is not critical to comparison of Wrangellia fragments because they would have experienced the same field: but the GAD hypothesis is critical for determining paleolatitude accurately.

Previous Work—Paleomagnetism of the Seven Devils: Hillhouse et al. (1982)

Paleomagnetic results of Hillhouse et al. (1982) were based on a collection of 235 samples from 25 sites in the Wild Sheep Creek Formation and four sites in the Huntington Formation. Samples were demagnetized thermally and with an alternating magnetic field. Demagnetization paths were analyzed, and directions derived from endpoints were sorted into three groups. Specimens in Group 1 were characterized by single or two-component demagnetization paths with unblocking temperatures over 585ºC. Restoring Group 1 directions to paleohorizontal (tilt-corrected coordinates) reduced scatter suggesting that magnetizations predated regional deformation (Hillhouse et al. 1982). Group 2 specimens were characterized by two (or more) component demagnetization paths with overlapping unblocking temperatures ranging from 200°C to 400°C. Tilt correction for Group 2 specimens resulted in a statistically significant increase in the Fisher precision parameter (Hillhouse et al., 1982) suggesting that the Group 2 magnetization also was acquired before regional deformation and should be used in tilt-corrected coordinates. Group 3 specimens were characterized by single component demagnetization paths with unblocking temperatures ranging between 200°C and 675°C. Group 3 failed a fold test indicating that the Group 3 magnetization was acquired after deformation of the Seven Devils terrane (Hillhouse et al., 1982) and should be used uncorrected for tilt. Seventeen of the 29 total sites from the study fall into Group 3.

The Seven Devils terrane recorded two magnetizations (Hillhouse et al., 1982). The first magnetization preserves a late Triassic remanence and is thought to have occurred before deformation of the region (Hillhouse et al., 1982). Both Group 1 and Group 2 represent the first magnetization, which is of late Triassic age. The second magnetization, which fails a fold test, was acquired via hydrothermal circulation set up by emplacement of the late Jurassic-Cretaceous Wallowa batholith (Hillhouse et al., 1982). Group 3 represents the second, Jurassic-Cretaceous age, magnetization. Site-mean directions for pre-deformation, tilt-corrected Group 1 and Group 2, and the uncorrected mean direction for Group 3 are given in Table 2 and shown in Figure 6. Group 1 and Group 2 magnetizations may be of similar age despite having a 40° deviation from antipodality if differential rotation of the three structural blocks in which the samples were collected accounts for that discrepancy. Group 3 sites that reached stable thermal endpoints gave a well-constrained uncorrected mean direction that is not congruent with the expected present day field direction for the Seven Devils terrane.

Table 2. Group Site-Mean Directions from Hillhouse et al. (1982).

	N	Dec	Inc	R	κ	α_{95}
Group 1	5	83.2	-31.1	4.7923	19	17.9
Group 2	6	318.6	33.8	5.8189	28	13.0
Group 3	17	38.6	71.8	16.7351	60	4.6

N: number of sites; Dec: Declination; Inc: inclination; R: resultant vector length; κ Fisher precision parameter; α_{95}: semi-angle of cone of 95% confidence about the mean.

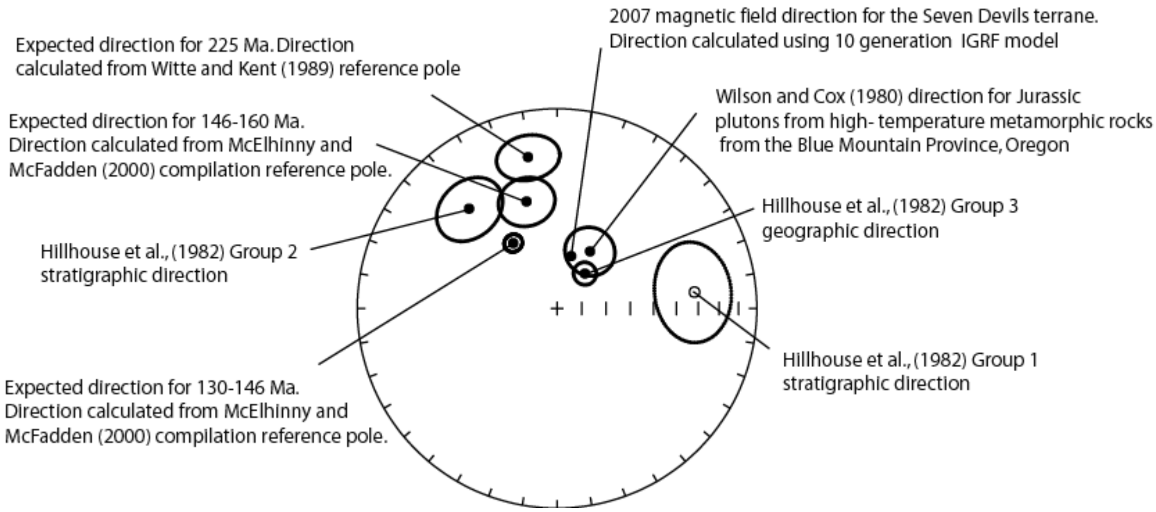

Figure 6. Equal area (EA) plot with Hillhouse et al. (1982) Group 1 (stratigraphic), Group 2 (stratigraphic), and Group 3 (geographic) directions. Expected directions for the Seven Devils terrane for the late Triassic, the late Jurassic, the late Cretaceous, and the present day are shown for reference. The 2007 direction was calculated using the 10th International Geomagnetic Reference Field (IGRF) model.

Hillhouse et al. (1982) correlated the Seven Devils terrane with Wrangellia based on the similarity of its paleolatitude to that of other Wrangellia fragments. Hillhouse et al. (1982) also noted that correcting the paleomagnetic pole obtained from Group 1 to counter the effects of late Mesozoic clockwise rotation of the BMP, determined by a paleomagnetic study of Blue Mountain Jurassic plutons (Wilson and Cox, 1980), brings the Seven Devils Group 1 pole into good alignment with paleomagnetic poles from the coeval Karmutsen Formation on Vancouver Island.

High unblocking temperatures and coercivities indicate that hematite was a significant carrier of NRM in many of the volcanic samples and all of the sedimentary samples (Hillhouse et al., 1982). Approximately ¾ of Group 1 and Group 2's high temperature magnetizations were carried by hematite; the remainder Group 1 and Group 2 high temperature magnetizations were carried by magnetite or had a bimodal distribution (Hillhouse et al., 1982). Cut and polished sections from the study area revealed that authigenic hematite was abundant and occurred as a pigment or as microcrystals. Microcrystalline hematite replaced hornblende and relict magnetite crystals were replaced by martite in volcaniclastic rocks. Sandstone quartz and feldspar grains were coated with microcrystalline hematite. Magnetite was common in greenish metabasalts and meta-andesites. Some magnetite crystals in the metavolcanics appeared pitted and were surrounded by faint halos of hematite pigment.

Present Study—Sampling and Composition

Samples from 22 sites from seven localities in the Wild Sheep Creek Formation of the Seven Devils Group (Table 3) were collected for this paleomagnetic study. All sites were in cuts along the Idaho Power and Light Company service road between Hells Canyon Park and Hells Canyon Dam (Figure 7).

Table 3. Locality Coordinates and Sites at Each Locality

Loc.	1	2	3	4	5	6	7
Sites	1-2	3	4-5	6	7-11	12-18	19-22
Lat.	45.23825°	45.23307°	45.23623°	45.1675°	45.16738°	45.16555°	45.0627°
Long.	116.7011°	116.7018°	116.7025°	116.7205°	116.7205°	116.7205°	116.7941°

Table 3. Loc, locality number; Sites, sites located at locality; Lat., North latitude; Long., West longitude.

Figure 7. Photograph of thesis study area; Snake River; and Idaho Power and Light Company road (left), along which collection sites are located. Photograph taken looking south.

Typically, cores and hand samples taken from meta-basalts and meta-andesites exhibit aphanitic groundmass with visible feldspar phenocrysts up to 1/3 of a centimeter in length (Figure 8). Vallier (1967) uses the terms spilite, keratophyre, and quartz keratophyre to describe the abundant albitized flows of basalt, andesite, and dacite present in Hells Canyon and the greater Seven Devils area. Using Vallier's (1967) terms, most samples collected for this study would be classified as keratophyres.

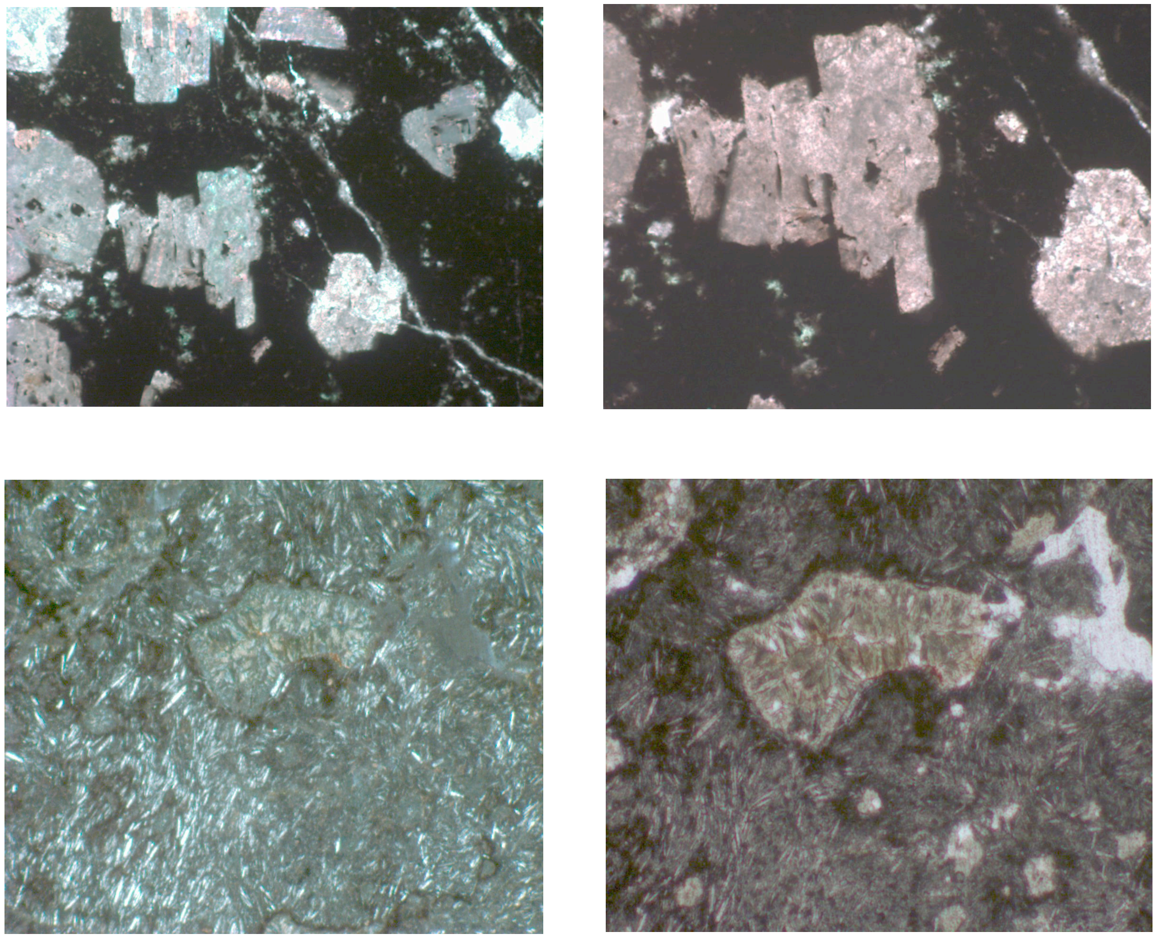

Figure 8. Thin section photographs of site 3 (top) and site 4 (bottom) specimens. These specimens are representative of most of the sample suite in hand-sample. Under polarized light (left) and plain light (right) a large plagioclase phenocryst (top) and smaller plagioclase microlites surrounding a chlorite-altered phenocryst (bottom) are observed. Approximate field of view 4mm x 6mm in all except upper right. Upper right specimen field of view approximately 2mm x 3mm.

Methods

Samples of layered volcanic and meta-volcanic rock were collected from 22 sites in the Wild Sheep Creek Formation (Figure 9, Appendix C). Most samples were collected with a portable rock drill in August and October of 2004. Four oriented block samples also were collected and cores from them drilled at Western Washington University. At each site several meters of section were sampled and samples oriented with a Brunton compass. When sufficient sunlight was available azimuths were checked with a sun compass. Discrepancies between Brunton and sun compass measurements were small indicating that magnetic azimuths were unbiased by local magnetic fields. One hundred forty-nine samples were cut into 153 specimens and demagnetized at Western Washington University's Paleomagnetism Laboratory. For convenience, year and study parts of sample names are omitted from some parts of the text below, e.g., 04TVS2-9 is referred to as 2-9, and because single specimens represent most samples, this designation holds for specimens as well.

Figure 9. Air photo of northern portion of study area. MK signifies localities (Loc) at which sites (S) were collected for this study. JH signifies localities at which Hillhouse et al. (1982) sampled. G1 (Group 1) and G2 (Group 2) indicate (Hillhouse et al., 1982) localities at which these groups were found (see below). Air photos and sampling locations for the entire extent of the Hillhouse et al. (1982) study area and the current study area can be found in Appendix C.

Sample processing followed conventional procedures. Anisotropy of magnetic susceptibility (AMS) was calculated from measurements made using a KLY-3 Kappabridge. Subsequent processing was in a magnetically shielded room. Remanent magnetization was measured using a 2-G 755R DC-SQUID magnetometer. Most samples were demagnetized thermally in air using an ASC Scientific TD-48 thermal demagnetizer. Some samples were demagnetized using a combination of thermal and alternating field methods. An alternating field (a.f.) generated by a D-Tech 2000 a.f. demagnetizer was used to demagnetize samples in steps of 5-20 mT, up to maximum fields of 200 mT. Demagnetization data were visually examined on orthogonal projections of vector endpoints (Zijderveld, 1967). Components of magnetizations were identified by linear segments of demagnetization paths; the characteristic component was defined as the last removed one whose path trended toward the origin. For specimens with only curvilinear paths it was hoped that the unresolved characteristic or ultimate component would lie in the plane defined by the last resolved component and the origin. Orientations of both lines and planes were obtained using principle component analysis (PCA; Kirschvink, 1980). Site mean directions were calculated via Tauxe's –lnp program, a formalization of McFadden and McElhinny's (1988) method for simulating a Fisher (1953) mean from a combination of lines and planes. This method of analysis is appropriate because study samples with streaked directions are better-represented by anchored planes than free lines. Directions for sites containing both streaked and non-streaked specimens are better constrained using a combination of lines and planes than they are with only lines. The same analytical methods were applied to data from Hillhouse et al. (1982) Group 1 sites to facilitate comparison and combination of the datasets. Calculation of mean directions and testing for timing of magnetization relative to deformation used bootstrap methods (Tauxe and Watson, 1994). Bootstrap procedures allow statistical testing of paleomagnetic data that are not Fisher-distributed. The low number of samples in many of the data sets in this study precludes formal testing for conformity to a Fisher distribution.

Major and minor element geochemical analyses were obtained for rocks from 9 sites at the Washington State University (WSU) GeoAnalytical Lab. Analyses were made by WSU staff on a ThermoARL Advant'XP+ sequential X-ray fluorescence spectrometer. Results can be found in Appendix B.

Paleomagnetic Results

Thermal demagnetization and combined thermal/alternating field demagnetization cleaned most samples nicely. Approximately half of the study samples are characterized by single-component demagnetization paths that decay linearly to orthogonal-plot origins (Figures 10, 11). Streaked or curvilinear demagnetization paths characterize most of the remaining samples (Figure 12). Poorly defined components obtained from demagnetization resulted in exclusion of samples 7-8, 9-2, 9-3, 9-4, 9-5, 15-3, 18-1, and 21-3 from study calculations. All five samples from site 22 lost their natural remanent magnetization (NRM) by the 400°C demagnetization step and were also excluded from the study. Samples 2-6 and 3-4 were destroyed in the field upon attempted core drilling, sample 7-7 may have been inadvertently inverted during cutting and marking, and sample 1-3 shattered during thermal demagnetization. The remaining 138 samples from 21 sites yielded fair to excellent results. Sites 1, 10, and 19 contain at least one, but not more than two, specimens that were given unit weight in study calculations instead of being averaged.

Unblocking temperatures for study samples range up to hematite's Néel temperature (690° C). Samples from sites 2, 5, 6, 15, 19, 20, and 21 lost all of their NRM before the magnetite Curie temperature (585° C) was reached (Figure 10). Samples from site 3 decayed exclusively above magnetite's Curie temperature (Figure 11, top). Components for samples from the remaining sites unblocked from below the magnetite Curie temperature up to the hematite Néel temperature (Figure 11, 12). Directions for these sites were derived from components taken above the Curie temperature and thus from only hematite.

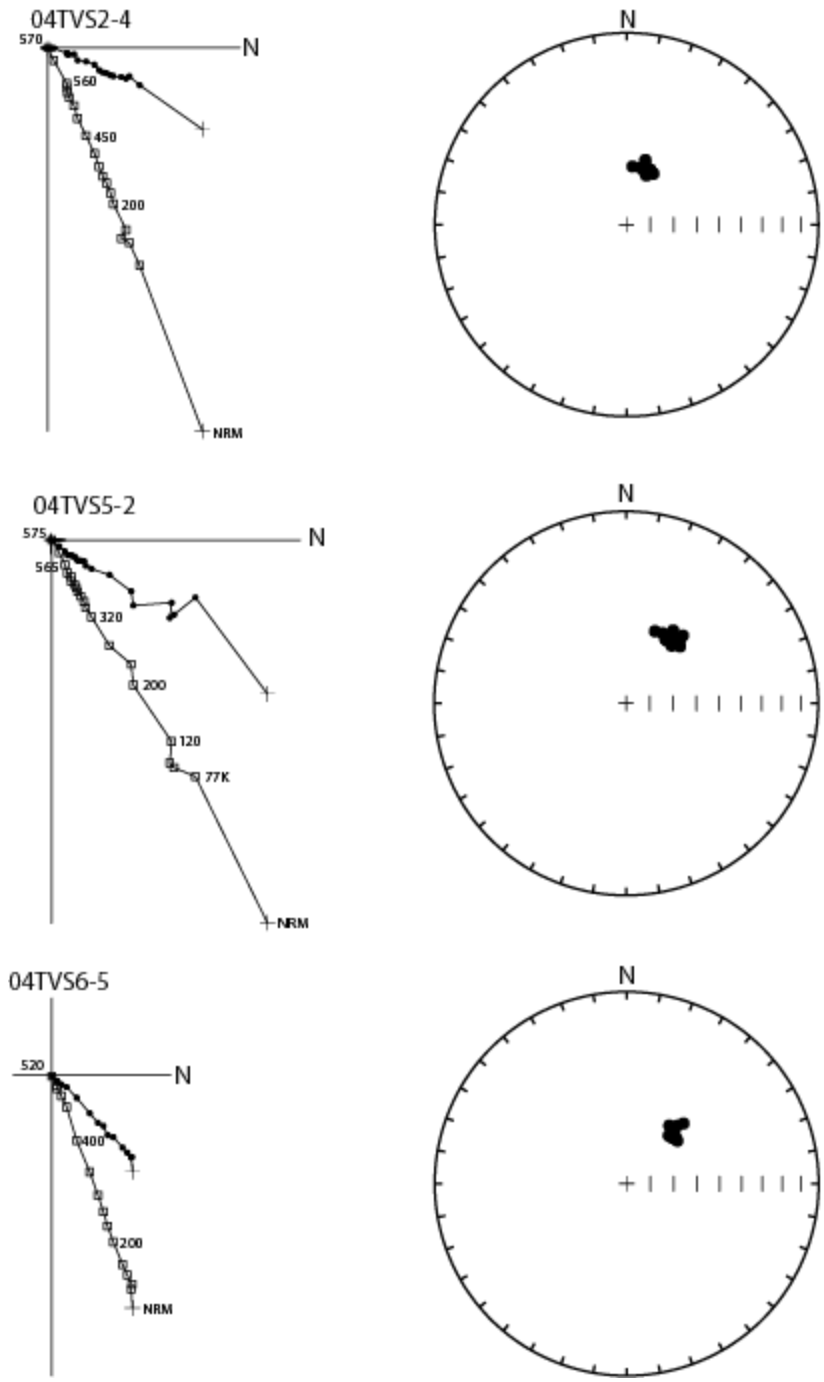

Figure 10. Orthogonal vector and equal area plots for specimens 04TVS2-4, 04TVS5-2, 04TVS6-5. Specimens are characterized by (nearly) single-component demagnetization paths that decay to the origin below the magnetite Curie temperature.

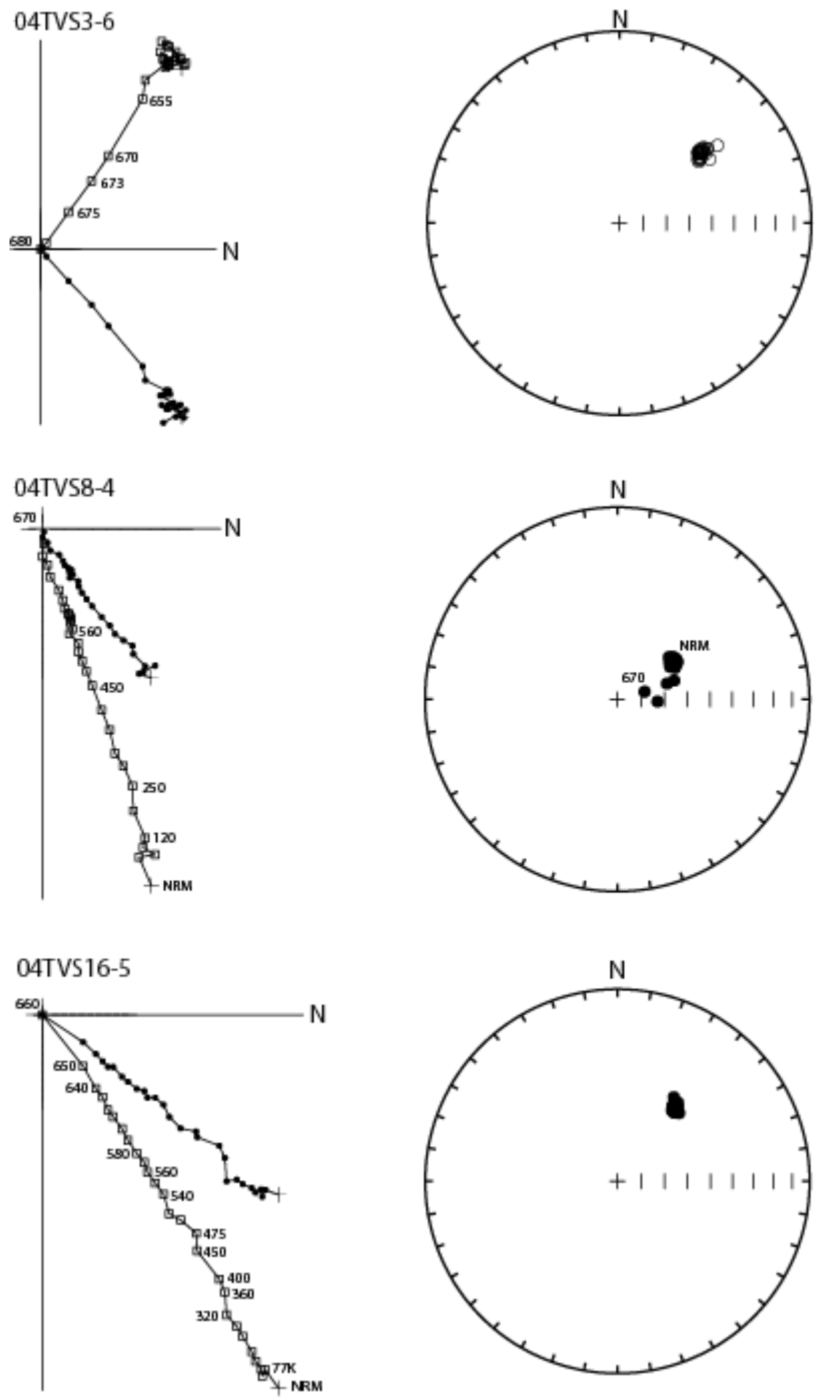

Figure 11. Orthogonal vector and equal area plots for specimens 04TVS3-6, 04TVS8-4, 04TVS16-5. Top specimen is characterized by a single-component demagnetization path that decays to the origin up to the hematite Néel temperature. Middle and bottom specimens are characterized by single-component demagnetization paths that decay through the magnetite Curie temperature and up to the hematite Néel temperature.

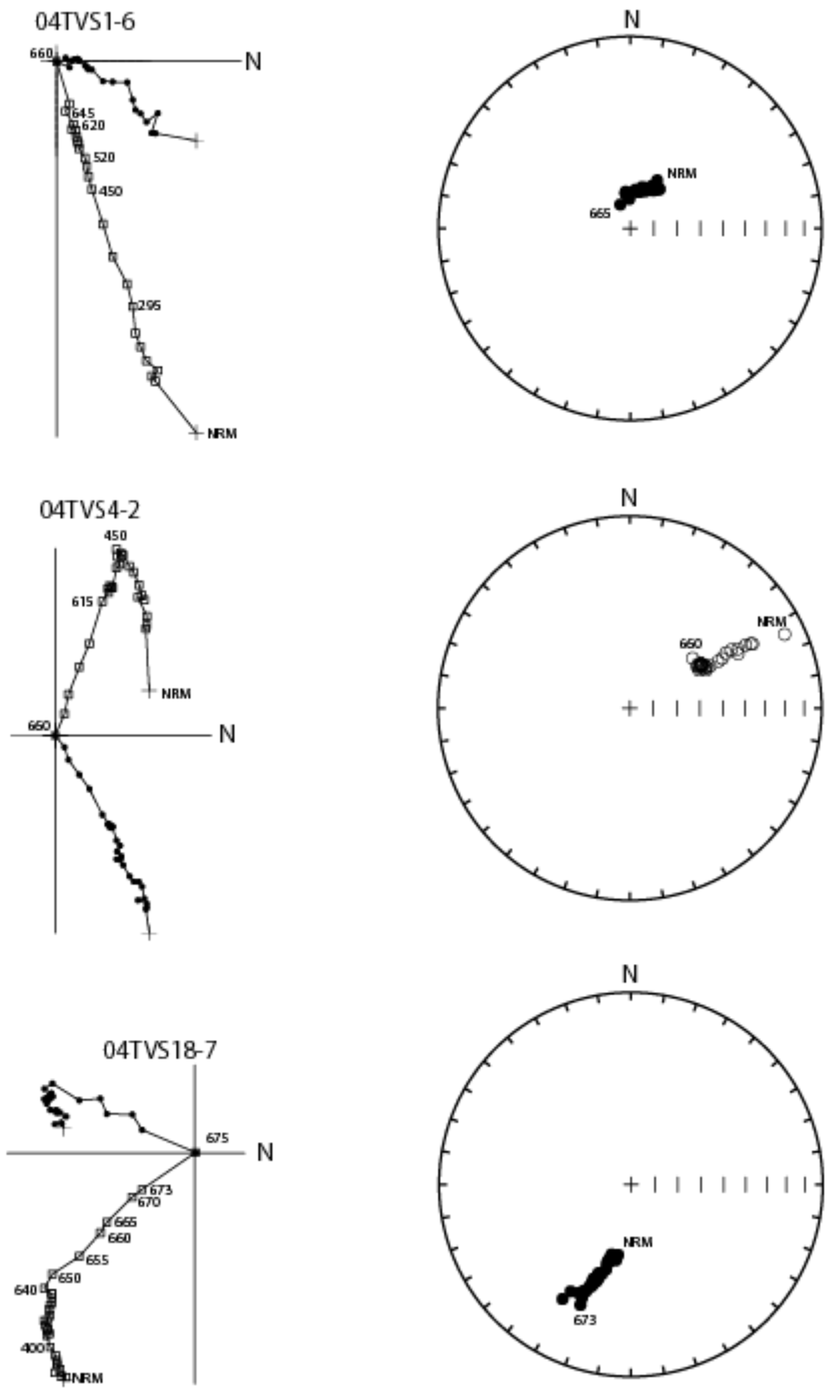

Figure 12. Demagnetization diagrams for specimens 04TVS1-6, 04TVS4-2, and 04TVS18-7. Orthogonal diagrams (left) are characterized by curvilinear demagnetization paths; Equal area plots show endpoints streaked along great circle paths.

Site-mean directions for 21 study sites in geographic coordinates are given in Table 4.

Table 4. Site-mean Data In Geographic (*in situ*) Coordinates

Name	Dec	Inc	α_{95}	NL	NP	NT	R	k	Stk	Dip	G
04TVS1	37.50	62.90	7.40	2	5	7	6.958	83	215	40	3
04TVS2	16.10	68.50	7.70	6	0	6	5.935	77	215	41	3
04TVS3	55.80	-45.00	6.70	7	0	7	6.927	82	227	60	1
04TVS4	84.60	-50.80	15.10	7	0	7	6.648	17	241	56	1
04TVS5	48.20	47.60	13.00	7	0	7	6.732	22	201	39	3
04TVS6	38.20	60.80	5.70	7	0	7	6.946	112	100	30	3
04TVS7	182.50	46.60	9.60	1	5	6	5.964	69	231	69	2
04TVS8	56.20	63.30	5.40	3	4	7	6.973	146	225	62	3
04TVS9	45.20	64.40	36.90	2	1	3	2.909	16	231	53	3
04TVS10	76.80	62.10	7.00	7	0	7	6.920	75	231	66	3
04TVS11	78.00	58.30	10.60	7	0	7	6.821	33	231	68	3
04TVS12	41.20	41.30	7.60	7	0	7	6.907	65	261	45	3
04TVS13	42.10	46.70	4.60	6	1	7	6.969	178	259	42	3
04TVS14	39.90	53.30	3.40	7	0	7	6.981	314	258	41	3
04TVS15	33.00	31.60	12.30	6	0	6	5.836	31	258	41	3
04TVS16	42.30	49.10	4.40	7	0	7	6.968	189	258	41	3
04TVS17	29.00	58.10	6.00	7	0	7	6.942	103	258	41	3
04TVS18	203.80	43.30	16.20	3	4	7	6.758	17	263	36	2
04TVS19	27.90	50.90	4.20	9	0	9	8.946	148	235	9	3
04TVS20	22.10	50.00	27.60	4	0	4	3.751	12	block	block	3
04TVS21	35.60	27.90	20.00	1	5	6	5.847	16	225	9	3

Name: sample name; Dec: declination; Inc: inclination; α_{95}: semi-angle of cone of 95% confidence about the mean; NL: number of lines used in site-mean calculation; NP: number of planes used in site-mean calculation; NT: total number of combined lines and/or planes used in site-mean calculation; R: length of resultant vector; k: κ, Fisher (1953) precision parameter; Stk: strike of bedding; Dip: Dip of bedding; G: Group the site was assigned to.

Twenty-one site-mean directions derived from principle component analysis of samples from each of 21 sites are divided into groups based on direction, clustering, and change with restoration to paleohorizontal (Figure 13). The largest group consists of seventeen site-mean directions whose tilt-corrected directions are downward and streak across the northeastern quadrant of the lower hemisphere of an equal-area projection. Another group consists of site-mean directions for sites three and four, both of which have upward tilt-corrected directions that are easterly and shallow. The third group consists of site-mean directions for sites 7 and 18, which have moderately steep, downward and westerly tilt-corrected site-mean directions. For clarity in forthcoming interpretation, discussion, and for comparison to Hillhouse et al. (1982), the large group of downward site-mean directions will be referred to as Group 3 because the overall group-mean direction for this group is similar to that of the Hillhouse et al. (1982) Group 3. The easterly site-means, from sites three and four, will be referred to as Group 1 as they share characteristics with Hillhouse et al. (1982) Group 1 sites. The site-means for the westerly sites, sites 7 and 18 will be referred to as Group 2 because they are similar to some Hillhouse et al. (1982) Group 2 site-mean directions. However, site-mean directions from site 7 and 18 samples are less-well characterized than sample-level data from Hillhouse et al. (1982) Group 2 sites.

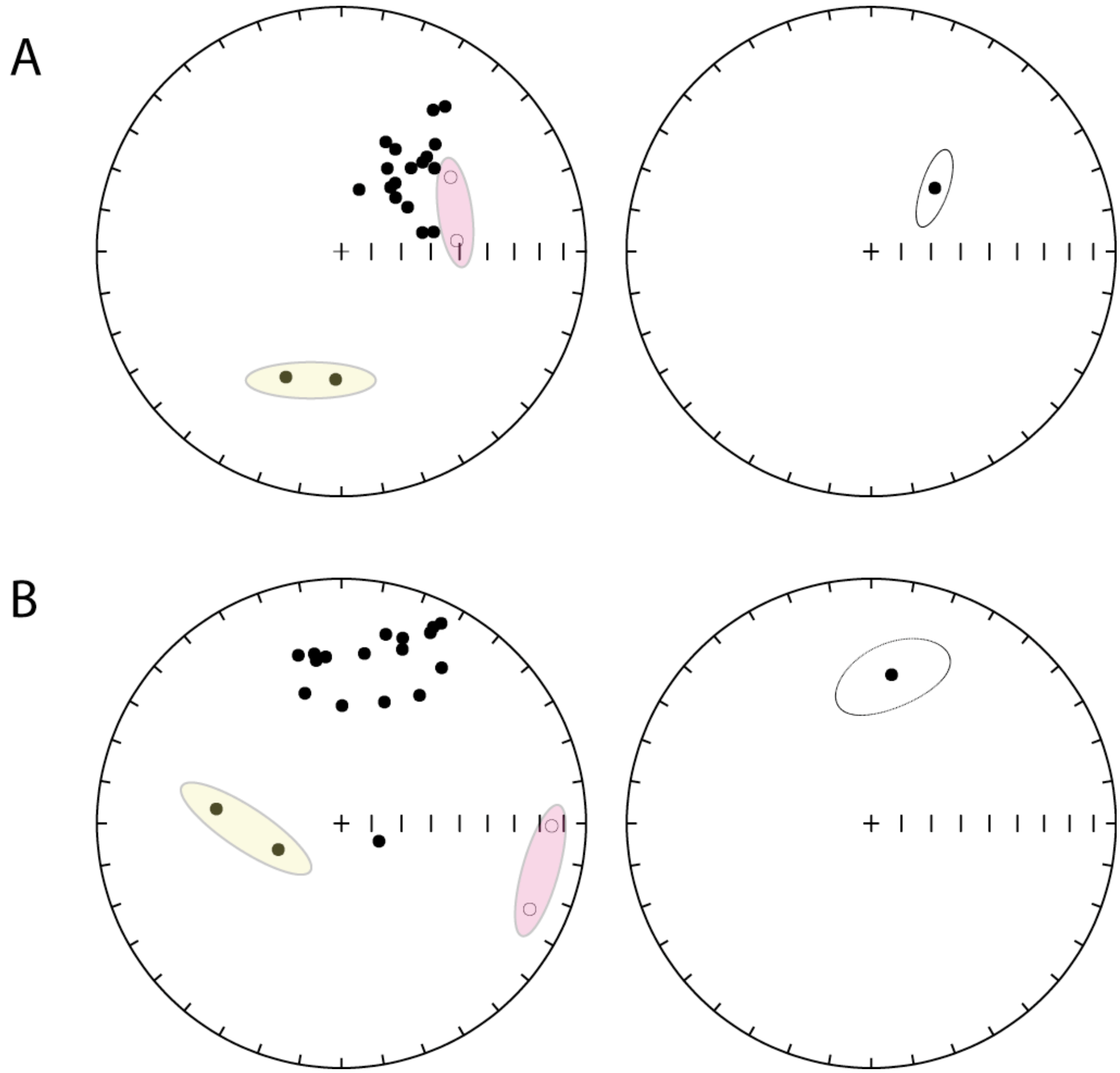

Figure 13. A: EA plot of site-mean directions for 21 individual sites (left) and overall mean-direction with 95% confidence limit, uncorrected for tilt. Bottom: same as above but after tilt correction. Pink highlights the directions of sites 3 and 4; yellow highlights the directions of sites 7 and 18. Open symbols plot on the upper hemisphere.

Group 3 site-mean directions, excluding site 20, fail a bootstrap fold test (Tauxe and Watson, 1994) and the specimens from which the directions were determined are interpreted to be remagnetized. Maximum eigenvalues (τ_1) for 500 site-mean directions calculated for this group (figure 14) are highest near 0% untilting and 95% of the trials are bound between -18% and 20% untilting. Site 20 was excluded from the group 3 fold test because it consists of block samples taken from different portions of a single flow. An independent fold test for site 20 yielded inconclusive results.

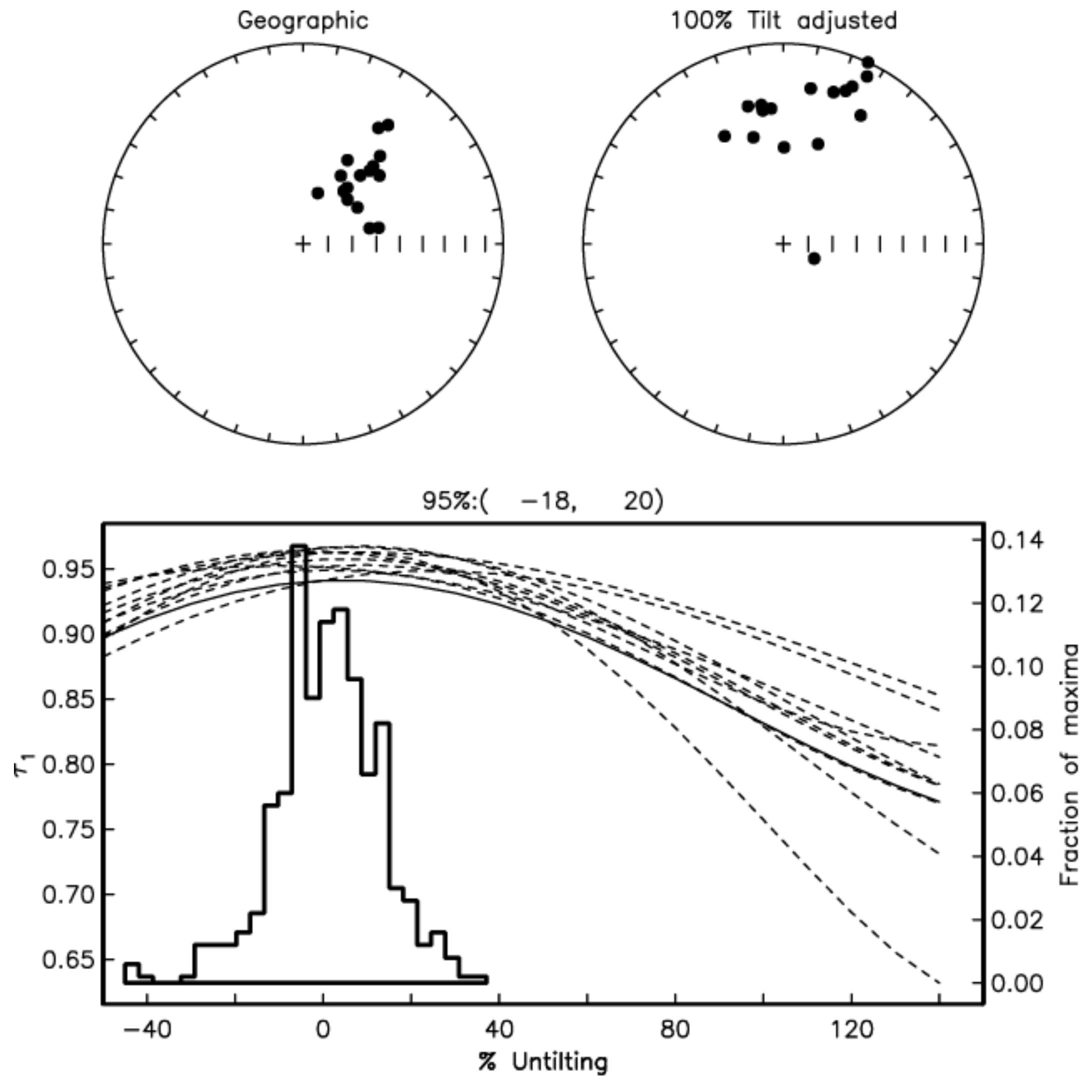

Figure 14. Bootstrap fold test (Tauxe and Watson, 1994) for Group 3 sites (excluding site 20). Maximum eigenvalues (τ_1) occur near 0% untilting providing strong evidence that Group 3 specimens have been remagnetized.

Site-mean directions for sites 9, 20, and 21 are within the cluster of Group 3 site means but are unacceptably imprecise. Their cones of confidence at the 95% confidence limit are well outside the range Van der Voo (1990) considerers appropriate for a high-quality paleomagnetic study. Excluding site means for sites 9, 20, and 21 from a Group 3 mean-direction calculation results in a Group 3 mean direction uncorrected for tilt of Dec: 42.7, Inc: 54.9, α95: 6.7 (Figure 15).

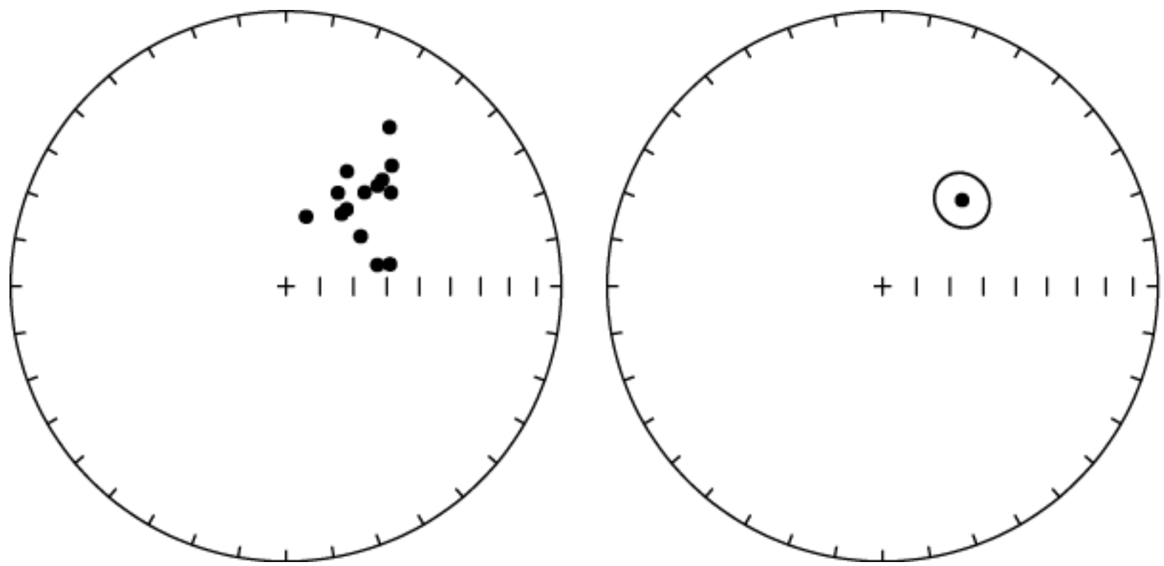

Figure 15. EA plot of 14 high-quality Group 3 site-mean directions (left) and Group 3 mean direction (right) of Dec: 42.7, Inc: 54.9, N:14, R: 13.6346, κ:35.7 and α95: 6.7.

Group One and Group Two

The two remaining sets of directions are significantly different from the Group 3 mean-direction. Directions from last removed components for sites 3 and 4 are vaguely anti-polar to directions from last removed components for sites 7 and 18, although the directions for sites 7 and 18 are steeper. Site 3 and site 4 mean directions are similar to directions of Hillhouse et al. (1982) Group 1 specimens and the directions for sites 7 and 18 are similar to, though more southerly than, Hillhouse et al. (1982) Group 2 site directions. The similar attitudes for sites in both Group 1 and Group 2, in addition to the low number of sites in both groups (N=2), preclude rigorous fold tests. However, EA projections of uncorrected and tilt-corrected directions show that site-mean directions for both groups appear to be closer together before correction (Figure 16).

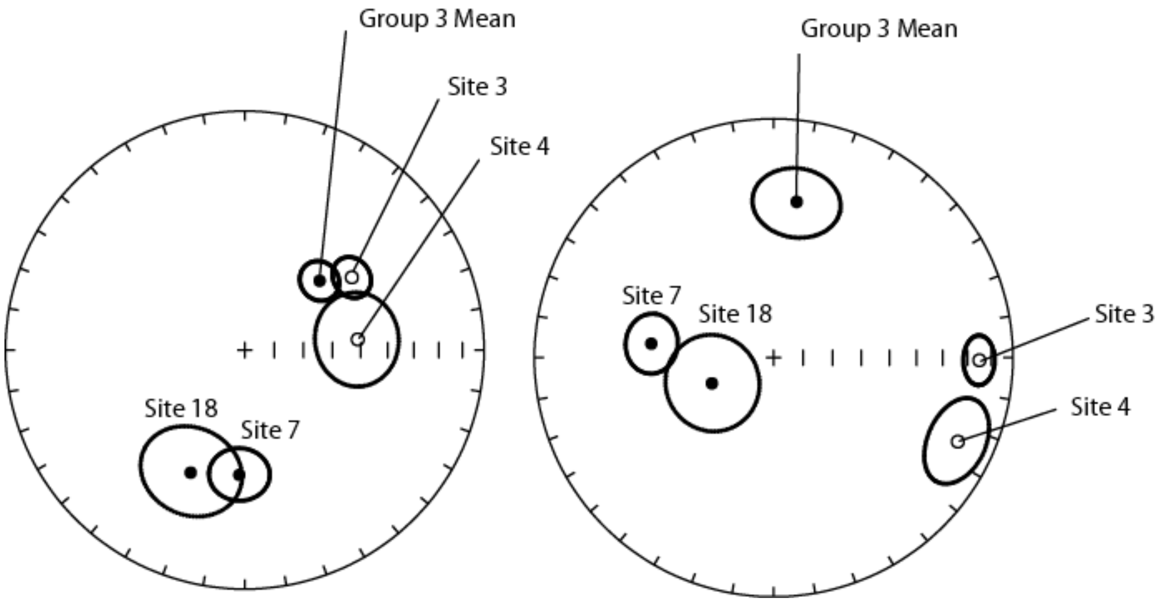

Figure 16. EA plots for unique groups from this study. Filled circles plot on the lower hemisphere of the projection and open circles plot on the upper hemisphere. Clustering of directions is tighter before tilt correction (left). Tilt-corrected directions (right) for sites 3 and 4 are easterly and shallow, while those for sites 7 and 18 are moderately steep, downwardly and westerly.

Reinterpreted Hillhouse Data

Advancements in paleomagnetic procedures (Kirschvink, 1980), and reliability guidelines for paleomagnetic data sets (Van der Voo, 1990), provide a framework to review the fidelity of older paleomagnetic data sets. Additionally, geologic research that has been completed in the Blue Mountain Province since 1982, along with data presented in this study, indicate that it is useful to reexamine Hillhouse et al. (1982) data to see how well it dovetails with recent, geologically-based interpretations of terrane relationships.

The introduction of the superconducting magnetometer coupled with developments in paleomagnetic statistics have changed the types and amount of data paleomagnetists typically collect and utilize in paleomagnetic studies. In the mid-twentieth century natural remanent magnetizations (NRMs) that were used to determine paleomagnetic poles were not thermally or magnetically cleaned. This procedure was replaced by blanket demagnetization (late 1950s) and then pilot demagnetization to stable endpoints (1960s-early 1980s) (Beck et al., 2001). Currently, principle component analysis (Kirschvink, 1980) is utilized in most paleomagnetic studies. To illustrate possible differences in paleomagnetic results that may arise from outdated analytical methods, Beck et al. (2001) reanalyzed results for Lesbos volcanic rocks in order to compare angular deviation of means for several demagnetization methods with results obtained from PCA. Beck et al. (2001) found that although older methodologies are often accurate, utilization of PCA might detect directional biases that would otherwise be missed.

Hillhouse et al. (1982) utilized pilot demagnetization to stable endpoints for their study (Figure 17). Pilot samples were step-demagnetized until sample direction(s) stopped changing in a significant way. Typically, pilot samples underwent eight to twelve demagnetization steps resulting in the removal of half to four-fifths of their magnetic intensity. Demagnetization prescriptions for the remainder of the specimens were based on the behavior of pilot specimens. Typically four to seven demagnetization steps were used to demagnetize remainder specimens to levels equivalent with pilot specimen endpoints. Intensity reduction for remainder specimens ranged from one-third to two-thirds of total original intensity. Mean directions were calculated from site directions measured after the single demagnetization step that produced the least scatter within a site.

In order to examine the fidelity of Hillhouse et al. (1982) data, as well as to maximize the compatibility of the two Group 1 data sets, Hillhouse et al. (1982) Group 1 sites were reanalyzed using PCA to standards used in this study. Visual examination of Hillhouse et al. (1982) Group 1 demagnetization data on orthogonal vector plots and EA projections shows that all five samples from site 18 and two samples from site 7 streak along remagnetization circles. The Hillhouse et al. (1982) Group 1 direction may be biased northward by an unresolved magnetic component carried by samples collected from sites 7 and 18. This bias is not accounted for by their stable end-point analysis.

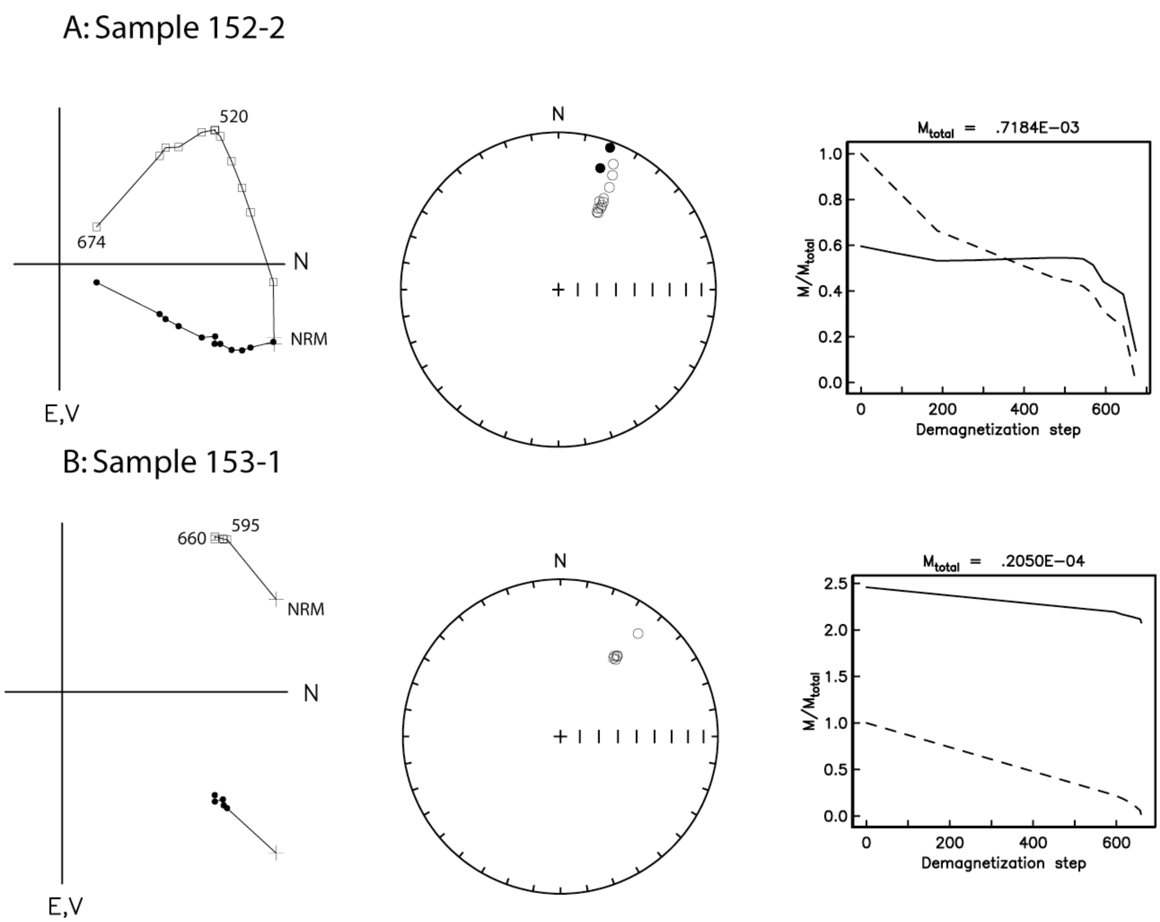

Figure 17. A: Orthogonal vector, EA, and total intensity plot for Sample 152-2 of Hillhouse et al. (1982) Site 7, Group 1. Sample 152-2 is a typical pilot sample with 13 demagnetization steps. The solid line on the total intensity plot represents decay of NRM intensity during demagnetization. The dashed line represents the decay of the vector sum difference for each successive demagnetization step. B: Orthogonal vector, EA, and total intensity plot for Sample 153-1 of Hillhouse et al. (1982) Site 7, Group 1. The solid line on the total intensity plot represents decay of NRM intensity during demagnetization. The dashed line represents the decay of the vector sum difference for each successive demagnetization step. Sample 153-1 is a non-pilot sample and the demagnetization procedure is representative of the bulk of the Hillhouse et al. (1982) sample suite. Component directions for these two samples were calculated from stable endpoints.

Great circle (plane) analysis and combined line and plane analysis was used on sites 18 and 7 respectively in an attempt to extract unbiased site directions. Planes from all five site 18 specimens were so parallel in orientation that great circle constraint was not feasible. Combined line and plane analysis on five specimens from site 7 resulted in a mean-direction with a large (>20°) $\alpha 95$ cone of confidence and a mean-direction that was well to the north of Hillhouse et al. (1982) site directions derived from volcanic sandstones and flow rocks. Because a site 18 mean-direction cannot be accurately constrained using plane analysis and because site 7 specimen magnetization components are not internally consistent, sites 18 and 7 should not be included in paleolatitude calculations for the Seven Devils terrane, as their magnetizations are not well resolved by present standards.

Hillhouse et al. (1982) Site 7 and Site 18 specimens were collected in volcanic breccias whereas the other Group 1 Hillhouse et al. (1982) samples were collected in subareal and subaqueous extrusive volcanic flow rocks and volcanic sandstones. Magnetization of breccias may be scattered depending upon the breccia emplacement temperature relative to the blocking temperature of the primary magnetic carrier. If the breccia emplacement temperature is high relative to the magnetic blocking temperature then the breccia's NRM will be similar to an NRM acquired by a volcanic flow rock. However, if the emplacement temperature of a breccia is low compared to the blocking temperature of the magnetic carriers then only the low temperature component would be in the local magnetic field direction. In this case the breccia's NRM would be similar to that acquired by a conglomerate. Breccia emplacement conditions for Hillhouse et al. (1982) sites 7 and 18 are not known and provide another reason for dismissal.

Van der Voo (1990) developed criteria to distinguish high quality paleomagnetic data from less robust data sets. A high quality paleomagnetic study requires enough sites/samples to sufficiently average out paleomagnetic secular variation and well-clustered directions. Van der Voo (1990) suggested that a value for α_{95} that is less than 16° be used to fulfill the latter criteria. Primary magnetizations from volcanic rocks in the Wild Sheep Creek Formation, if acquired quickly, may not average out paleomagnetic secular variation. Group 1 has an α_{95}=17.9°, which falls outside the high quality range. However, in Fisher statistics the α_{95} value is very sensitive to sample size when n is < 7. For small sets of data the k value is a better estimator of data scatter than α95. If $k > 15$ or approximately so, then a data set is non-random. The Hillhouse et al. (1982) k value for Group 1 is 19.

An additional requirement for a high quality paleomagnetic study is well-defined geochronology (Van der Voo, 1990). The Wild Sheep Creek Formation is bracketed by the fossil bivalves *Daonella degeeri* and D. *frami* found at the base of the formation (Jones, 1977) and upper Triassic bivalves found in the Martin Bridge Limestone (Hoover, 1983). Vallier (1977) assigned the Wild Sheep Creek Formation to the Ladinian and Carnian ages of the Triassic. This is sufficient to meet the criteria of Van der Voo (1990). However, it should be noted that the age constraints for the Huntington Formation are poor. Fossils in the middle part of the formation indicate a Carnian-Norian age but locations that Hillhouse et al. (1982) reported show that the sites sampled are up-section from the fossils. Therefore the rocks sampled may be of Norian age or younger, 5-10 million years younger than Wild Sheep Creek Formation samples in Hells Canyon. Uncertainties also exist about which unit Hillhouse et al. (1982) sampled at the Imnaha location and the exact ages of the units sampled. Rocks at the Imnaha location are mapped as Clover Creek Greenstone but they may be contiguous with the Lower Sedimentary Series and the Doyle Creek Formation. If Hillhouse et al. (1982) sampled the Lower Sedimentary Series and/or Doyle Creek Formation they may have sampled rocks as young as 215 Ma, rocks 10 Ma or more years younger than Wild Sheep Creek Formation sampled in Hells Canyon (LaMaskin, personal comm.).

Hillhouse Group 1

Hillhouse et al. (1982) Group 1 specimen directions are distinct from the Group 2 and Group 3 specimen directions but may not be primary. Resultant directions from sites 8, 9, and 10 were compared to original Hillhouse et al. (1982) Group 1 site directions derived from vector endpoints (Figure 18). A parametric fold test (Tauxe and Watson, 1994) was preformed on a new Group 1 data set consisting of reinterpreted (PCA) Hillhouse et al. (1982) sites 8, 9, and 10 combined with sites 3 and 4 from this study (Figure 19).

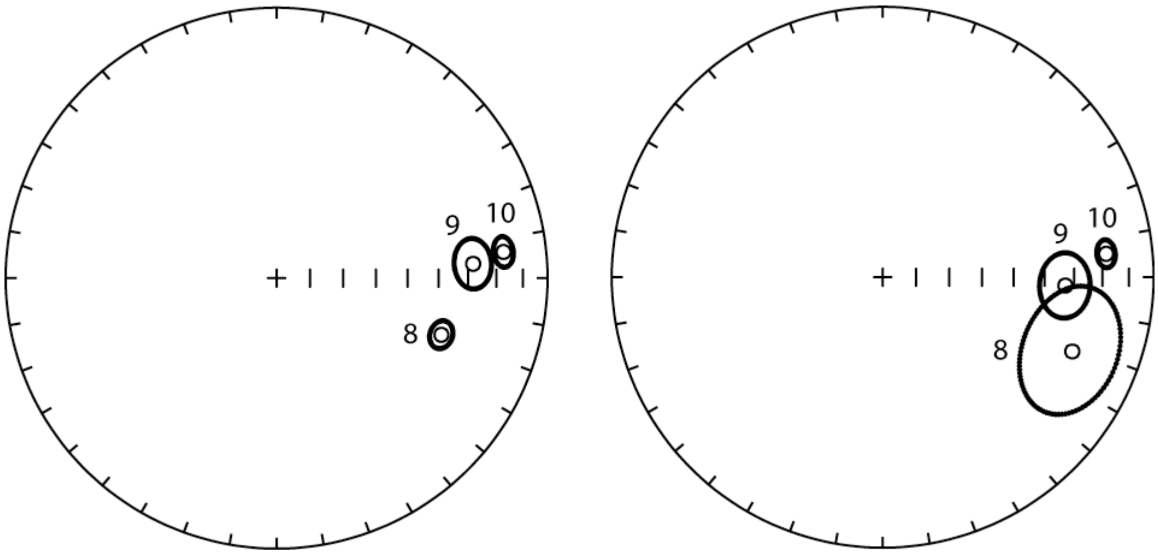

Figure 18. Equal area projections of tilt-corrected mean directions and their α95 cones of confidence for sites 8, 9, and 10 from Hillhouse et al. (1982) for vector endpoints (left) and least square line fit directions PCA (right). Open symbols project on the upper hemisphere.

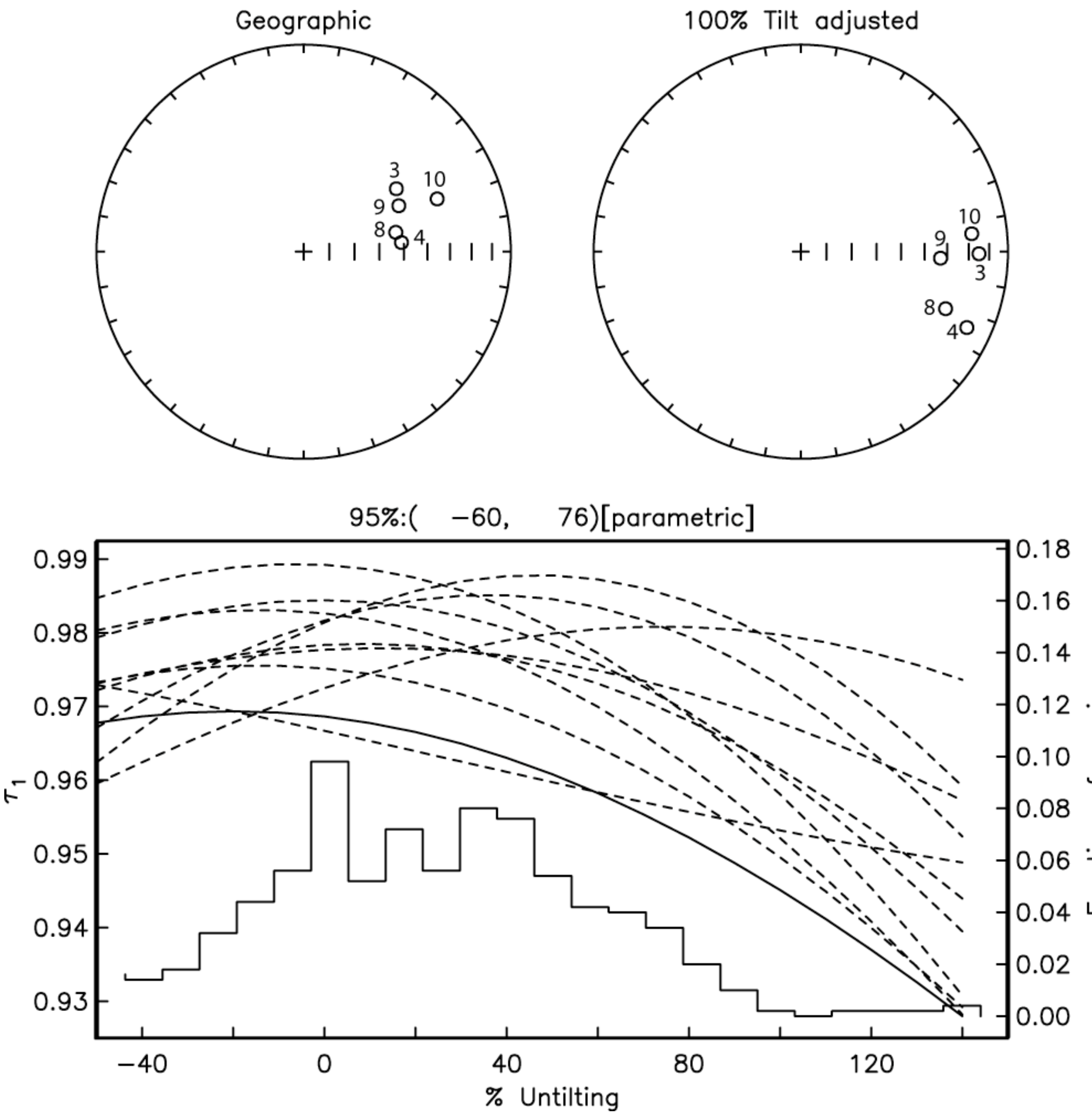

Figure 19. Parametric bootstrap fold test for combined Group 1 sites 8, 9, 10 (Hillhouse et al., 1982), 3, and 4 (this study). Maximum eigenvalues (τ_1) occur near 0% untilting. The distribution is broad, but corrections with 76% or more restoration to paleohorizontal produce significantly lower τ_1, at the 95% confidence level suggesting that magnetizations are not primary.

The new combined Group 1 fold test (Figure 19) is negative. The hypothesis that the magnetization was acquired in the tilt-corrected coordinate system can be rejected at the 95% confidence level. Maximum eigenvalues occur near 0% untilting: at the 95% confidence interval the maximum eigenvalues of para datasets range from -60% to 76%

untilting. There are two reasonable interpretations for these results. If maximum eigenvalues for the fold test occur at 0% untilting then the Group 1 site rocks have been remagnetized in their present relative orientations. Alternatively, if the maximum eigenvalues occur somewhere between -60% to 76% untilting (excluding 0% untilting) then the Group 1 site-directions distribution could be the result of a syn-deformational magnetization event or improper structural restoration due to unrecognized complex folding or faulting. Poles to volcanic bedding (n=5) cluster south-southeast for the combined Group 1 sites but when poles to bedding for Hillhouse et al. (1982) sites 7 and 18, and site 1 (this study) are added, a weakly streaked distribution becomes apparent (girdle strike/dip of 052/47: right hand rule). The girdled poles to volcanic bedding could be interpreted as tilting of a cylindrical fold. Site 1 from this study contained two samples with characteristics similar to those of other Group 1 sites. Sites 7 and 18 were dismissed from paleomagnetic calculations (see above) but if Group 1 is broadened to include them there is a hint that the geographical region near the Group 1 site locations, which is located a few hundred meters south of Hells Canyon Dam, may have undergone complex folding.

Sites 8, 9, 10 from Hillhouse et al. (1982) were grouped with sites 3 and 4 from this study because site-mean directions were similar, magnetic behavior was similar, and because sites 3 and 4 were collected proximal to Hillhouse et al. (1982) sites 8, and 9 and 10. For possible future work, 20 to 30 additional Group 1 sites collected and analyzed via identical methods on similar instruments would be beneficial for statistical purposes.

With an increase in the number of Group 1 sites greater-than Fisherian dispersion of declination due to inaccurate structural correction could be tested.

Hillhouse Group 2

The Hillhouse et al. (1982) Group 2 magnetization is the only group from the 1982 study that statistically passed a fold test. Group 2 α_{95} is 13° and passes Van der Voo's (1990) criteria for a high quality paleomagnetic data. However, use of the Group 2 mean direction is complicated by the fact that Group 2 study sites were collected from two formations located in separate tectonic units—the Huntington Formation of the Olds Ferry arc and the Wild Sheep Creek Formation of the Seven Devils arc. When Group 2 sites are parsed into their respective terranes, fold tests are inconclusive due to the small size of the data sets (Figure 20).

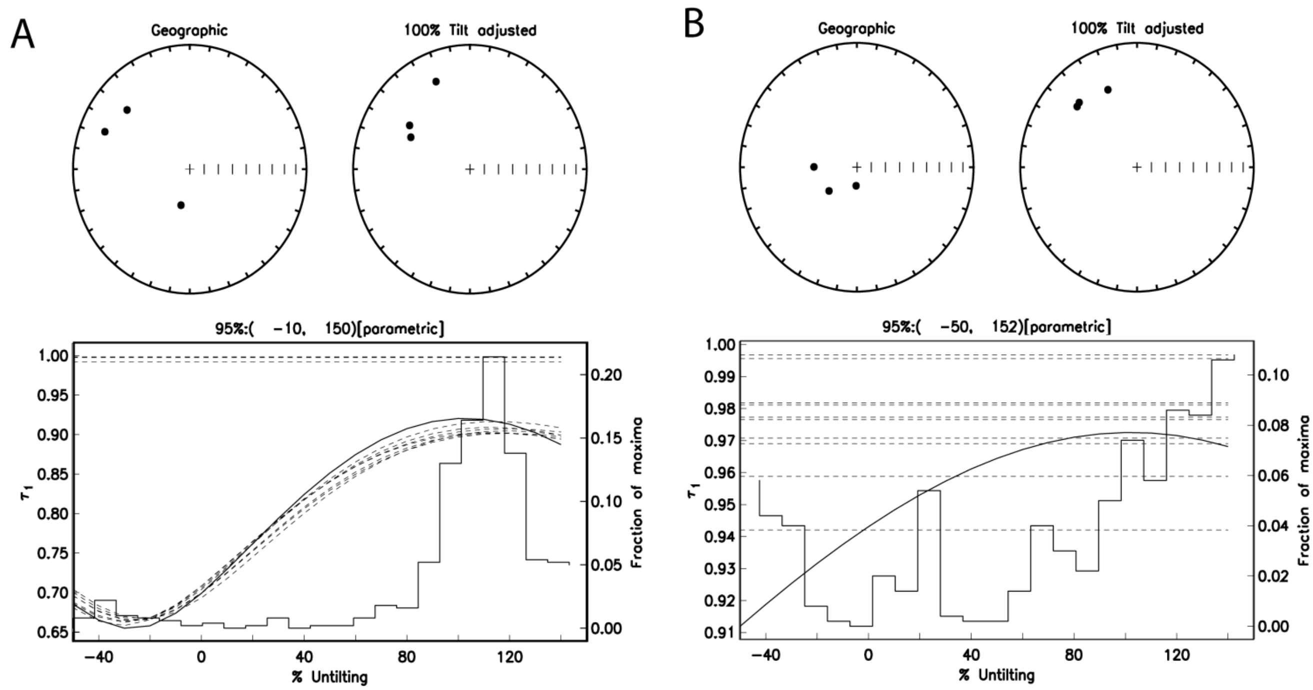

Figure 20. Parametric fold test for Huntington and Wild Sheep Creek subgroups used in Hillhouse et al. (1982) Group 2 result. A: Three sites collected in the Wild Sheep Creek Formation; B: Three sites from the Huntington Formation. These, and all other, fold tests are inconclusive due to the small (N = 3) number of sites in each sub-group, although it can be noted that both sets of data have best clustering near 100% tilt correction.

Because neither Group 2 subset passes a fold test it is not possible to reject at the 95% confidence level the hypothesis that the magnetization of either subgroup postdates folding. However, improvement of clustering with tilt correction suggests that the remanence might be primary. Available paleomagnetic data for Group 2 can be used to generate two reasonable hypotheses: 1: if the overall Group 2 mean direction is primary then the Olds Ferry and Seven Devils arcs shared a common tectonic framework at the time the Group 2 magnetization was acquired and have not undergone substantial amounts of differential vertical axis rotation. 2: If the overall Group 2 mean direction is not primary then one or both of the Seven Devils and/or Olds Ferry arcs have likely been remagnetized.

Given the small number of sites with these magnetizations, and the quality of the available Group 2 paleomagnetic data, it is difficult to robustly test either of the two hypotheses outlined above.

The parsed Group 2 Seven Devils and Huntington subgroups (n=3 for each) can be tested to determine if they are likely to share a common direction in tilt-corrected coordinates. If the subgroups do share a common direction the hypothesis stating that the Seven Devils and Olds Ferry arcs shared a common tectonic framework could be (weakly) supported. Lisa Tauxe (1998; program cart_hist) coded a method to determine if two datasets are distinct. Bootstrapped component vector-means are converted to Cartesian coordinates and plotted as histograms, with intervals containing 95% of the bootstrap trials used to define the 95% confidence limits for each. If the 95% confidence intervals for all three Cartesian components overlap, the datasets cannot be distinguished with 95% confidence and are considered to share a common mean. Testing the Wild Sheep Creek and Huntington Group 2 subgroups results in overlap at the 95% confidence interval for all directional components (Figure 21). This suggests that the Seven Devils and Olds Ferry arc terranes may have shared a common tectonic framework at the time of the magnetization event and/or that the rocks were remagnetized prior to significant deformation.

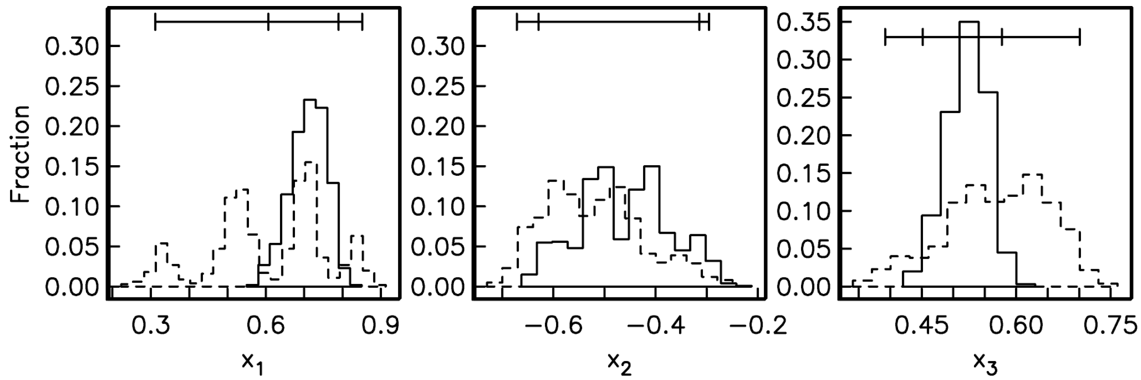

Figure 21. Histogram of shared directional components of the Wild Sheep Creek and Huntington subgroups. X_1 represents the north component, X_2 the east component, and X_3 the vertical component. Solid histogram represents the Wild Sheep Creek Formation of the Wallowa-Seven Devils terrane and the dashed histogram represents the Huntington Formation of the Olds Ferry terrane. The bars at the tops span 95% of trial results for each component. Lack of empty space between bars indicate overlap and therefore that the directions of the two terranes are indistinguishable.

Magnetic inclination, and thus paleolatitude, for the Hillhouse et al. (1982) overall Group 2 mean derived from six tilt-corrected site-means does not differ statistically from the overall magnetic inclination for the means of Group 2 sites when those sites are parsed into the Wallowa-Seven Devils (n = 3) and Olds Ferry (n = 3) terranes (Table 5). Given the similarity of these directions, the Group 2 sites will be re-lumped together during some of the discussion below.

Table 5. Calculated paleolatitude for two Northwest Oregon terranes using Hillhouse et al. (1982) Group 2 paleomagnetic data.

Formation/Ref Frame	Dec	Inc	N	R	k	α_{95}
Wild Sheep Creek (UC)	288.3	46.3	3	2.4575	3.7	76.5
Huntington (UC)	240	70.7	3	2.9136	23.1	26.2
Total (UC)	271.5	61.6	6	5.1475	5.9	30.2
Wild Sheep Creek (TC)	314	36.4	3	2.8767	16.2	31.7
Huntington (TC)	322.5	31.2	3	2.9585	48.2	17.9
Total (TC)	318.6	33.8	6	5.8189	28	13

Table 5. Name/Ref Frame: Name of formation and reference frame. The Wild Sheep Creek Formation is located in the Wallowa-Seven Devils Terrane. The Huntington Formation is located in the Olds Ferry terrane. UC: uncorrected direction. TC: Tilt-corrected direction. Dec: declination. Inc: inclination. N: number of sites used in calculation. R: length of resultant vector. k: κ, Fisher (1953) precision parameter. α_{95}: semi-angle of cone of 95% confidence about the mean.

Discussion

Paleomagnetism can be used as a diagnostic tool given that certain criteria are meet (see above). Most importantly, rocks used in paleomagnetic studies must preserve the direction of the Earth's geomagnetic field from the time and location of their formation; this direction also has to be able to be isolated through laboratory procedures. To accurately determine paleolatitude rocks also must also acquire their magnetizations slowly enough to average out paleosecular variation caused by non-dipole elements of the Earth's magnetic field. Most of the samples from both this study and from Hillhouse et al. (1982) fail a fold test and have been interpreted as remagnetized (Group 3): these late Triassic rocks no longer preserve the direction of the late Triassic geomagnetic field. Thermal cleaning of Group 1 and Group 2 samples yielded last removed components that may preserve a late Triassic field direction or an ancient field direction of unknown age. Neither the Group 1 nor Group 2 mean direction is similar to the expected present-day direction for the Wallowa-Seven Devils terrane or the expected direction for a reverse polarity field. Paleosecular (PSV) variation is problematic because the magnetization method(s) of Seven Devils rocks are not known with certainty. If the volcanic flows sampled acquired their magnetizations quickly after extrusion then paleosecular variation would not be averaged out. Thin section work completed by Hillhouse et al. (1982) documents abundant, authigenic microcrystalline hematite in the bulk of his sample suite. Secondary hematite could acquire a magnetization either quickly or slowly depending on growth and oxidation conditions. If the formation of hematite is associated with hydrothermal circulation, growth and oxidation conditions could vary spatially and temporally. The Fisher (1953) precision parameter (κ) for individual sites ranges from 12 to 189 in this study and from 15 to 1009 in Hillhouse et al. (1982). At this time there is no way to know if, and by how much, Seven Devils paleomagnetic results are biased by paleosecular variation, but it is likely that most of the rocks sampled in both studies acquired their magnetizations over timescales less than those required (10^3-10^5 years) to average out PSV.

Although the Group 1 and Group 2 data sets (Hillhouse et al., 1982; this study) are small some evidence suggests that the Group 1 and Group 2 magnetizations predate the Group 3 overprint and may be primary (Hillhouse et al., 1982; this study). To summarize: the Group 1 and Group 2 magnetizations are different from the Group 3 magnetization; the fold tests of the parsed Group 2 directions, although statistically inconclusive, cluster most tightly at approximately 100% untilting, which suggests positive fold tests; and the Group 1 mean-direction's negative inclination implies that it is an ancient direction or that the volcanic units of the Seven Devils terrane originated in the southern hemisphere. While this evidence is not robust by commonly accepted standards in paleomagnetism (Van der Voo, 1990) the data that constitutes it are not random. One working hypothesis is that the (Hillhouse et al., 1982) Group 1 and Group 2 directions are primary and in this case comparing paleolatitudes for the Seven Devils and Huntington terranes with results from Wrangellia and other North American terranes is a worthwhile and informative exercise.

Paleolatitudes for the Seven Devils terrane fall within the range established for other Wrangellia correlatives (Table 1) so paleomagnetism cannot be used to definitively discredit a terrane link between the Wallowa-Seven Devils terrane and Wrangellia.

Remember, however, that magnetic inclination data provide no constraint on paleolongitude so it is possible that large East-West distances separated terranes with similar paleolatitudes from each other, and from North America.

The paleomagnetic poles calculated from the tilt-corrected Group 1 and Group 2 mean-directions and the paleomagnetic pole calculated from the uncorrected Group 3 mean-direction (Figure 22) show the relative positions of the Seven Devils terrane, the Olds Ferry terrane, and the North America apparent polar wander path (Torsvik et al., 2001). The Group 1 pole is distal to the North American apparent polar wander path but the Group 2 pole coincides with it. This is interesting because preliminary detrital zircon data from the Blue Mountain province (LaMaskin, 2007) suggests that the Olds Ferry arc may have originated as a fringing arc complex. Note, though, that the Group 2 paleomagnetic pole was determined from data that contained sites located in separate tectonic units and that the paleomagnetic poles in Figure 22 have not been corrected for the well-documented and accepted clockwise rotation of terranes located in the Blue Mountain Province (Wilson and Cox, 1980; Harbert, 1995; Housen, 2007).

Discordant paleomagnetic directions (Wilson and Cox, 1980) for Blue Mountain plutons (relative to stable North America) indicate that the Blue Mountains have either undergone 60 +/- 29° of clockwise rotation relative to North America since the late Jurassic/early Cretaceous (160 Ma-125 Ma) or have been tilted. Discordant paleomagnetic directions found in some marginal terranes have been attributed to pluton tilting rather than large-scale latitudinal displacement or vertical axis rotation (Butler et al., 1989). Pluton tilting has been documented at several sites in the North America cordillera including the Mt. Stuart Batholith in Washington State (Ague and Brandon, 1996). Because no paleohorizontal indicators exist for Blue Mountain plutons it is impossible to eliminate tilting as a potential source of error in the Wilson and Cox (1980) rotation estimate. It is likely that Blue Mountain plutons have undergone both mild tilting and moderate to substantial vertical-axis rotation. Based on rotation estimates for the Clarno Volcanics in central Oregon (Beck, 1978; Grommé et al., 1986) the Blue Mountain Province has rotated approximately 16 +/- 8° since the Eocene. Sedimentary rocks from the Mitchell Inlier (Housen and Dorsey, 2005) have undergone 37 +/-7° of clockwise rotation indicating that the Blue Mountain Province has been rotated approximately 40° clockwise since late Cretaceous time.

Paleomagnetic work in the Blue Mountain Province subsequent to Wilson and Cox (1980) has established the presence of a regional magnetic overprint (remagnetization), or overprints, with a direction(s) similar to that obtained by Wilson and Cox (1980) for Blue Mountain plutons (Figure 23) (Hillhouse et al., 1982; Harbert et al., 1995; this study: and Housen, 2007). Most workers (e.g. Dickinson, 2004) assume that pluton tilting has had only a negligible to small effect on rotation estimates for the Blue Mountain Province. So, Group 1 and Group 2 mean-directions (Hillhouse et al., 1982) can be rotated counterclockwise to restore them to their late Jurassic/early Cretaceous orientations. Combining data from several studies (Wilson and Cox, 1980; Hillhouse et al., 1982; Harbert et al., 1995; this study; and Housen, 2007) indicates that 71° of counterclockwise rotation is the most appropriate value for the counter-rotation correction.

Recalculating Group 1 and Group 2 paleomagnetic poles after performing the counterclockwise rotation in direction-space shifts the Group 1 and Group 2 poles away from the North America polar wander path (Figure 24). The positions of these poles, far from the North American polar wander path, indicate that the Blue Mountain Province has had a very large post-Triassic, but pre-late Jurassic-early Cretaceous, rotation or translation. Calculating the expected Triassic direction for the Blue Mountain Province for its present location and comparing that direction to the observed direction yields net rotation from 210 Ma to the present. Subtracting 71° degrees of inferred post-Jurassic clockwise rotation from the net value shows that the Group 1 associated rocks underwent 154.8° of clockwise or 205.2° of counterclockwise vertical axis rotation between 210 Ma and the late Jurassic. Group 2 associated rocks underwent similar rotations: 99.4° of clockwise or 260.6° of counterclockwise vertical axis rotation between 210 Ma and the late Jurassic. These rotations should be accounted for in studies relating these rocks to a North America based framework.

Hillhouse et al. (1982) noted that when the post-Jurassic clockwise rotation of Blue Mountain terranes is removed the paleomagnetic pole for Group 1 comes into agreement with several poles from the Karmutsen Formation from Vancouver Island; most favorably with the pole for the Yole and Irving (1980) X magnetization (Figure 22). Hillhouse et al. (1982) use the agreement of the Seven Devils and Karmutsen poles to support the argument that the Seven Devils terrane was once part of Wrangellia

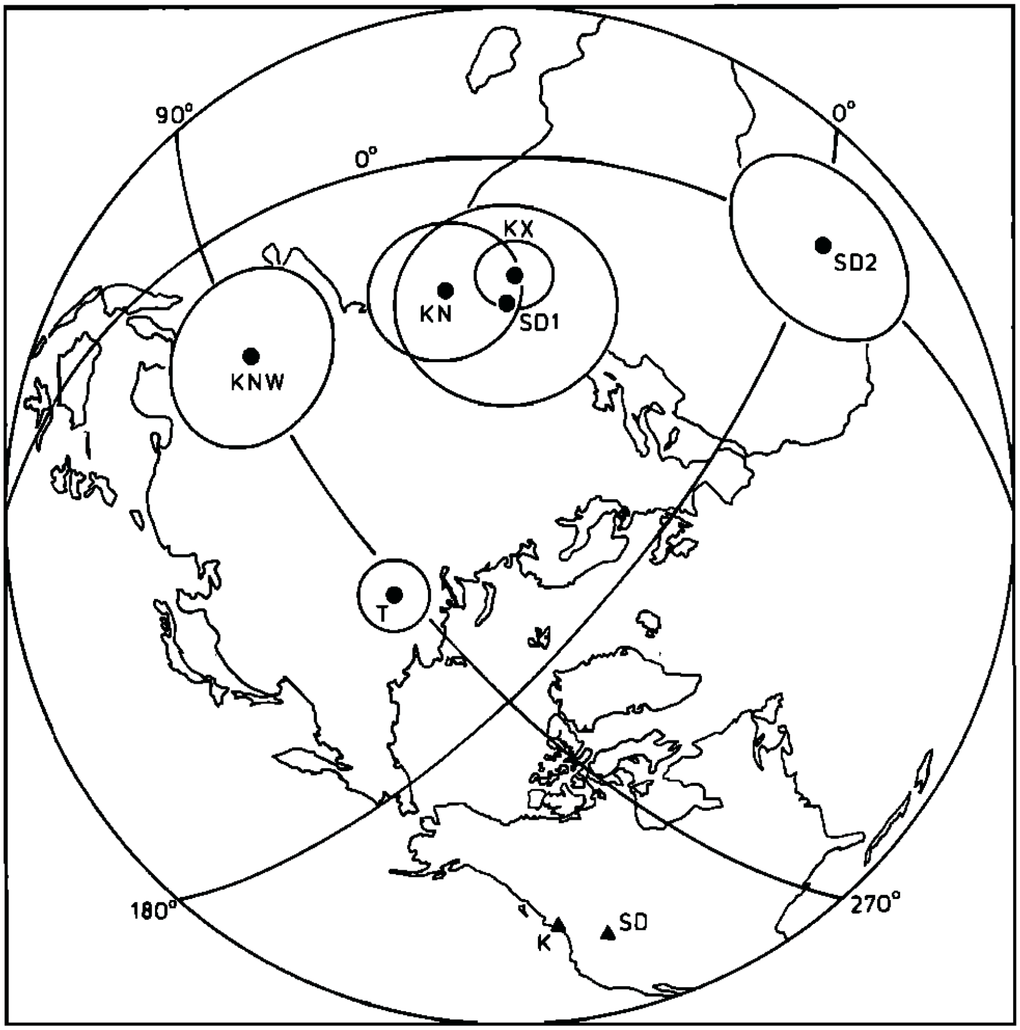

Figure 22. Modified copy of Hillhouse et al. (1982) figure 15 showing paleomagnetic poles for the Karmutsen formation on Vancouver Island (KNW, KN, KX) and for the Wild Sheep Creek and Huntington Formations of the Seven Devils and Olds Ferry arc terranes (SD1, SD2). Two Karmutsen poles overlap with the paleomagnetic pole for Hillhouse et al. (1982) Group 1 indicating that Vancouver Island and the Seven Devils terrane may have shared the same paleolatitude.

However, Hillhouse et al. (1982) neglected to account for post-Jurassic vertical axis rotation of Vancouver Island in their analysis. Paleomagnetic studies of the early-mid Jurassic Bonanza Volcanics (Irving and Yole, 1987) indicate significant rotation of portions of Vancouver Island relative to North America. Correcting the X and Y paleomagnetic poles (Yole and Irving, 1980) of the Karmutsen Formation for post-Jurassic rotation of Vancouver Island before comparing them to the Seven Devils Group

1 and Group 2 poles is a more robust analysis than that of Hillhouse et al. (1982) because it accounts for rotation of both the Blue Mountain Province and Vancouver Island.

Corrected paleomagnetic poles for the Seven Devils Group 1 and Group 2 (Hillhouse et al., 1982) and the Karmutsen Formation X and Y (Yole and Irving, 1980) poles are plotted in Figure 25. In this analysis the Seven Devils Group 2 pole coincides with the Karmutsen Formation X pole, whereas in Hillhouse et al. (1982) Figure 15 it is the Group 1 pole that coincides with the Karmutsen X pole.

If the Seven Devils terrane and the Olds Ferry terrane were separate for most of their pre-accretionary histories this result may indicate that the Group 2 direction was acquired from a pre-tilting remagnetization. The concordance of the Group 2 (Blue Mountain Province) and X (Vancouver Island) paleomagnetic poles may indicate that these two portions of Wrangellia shared the same position during a post-Triassic but pre-late Jurassic remagnetization event. This result also indicates that the Group 1 and X poles are distinct from each other and from North America suggesting a dissimilar prior history.

The concordance of these poles (Figure 25) suggests that Seven Devils and/or Huntington terranes may have been attached to what is now Vancouver Island in the late Triassic. However, based on the stratigraphy, biostratigraphy, and geochemistry of the Karmutsen Formation and related Triassic and Jurassic units on Vancouver Island, some geologists believe the link between Vancouver Island and the northern Wrangellia sections, which are located in Alaska, need to be reexamined (Andrew Greene, personal comm.; Erik Katvala, personal comm.).

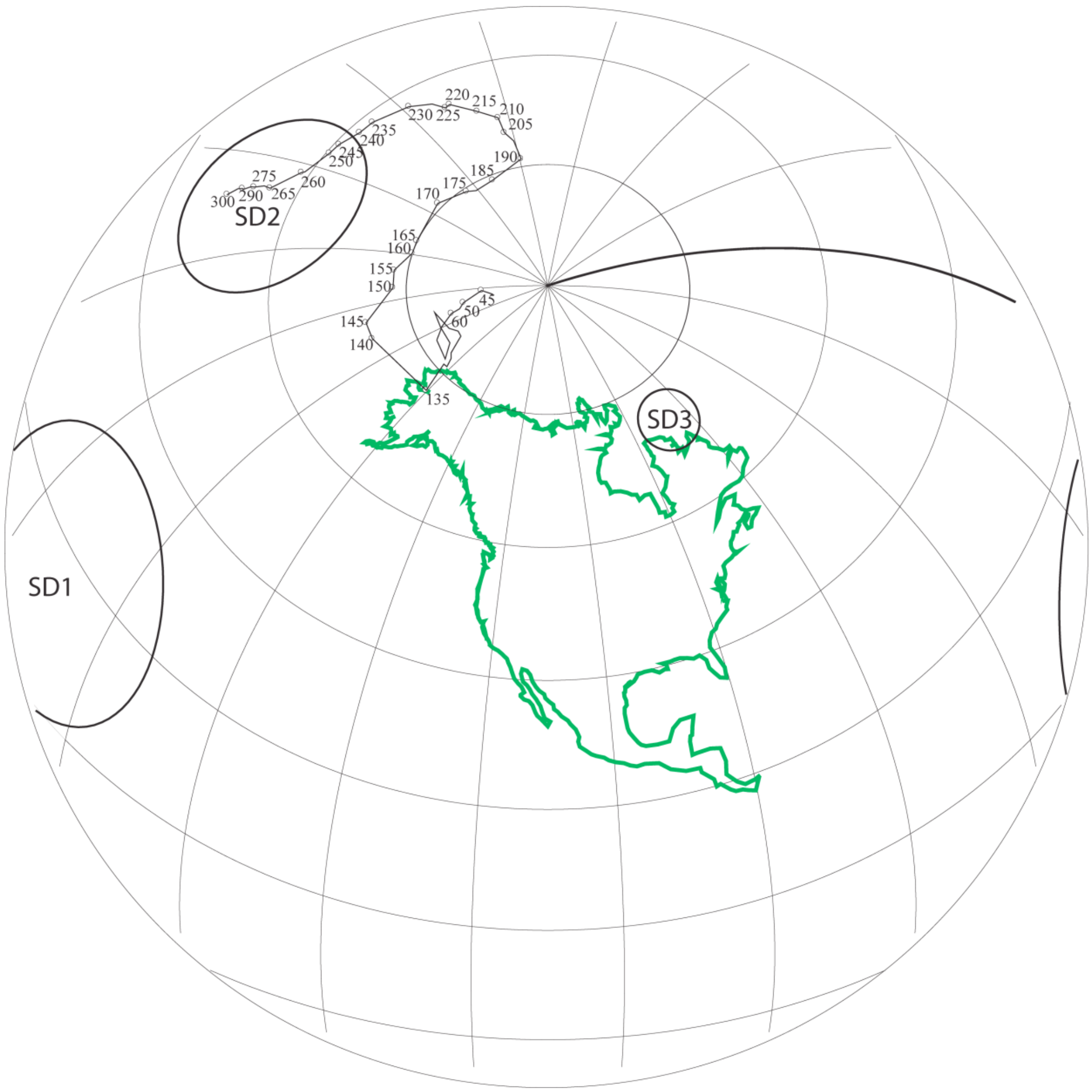

Figure 23: Paleomagnetic poles for Hillhouse et al. (1982) Group 1 (SD1), Group 2 (SD2), and Group 3 (SD3) with the North America polar wander path (Torsvik et al., 2001) for reference.

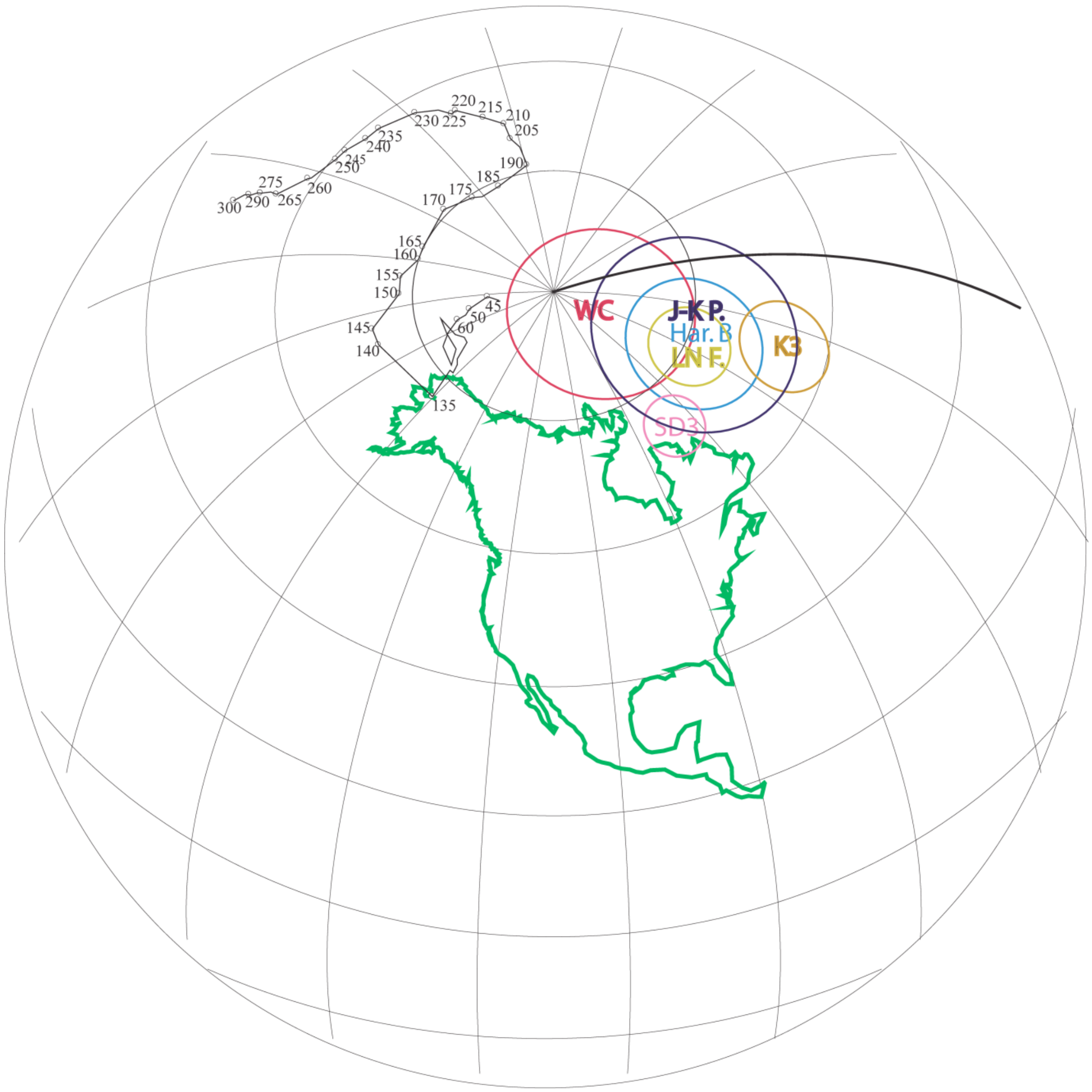

Figure 24:Paleomagnetic poles for Blue Mountain plutons and remagnetized rocks from several studies in the Blue Mountain Province: SD3; Group 3 from Hillhouse et al. (1982); K3; Group 3 from this study; WC; pole for Blue Mountain plutons (Wilson and Cox, 1980); Har B; Group B from Harbert et al. (1995); J-KP; pole for direction from selected and new Jurassic-Cretaceous Blue Mountain plutons (Housen, 2007); LNF; pole for direction from remagnetized rocks from the Lonesome Formation (Housen, 2007.).

Figure 25: Poles for Hillhouse et al. (1982) Group 1 (SD1) and Group 2 (SD2) mean-directions after correction for 71° of post-Jurassic clockwise rotation. The North America polar wander path (Torsvik et al., 2001) is shown for reference.

Figure 26: Corrected paleomagnetic poles for Hillhouse et al. (1982) Group 1 (SD1) and Group 2 (SD2) shown with poles for the Karmutsen X (Kar.X) and Karmutsen Y (Karmutsen Y) magnetizations (Yole and Irving,1980) that have been rotated using the direction for the Jurassic Bonanza volcanics (Irving and Yole, 1987) to correct for post-Jurassic rotation of Vancouver Island. The North America polar wander path (Torsvik et al., 2001) is shown for reference.

Several other North American terranes (excluding Wrangellia) have been brought up in discussions regarding the origin of the Wallowa-Seven Devils terrane and should be mentioned here. Some researchers have never favored a Wrangellia-Seven Devils connection and have suggested that the Seven Devils terrane may have been attached to either the Stikinia or Quesnellia sub-terrane of the Intermontane terrane located in British Columbia, Canada. Stikinia and Quesnellia are allochthonous and their volcanic histories and stratigraphies are similar to that of the Wallow-Seven Devils terrane when examined at a coarse level. Serious, multidisciplinary, methodical inquires into these suggestions have not yet been undertaken but paleomagnetic data for Stikinia and Quesnellia can be compared to the paleomagnetic poles for the Group 1 and Group 2 mean-directions (Table 6.) (Hillhouse et al., 1982).

Table 6. Triassic-Jurassic Paleomagnetic Poles for Select North American Terranes

Terrane	Fm./Unit	Age	P lat	P long	(dp/dm)/A_{95}	Study
Seven Devils	Wild Sheep Creek	Carnian-Norian	7.6° S*	350.3° E*	17°*	Hillhouse et al. (1980)
Seven Devils/Olds Ferry	Wild Sheep Creek/Huntington	Carian-Norian	46.6° N*	130.0° E*	14°*	Hillhouse et al. (1980)
Stikinia	Savage Mt. Fm.	Late Triassic	38° N	133° E	(15°, 10°)	Monger and Irving (1980)
Stikinia	Savage Mt. Fm	Late Triassic	24° N	146° E	(16°, 9°)	Monger and Irving (1980)
Quesnellia	Guichon Batholith	198 +/- 8 Ma	52° N	347° W	(5°, 9°)	Symons (1983)
Quesnellia	Cooper Mt. Intrusions	198 Ma	57.3° N	11.8 ° W	(27°, 4.4°)	Symons (1984)

Table 6. Terrane, Formation or Unit (Fm./Unit), Age, Pole Latitude (P lat), Pole Longitude (P long), error (dp/dm/ A_{95}), and Study for several North American terranes. * Virtual Geomagnetic Pole (VGP).

Table 6 illustrates that Stikinia and Quesnellia may have been located at the same or a similar paleolatitude as the Seven Devils terrane in the late Triassic. Note that the paleomagnetic poles in Table 6 have not been corrected for known, unknown, or inferred vertical axis rotations of the terranes listed in the first column. A paleogeographic reconstruction (Figure 27) shows the ranges of late Triassic paleolatitude for Stikinia and Quesnellia in comparison to Wrangellia and North America.

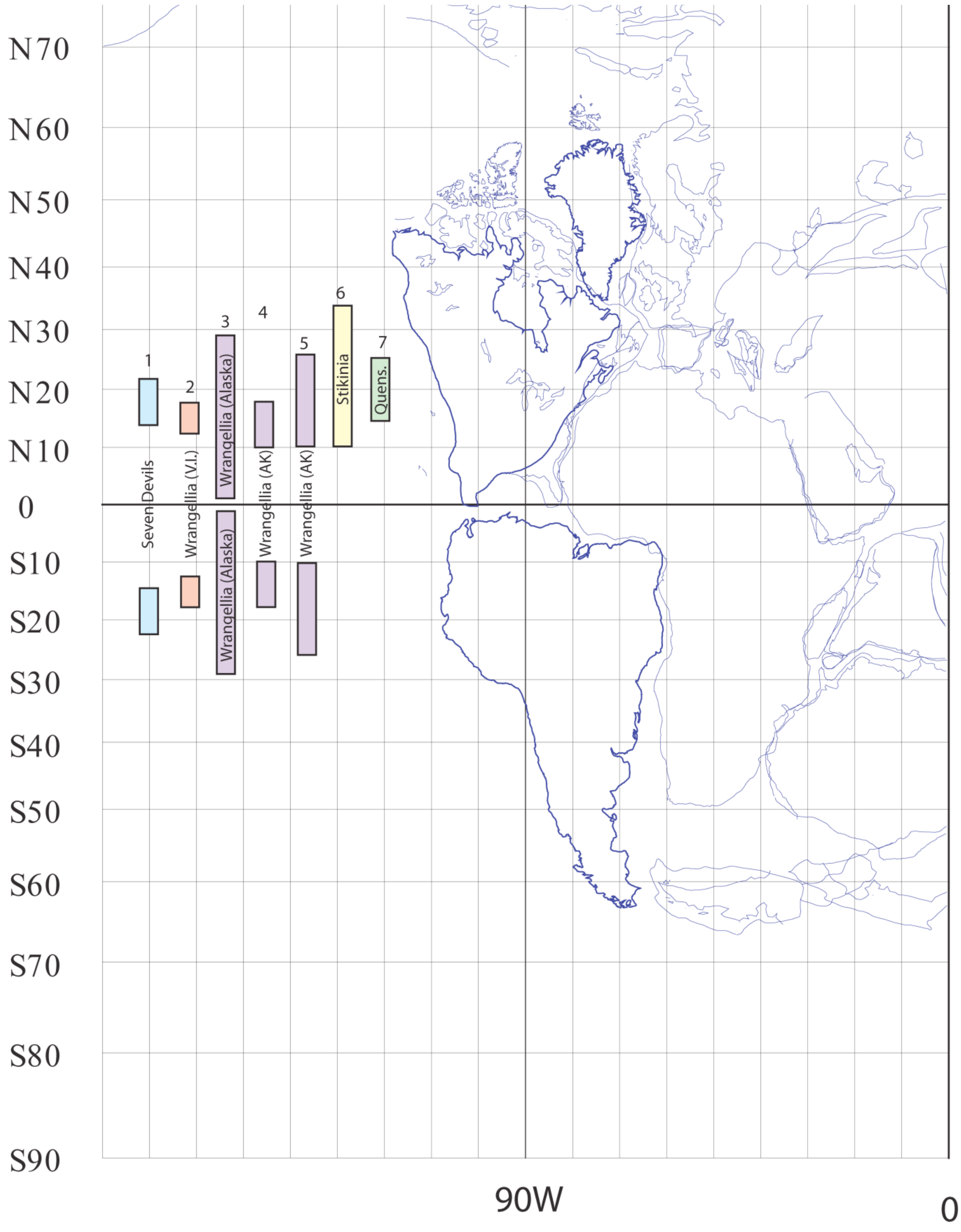

Figure 27. Paleogeographic reconstruction of the Western Hemisphere (200 ma.). Vertical pastel bars indicate established latitudinal ranges for several North American terranes. 1: Seven Devils terrane; 2: Wrangellia from Karmutsen Formation; 3: Wrangellia from the Nikolai Greenstone; 4: Wrangellia from the Nikolai Greenstone; 5: Wrangellia from Nikolai equivalent basalt; 6: Stikinia; 7: Quesnellia.

Recent studies (Wyld and Wright, 2001; Kays et al., 2006) have posited that the Blue Mountain Province was once located proximal to or attached to the Klamath Mountains of Southern Oregon and Northern California. While there have been paleomagnetic studies completed in the Klamaths, all of the data compiled by Mankinen et al. (2002) are from rocks that pre-date the Triassic by several 100s of millions of years. Mankinen et al. (2002) conclude that the eastern portion of the composite Klamath terrane began forming in a rift basin marginal to Rodinia and Laurentia during the Neoproterozoic and remained tectonically related to the Laurentia from the Neoproterozoic to the breakup of Rodinia. The western portion of the composite Klamath terrane is composed of several terranes that were accreted to the eastern Klamaths starting in the middle Devonian. Paleomagnetic data for the North Fork terrane suggests that it originated from 10° further south than Permian portions of the eastern Klamaths (Mankinen et al., 2002). Accretion of the western Klamaths continued from the middle Devonian until the Jurassic.

It is possible that the Seven Devils terrane is related to the Klamaths but at this time I believe those in favor of this association require better data to support their argument. I would also argue, though, that the evidence linking the Wallowa-Seven Devils terrane to Wrangellia is not much more conclusive than the evidence linking the Wallowa-Seven Devils terrane to the Klamaths. One question that needs to be addressed in both cases is: How much geochemical, stratigraphic, structural, and fossil variation is permissible within the boundaries or extent of a terrane/composite terrane?

Appendix A: Magnetic Anisotropy of Seven Devils Study Rocks

Anisotropy of magnetic susceptibility (AMS) were obtained for all study samples (see Data Appendix) and magnetic fabric orientations were compared to volcanic bedding planes at each locality (Figure 24). Primary magnetic fabrics in extrusive and shallow intrusive igneous rocks may be attributed to mimicking of paramagnetic mineral fabrics through/by ferromagnetic mineral development/mantling (Tarling and Hrouda, 1993). Most basaltic magma flows are less than 10% magnetically anisotropic and have fabrics that tend to be oblate with the minimum susceptibility axis (K_{min}) perpendicular to the foliation plane (Tarling and Hrouda, 1993). Since the foliation plane often lies close to the flow plane, intermediate and maximum susceptibility axes will often girdle the perimeter of a stereo-projection in a tilt-corrected coordinate system. Deviance from this fabric geometry may be the result of an inverse fabric. Submarine basalt flows may have more random fabrics than subaerial basaltic flows and this difference, if more firmly established, may be do to degassing processes (Tarling and Hrouda, 1993).

Minimum, intermediate, and maximum susceptibility axes for sites 1-22 are plotted, with site bedding plane orientations, for all seven study localities (Figure 24).

Locality 1 contains sites with poorly constrained anisotropy of magnetic susceptibility. K_{min} for Locality 1 sites is sub-perpendicular to the bedding planes. Localities 2 and 4 each consist of a single site; site 3 and 6 respectively. K_{min} for both sites is parallel to the bedding plane orientation suggesting inverse fabrics. An inverse fabric is consistent with the inferred magnetic mineralogy for site six, magnetite, but is inconsistent with the inferred magnetic mineralogy for site 3, hematite. Evidence for the presence of hematite consists of site 3's high unblocking temperature and the inability to completely saturate site 3 specimens with a 20,000 Oe field using a Vibrating Sample Magnetometer (VSM). Inverse fabrics occur only in single-domain titanomagnetites and maghaemites, not in hematite, multi-domain titanomagnetites, or multi-domain maghaemites (Tarling and Hrouda, 1993). This suggests that the magnetic carrier of remanence and the magnetic carrier of susceptibility for site 3 specimens may consist of separate minerals, or, alternatively, that the volcanic flow bedding plane for site 3 was improperly identified in the field. Locality 3 sites have poorly constrained anisotropy of magnetic susceptibility when compared to the entire sample suite and K_{min} axes are sub-perpendicular to the bedding planes. Locality 5 sites have K_{min} axes that are nearly perpendicular to Locality 5 bedding planes. The maximum and intermediate magnetic susceptibility axes both lay close to Locality 5 bedding planes: i.e. the magnetic foliation lies close to the flow plane. Locality 6 sites have moderately inclined bedding planes with a progression of K_{min} axes ranging from sub-parallel to perpendicular. Locality 7 sites have very gently inclined bedding planes with perpendicular K_{min} axes.

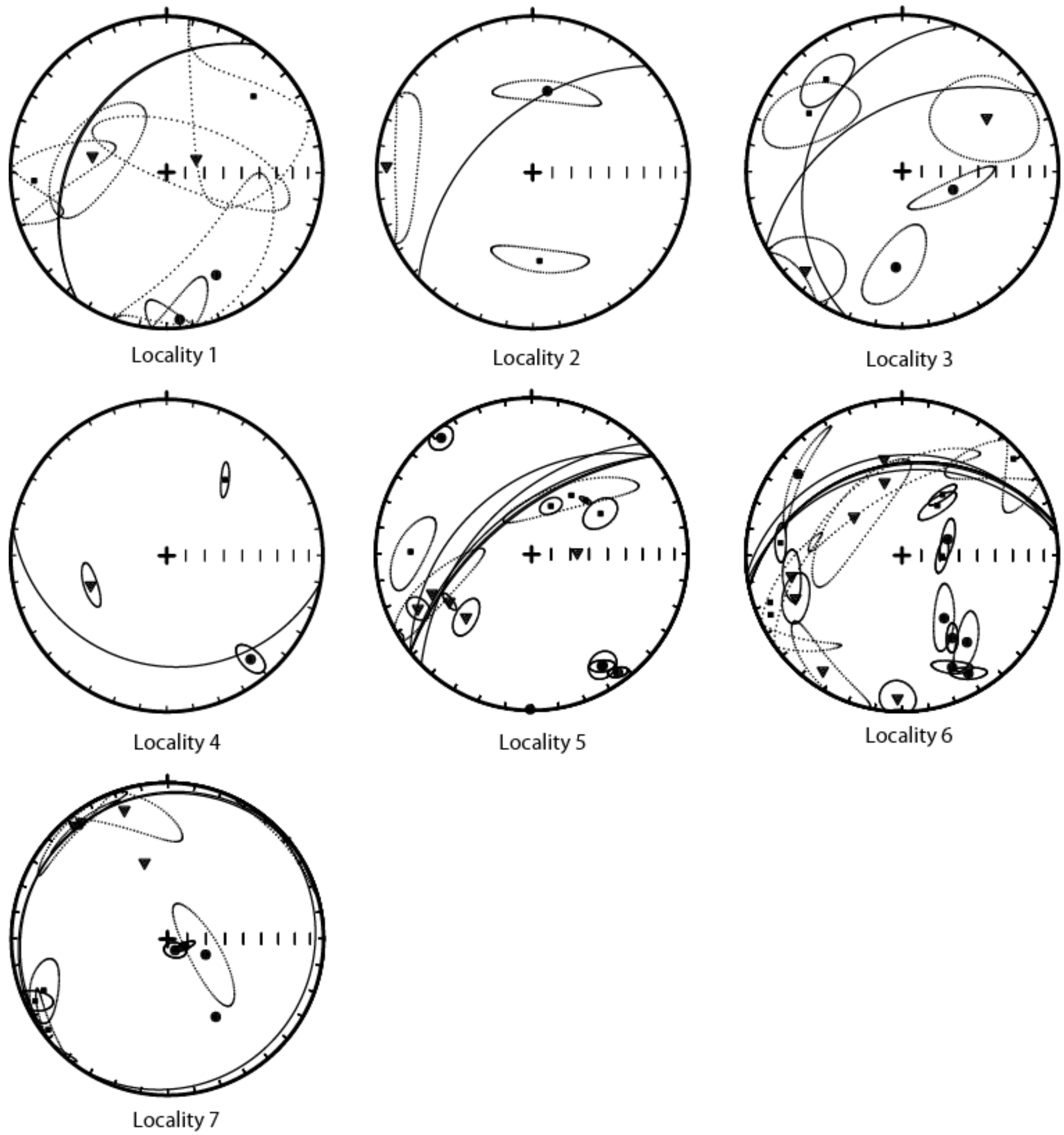

Figure 28. EA plots (geographic coordinates) with anisotropic magnetic susceptibility axes and volcanic bedding planes for sites 1-22 at localities 1-7. Circles represent minimum susceptibility axes, triangles intermediate axes, and squares maximum susceptibility axes.

Appendix B: Geochemistry of Seven Devils Study Rocks

Table 7. Geochemistry of Seven Devils Study Rocks

Site	04tvs-1a	04tvs-1b	04tvs-2	04tvs-3	04tvs-4	04tvs-5	04tvs-8	04tvs-10	04tvs-13
Locality From:	1	1	1	2	3	3	5	5	6

Normalized Major Elements (Weight %):

SiO2	51.91	53.20	53.95	51.19	49.20	54.18	46.42	57.83	52.88
TiO2	1.75	1.63	2.62	1.30	1.81	1.69	0.87	1.12	0.99
Al2O3	16.79	16.57	14.02	19.79	16.15	14.43	13.97	17.69	16.28
FeO*	12.03	11.53	13.99	10.28	13.17	13.00	7.62	10.43	10.38
MnO	0.18	0.16	0.23	0.13	0.26	0.22	0.16	0.05	0.12
MgO	6.49	4.99	4.01	3.62	8.15	4.52	2.74	3.48	2.71
CaO	6.30	7.17	6.56	7.24	6.72	8.16	21.96	2.84	10.29
Na2O	2.88	3.04	4.16	3.95	4.30	2.98	3.94	3.87	4.36
K2O	1.46	1.50	0.08	2.35	0.02	0.63	1.61	2.43	1.59
P2O5	0.22	0.20	0.39	0.17	0.21	0.20	0.69	0.26	0.40
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Major elements are normalized on a volatile-free basis, with total Fe expressed as FeO.

Unnormalized Trace Elements (ppm):

Ni	37.20	32.40	21.50	32.40	29.00	12.60	10.90	13.10	14.50
Cr	46.80	48.00	20.10	43.60	27.60	4.40	12.20	8.10	11.60
Sc	41.10	37.60	46.80	32.20	47.70	44.50	24.00	30.10	28.80
V	276.90	285.50	488.00	305.40	387.20	433.00	140.50	217.90	141.40
Ba	275.00	304.00	20.20	387.00	18.80	250.90	127.10	255.80	210.20
Rb	30.50	30.50	0.80	45.10	0.00	4.70	26.10	47.40	32.20
Sr	162.10	183.90	47.60	81.50	85.80	162.30	166.10	169.90	193.20
Zr	101.10	95.70	164.10	62.60	87.00	86.10	56.80	101.20	64.50
Y	38.90	36.00	61.60	27.70	39.60	37.40	27.20	28.90	29.10
Nb	3.10	3.00	4.70	2.00	2.80	3.70	3.00	3.20	2.90
Ga	20.90	18.50	16.50	17.30	16.20	18.90	11.00	16.80	17.00
Cu	7.70	2.80	465.50	8.10	33.50	149.40	10.00	5.00	6.50
Zn	114.00	87.90	124.60	81.10	165.40	116.50	58.30	117.50	110.00
Pb	3.50	3.50	0.70	2.90	2.20	2.00	6.60	7.10	6.10
La	8.60	6.80	10.30	4.30	5.80	5.20	7.60	9.30	5.80
Ce	18.20	18.70	28.10	16.40	18.60	17.00	8.80	26.30	17.60
Th	0.00	0.00	0.00	0.00	0.00	0.00	2.30	0.00	0.00
Nd	16.10	14.90	22.20	12.20	17.70	13.70	7.20	17.60	12.20
sum tr.	1201.70	1209.70	1543.30	1161.8	984.90	1362.30	705.70	1075.20	903.60
in %	0.12	0.12	0.15	0.12	0.10	0.14	0.07	0.11	0.09
sum m+tr	96.03	95.77	95.04	93.23	94.43	97.15	83.06	95.46	91.25
M+Toxides	96.07	95.80	95.10	93.26	94.46	97.19	83.08	95.49	91.28

Site	04tvs-1a	04tvs-1b	04tvs-2	04tvs-3	04tvs-4	04tvs-5	04tvs-8	04tvs-10	04tvs-13
Locality Collected From:	1	1	1	2	3	3	5	5	6

Unnormalized Trace Elements (oxides) (ppm):

NiO	47.34	41.23	27.36	41.23	36.90	16.03	13.87	16.67	18.45
Cr2O3	68.40	70.16	29.38	63.72	40.34	6.43	17.83	11.84	16.95
Sc2O3	63.04	57.67	71.78	49.39	73.16	68.26	36.81	46.17	44.18
V2O3	407.35	420.01	717.91	449.28	569.62	637.00	206.69	320.56	208.02
BaO	307.04	339.42	22.55	432.09	20.99	280.13	141.91	285.60	234.69
Rb2O	33.35	33.35	0.87	49.32	0.00	5.14	28.54	51.84	35.21
SrO	191.70	217.48	56.29	96.38	101.47	191.94	196.43	200.92	228.48
ZrO2	138.02	130.65	224.03	85.46	118.77	117.54	77.54	138.16	88.06
Y2O3	49.40	45.72	78.23	35.18	50.29	47.50	34.54	36.70	36.96
Nb2O5	4.43	4.29	6.72	2.86	4.01	5.29	4.29	4.58	4.15
Ga2O3	28.09	24.87	22.18	23.26	21.78	25.41	14.79	22.58	22.85
CuO	9.64	3.51	582.71	10.14	41.93	187.02	12.52	6.26	8.14
ZnO	142.78	110.09	156.06	101.58	207.16	145.91	73.02	147.17	137.77
PbO	3.77	3.77	0.75	3.12	2.37	2.15	7.11	7.65	6.57
La2O3	10.09	7.97	12.08	5.04	6.80	6.10	8.91	10.91	6.80
CeO2	22.37	22.99	34.54	20.16	22.86	20.90	10.82	32.33	21.63
ThO2	0.00	0.00	0.00	0.00	0.00	0.00	2.54	0.00	0.00
Nd2O3	18.78	17.38	25.89	14.23	20.65	15.98	8.40	20.53	14.23
U2O3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
sum tr.	1545.61	1550.56	2069.35	1482.4	1339.11	1778.73	896.57	1360.46	1133.14
in %	0.15	0.16	0.21	0.15	0.13	0.18	0.09	0.14	0.11

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